Project AIR FORCE

BOMBER R&D SINCE 1945

THE ROLE OF EXPERIENCE

Mark A. Lorell

with

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Prepared for the United States Air Force

RAND

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.520. laAnecdotal evidence suggests that experience plays a critical role in the cost-effectiveness design and development of successful military aircraft. Understanding the true situation may be essential to meet Air Force needs despite declining R&D budgets, few new programs starts, and industry contraction. To examine this issue, the authors explore the history of U.S. bomber production since the end of World War II. They conclude that relevant experience does, indeed, matter--firms develop valuable system-specific knowledge in ongoing work, and experience in important new technologies has a distinct advantage. There is far less correlation between commercial and aircraft than was once thought, so such experience is unlikely to be useful. And since major breakthroughs in technology, design approaches, and concepts have come far more often from government labs than from the commercial sector, the contribution of "dual-use" technology to future military aircraft design and development may be limited.
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PREFACE

This report assesses the major trends in the history of jet bomber design and development in the United States since World War II to evaluate the role of prior bomber and related research and development (R&D) experience among prime contractors. It builds on earlier RAND research reported in Drezner et al. (1992). A later report will include a similar survey of fighter aircraft design and development. This research is part of a larger study intended to provide a conceptual framework to analyze the future of Air Force industrial-base R&D activities. It is meant to complement another project document being prepared by Michael Kennedy, Susan Resetar, and Nicole DeHoratius that addresses the larger research effort by presenting a conceptual framework and preliminary observations for assessing military aerospace design and development capability. Some of the research and analysis in this report also appears in a RAND report being prepared by John Birkler et al., which will be a preliminary analysis of industrial-base issues and implications for future bomber design and production.

Decisionmakers and budget and program planners who are concerned about how the declining size and experience base of the U.S. military aerospace industry may affect industry's ability to support future programs based on military requirements will find this work helpful. This research should be of interest not only to our sponsor, the U.S. Air Force, but to other government agencies that are responsible for supporting military aerospace R&D as well (the Navy, Army, Advanced Research Projects Agency, and National Aeronautics and Space Administration).

This research project was sponsored by the Air Force Acquisition Headquarters and the Aeronautical Systems Center at Wright Patterson Air Force Base. It was performed within the Resource Management and System Acquisition Program of RAND's Project AIR FORCE.

PROJECT AIR FORCE

Project AIR FORCE, a division of RAND, is the Air Force federally funded research and development center (FFRDC) for studies and analyses. It provides the Air Force with independent analyses of policy alternatives affecting the development, employment, combat readiness, and support of current and future aerospace forces. Research is being performed in three programs: Strategy, Doctrine, and Force Structure; Force Modernization and Employment; and Resource Management and System Acquisition.

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Past and ongoing RAND research suggests that the role of experience—of steadily building up and maintaining expertise over time through constant "learning by doing"—plays a critical role in the cost-effective design and development of successful military aircraft. Yet most of the evidence supporting this statement is anecdotal. Achieving a better understanding of the role of experience in military aircraft R&D may be crucial for maintaining a viable U.S. industry-base capability for the future in an era of declining R&D budgets, few new program starts, and industry contraction. This report attempts to discover insights and clarifications about the role of experience in military aircraft R&D through a systematic and thorough review of the overall historical record from the early 1940s to the present of the major prime contractors in developing new bomber aircraft.[1] This research complements and supports other theoretical and historical research reported elsewhere.[2]

Our analysis uses the distinctions regarding aerospace contractor capabilities developed by Hall and Johnson (1968). These two ana-

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[1]Our analysis covers dedicated heavy (strategic) and medium (tactical) bombers but excludes "attack" aircraft, such as the A-7 or A-10, and fighter-bombers, such as the F-4E or F-15E.

[2]Michael Kennedy, Susan Resetar, and Nicole DeHoratius of RAND are preparing a report that addresses the main preliminary findings of the larger research effort, which presents a conceptual framework and preliminary observations for assessing military aerospace design and development capability.

lysts argue that three types of capabilities are resident in the aerospace industry: *general, system specific,* and *firm specific.* General capabilities are possessed by all active contractors in the industry and are necessary for all firms to function and survive in the industry. System-specific capabilities are only possessed by certain firms that specialize in specific types of aerospace systems. We argue that system-specific capabilities are critical for successful bomber R&D and are directly related to experience in developing bombers. Firm-specific capabilities are possessed by only one or a handful of firms and arise from unique activities or a combination of all activities of that firm. Firm-specific capabilities are also largely a product of experience. However, we determine that firm-specific capabilities have often been extremely important during the history of bomber R&D and have not always been the result of experience in bomber development. We conclude, however, that both system- and firm-specific capabilities are necessary for contractor success.

For analytical purposes, this report divides the five decades since World War II into three broad periods of bomber development. Each period is characterized by different clusters of dominant technology challenges, military requirements, procurement environments, and attitudes toward the role and importance of the heavy bomber.

The first period covers about 15 years from the mid-1940s to the end of the 1950s. It is characterized by the central role of the bomber in U.S. military planning in the era dominated by nuclear weapons and the doctrine of massive retaliation. More importantly, it is a period of dramatic technological change and innovation, when the government funded large numbers of procurement and technology demonstration programs.

The second period stretches from the beginning of the 1960s into the mid-1970s. It is characterized by increasing doubts about the role and utility of the strategic bomber, as national leaders discarded the massive retaliation doctrine in favor of flexible response, with its greater emphasis on conventional operations. A combination of technology trends, the emergence of new weapon systems, skyrocketing R&D costs, dramatic changes in procurement approaches by the government, and changing doctrine led to a period of great uncertainty in bomber R&D. Not a single new bomber completed development during this period.

Finally, the third period, which extends from the mid-1970s to the present, is dominated by the stealth revolution. Similar to the first period, this period is characterized by dramatic advances in technology that breathe new life into the strategic bomber and shake up the existing leadership ranks in bomber R&D among aerospace contractors.

CONCLUSIONS

Based on our examination of the history of bomber R&D in the United States since the mid-1940s, we conclude that:

- Experience matters. Prime contractors tend to specialize and thus develop system-specific expertise. For most of the period under consideration, successful contractors built on a clear and uninterrupted progression of related R&D programs, as well as design and technology projects. A strong experience base in specific types of military aircraft R&D or in specific technology areas appears to have been extremely important. Special measures for maintaining the experience base may be critical for a viable aerospace industry capable of meeting future military requirements.
- The historical evidence indicates far less correlation between expertise in commercial transport development and successful bomber R&D than originally anticipated. However, there appears to be a strong link between expertise in fighter development and bomber R&D. Therefore, commercial aircraft development programs are unlikely to provide the necessary experience base for future military aircraft R&D programs.
- During periods of normal technological evolution, high intraindustry entry barriers prevent prime contractors from changing their areas of specialization, further suggesting the importance of system-specific expertise. During periods of radical technological change, however, entry and success in new areas of specialization take place, causing major changes in R&D leadership. This suggests that a dynamic military aircraft industrial base may require more than two or three prime contractors or specialized divisions.

- Over the last 50 years, dedicated military R&D conducted or directly funded by the U.S. government has been critical in the development of new bomber capabilities. Major new breakthroughs in bomber technology, design approaches, and concepts have come far more often from government labs than from the commercial sector. As a result, the contribution of "dual use" technology to future military aircraft design and development may be relatively limited.

ABBREVIATIONS

AMSA	Advanced Manned Strategic Aircraft
ARPA	Advanced Research Projects Agency
ATA	Advanced Tactical Aircraft
ATB	Advanced Technology Bomber
ATF	Advanced Tactical Fighter
CAS	Close air support
CSIRS	Covert Survivable In-weather Reconnaissance and Strike
DARPA	Defense Advanced Research Projects Agency (now ARPA)
DoD	Department of Defense
FBW	Fly-by-wire
GE	General Electric
GEBO	Generalized Bomber Study
ICBM	Intercontinental ballistic missile
IOC	Initial operational capability
IR	Infrared
LTV	Ling Temco Vought
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
OSD	Office of the Secretary of Defense
R&D	Research and development
RAM	Radar absorbing material
RCS	Radar cross section
RFP	Request for proposal
SAC	Strategic Air Command
TFX	Tactical fighter, experimental
THAP	Tactical High-Altitude Penetrator

UAV	Unmanned aerial vehicle
VG	Variable geometry
XST	Experimental stealth technology test bed

Chapter One

INTRODUCTION

BACKGROUND AND OVERVIEW

Past and ongoing RAND research suggests that the role of experience—of steadily building up and maintaining expertise over time through constant "learning by doing"—plays a critical role in the cost-effective design and development of successful military aircraft. Drezner et al. (1992, p. 14) argued that "experience in designing, building, and testing aircraft is a crucial asset for design capability." These RAND analysts further maintained that:

> [T]o be really good at designing combat aircraft, members of a design team must have had the experience of designing several such aircraft that actually entered the flight-test stage. Paper designs and laboratory development are important, but they are not a substitute for putting aircraft through an actual flight-test program. (Drezner et al., 1992, p. 16.)

Much of the evidence that supports these views, however, is subjective and anecdotal. The crucial importance of experience seems intuitively reasonable, and is supported almost universally by the strongly held opinions of aerospace industry managers and engineers. Yet it is difficult to amass quantifiable data that demonstrate conclusively and with precision the importance of experience in the design and development of military aircraft.

Achieving a better understanding of the role of experience in military aircraft research and development (R&D) may be crucial for maintaining a viable industry base for the future. With the continually shrinking number of new program starts and ongoing contraction of the aerospace industry, defense planners may need to implement special measures to maintain the capability of the aerospace industry to meet future military R&D requirements. The effective formulation of such measures requires an in-depth understanding of all the factors that contribute to superior design and development capabilities.

This report attempts to discover insights and clarifications about the role of experience in military aircraft R&D through a systematic and thorough review of the overall historical record of the major prime contractors in developing new bomber aircraft. A forthcoming companion report examines the major historical trends in fighter design and development since World War II.[1] Our objective is to learn to what extent—and how—prime contractors built and maintained a competitive design and development capability for bomber and fighter aircraft over the past 50 years through experience and learning by doing. We are interested in improving both our understanding of the relative importance of experience in maintaining design and development capability and the processes through which firms acquire experience. This work complements and supports other theoretical and historical research being reported elsewhere.[2]

We recognize that such an approach has many methodological limitations. To assemble a meaningful sample of cases, a considerable period covering several decades must be surveyed. Over such a long time, the technologies, requirements, acquisition regulations, R&D approaches, definitions of a successful program, and a myriad of other important factors often change radically. In addition, detailed data on costs, the numbers and experience of engineers at firms assigned to specific projects, and a wide variety of other key program attributes are often no longer available. Thus, even a careful and

[1]The companion report on the importance of experience in the development of fighter aircraft, by the same authors, is currently in preparation.

[2]Michael Kennedy, Susan Resetar, and Nicole DeHoratius of RAND are preparing a report that addresses the main preliminary findings of the larger research effort, which presents a conceptual framework and preliminary observations for assessing military aerospace design and development capability.

systematic examination of the historical record is not likely to provide quantifiable results showing the precise importance of experience. Nonetheless, we believe that an historical overview can yield a range of significant insights and inferences about the R&D process and the role of experience that complements other research approaches.

We chose to examine the overall U.S. industry record in designing and developing jet bomber aircraft over the 50 years spanning the early 1940s to the mid-1990s. This period encompasses the introduction and rapid rise to near-total dominance of jet-powered military aircraft and coincides with the post–World War II era dominated largely by the Cold War. In this report, we focus primarily on the development of strategic and dedicated medium bombers during this period. Strike and attack aircraft derived from fighters, such as the F-15E, and those developed explicitly for tactical and close air support operations, such as the A-7 or the A-10, are not included. However, this report does touch on the development of a variety of fighters, prototypes, technology demonstrators, unmanned flying vehicles, and military and commercial transports, when there appears to be a close relationship between their design and technology challenges and those for bombers. Less attention is devoted to specialty aircraft, trainers, missiles, space vehicles, and so forth, although these other types are not entirely ignored.

There are several reasons for the selection of this approach. By focusing on the development of dedicated bomber aircraft in this report, we bound the problem and are able to work with a manageable though highly diverse number of programs. More importantly, we believe the skills and knowledge base necessary to develop bombers—as well as fighters—are in many respects unique. Broad generic design methodologies, technologies, processes, and management approaches are applicable to many types of aircraft and other aerospace products. Yet the performance and technological demands confronting developers of modern jet bombers and fighters usually far exceed those of contemporary commercial transports, and of many other types of aircraft, in design, materials, avionics (radars and other electronics), engines, system integration, and many other important aspects. Bomber design and development appear to require skills and approaches that sometimes differ significantly from other types of aircraft, including fighters.[3]

Nonetheless, bombers have historically had more central design and technology issues in common with large aircraft and other types of platforms than with fighters. Heavy subsonic bombers, such as the Boeing B-47 and B-52 developed in the early 1950s, posed some design and R&D problems similar to those for contemporary fighters, as well as some similar to those for commercial jet transports, military transports, and aerial tankers that were under development at about the same time. On the other hand, the Convair B-58 and the North American B-70 supersonic bomber programs launched in the 1950s provided major technology challenges that differed significantly from contemporary commercial and military transport aircraft development efforts. In many respects, these challenges were more akin to those posed by the most advanced fighters of the period, especially in the case of the B-58. Particularly in the 1950s, a clear R&D synergy existed between supersonic bombers and fighters, as well as between subsonic bombers and other large aircraft, such as tankers, military transports, and commercial transports. Consequently, it would be misleading to examine bomber R&D without referring to developments in other types of aircraft, especially fighters.

RESEARCH APPROACH AND METHODOLOGY

The central research hypothesis of this report is that experience is a key factor that helps aerospace prime contractors build and maintain credible capabilities in military R&D. If this hypothesis is correct, we would assume that extensive prior experience in bomber development and closely related weapon systems and technologies was a critical factor behind the success of those U.S. prime contractors that succeeded in bomber R&D in the postwar period.

To investigate this hypothesis, we follow the methodology laid out below:

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[3]An extended discussion of the unique characteristics of bomber R&D is included in forthcoming RAND work by John Birkler et al., a report providing a preliminary analysis of industrial-base issues and implications for future bomber design and production.

- Generate clear and simple definitions of contractor R&D "credibility" and "success."
- Define and explicate the concept of "experience."
- Compare and contrast differing periods characterized by dramatically different technology drivers, procurement environments, and so forth.
- Examine what historical correlations exist between "success" and "experience," using the development of bombers in the United States from the early 1940s to the mid-1990s as the sample.

Defining "Credibility" and "Success"

To investigate our hypothesis, it is important to arrive at a clear understanding of what is meant by "credibility" and "success." It is nearly impossible to pick acceptable and fair criteria for judging and comparing the relative success of R&D programs over a half-century period in the areas of cost, schedule, performance, and operational success. The variations over this period in procurement regulations, acquisition styles and philosophies, rates of technological change, levels of technical uncertainty and risk, and so forth, are too great to arrive at a simple list of reasonable criteria. Put simply,

> A contractor is defined as having credible R&D capabilities if it is taken seriously by the governmental customer and the industry press on entering design, technology demonstration, and/or R&D contract competitions.

We define a *successful* contractor as one that

- wins one or more major competitive R&D contracts
- completes R&D
- develops a weapon system that is accepted by the military and that is operationally deployed.

Industry leaders are defined as those successful contractors that repeatedly win design competitions over time and satisfactorily complete R&D according to the above criteria. By and large, industry leaders are also widely recognized by a general consensus of the government customers and the industry as a whole during any given period.

A critical assumption of these definitions is that—at least in the great majority of instances—the company that wins a major competition has been judged primarily on the technical merit of its proposed design and its anticipated capability to develop the aircraft successfully. In other words, the best design, with the most credible and capable contractor, is assumed to win the competition. Although this notion has often been attacked in the popular press and elsewhere, it has never been proven wrong. Indeed, considerable evidence presented in this report and elsewhere suggests that this assumption is for the most part accurate.[4]

Defining "Experience"

Most simply put, experience is defined as significant previous design and/or R&D work that provides and improves skills necessary to design and develop bombers credibly and successfully. To refine our definition further, however, we make several important conceptual distinctions that two RAND analysts, G. R. Hall and R. E. Johnson, originally developed nearly three decades ago regarding the skills and capabilities resident in the aerospace industry (Hall and

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[4]In an unpublished manuscript, Frederick Biery (formerly of RAND) notes that it is commonly alleged that economic and political considerations play a central role in the selection of contractors to develop major weapon systems. After examining 31 major aerospace weapon system programs from the 1960s through the 1980s, Biery found no evidence to support this hypothesis. Rather, he concluded that strategic, bureaucratic, and technological factors are more important for explaining the selection of winners. Another recent published scholarly study (Mayer, 1991, p. 210) concluded

> Put simply, congressional support of defense spending and of Pentagon contracting decisions is based less on pork barrel than is widely assumed. There is little systematic evidence that members vote against their policy preferences on weapon programs because of local economic impact; the Pentagon does not, indeed cannot, distribute defense contracts (as opposed to bases) for political purposes. Political explanations of contracting decisions describe neither process nor outcomes adequately and oversimplify a vastly complicated decision-making structure. Indeed, one reason pork barrel explanations are so attractive is that they are simple, parsimonious, and persuasive. They are also mostly wrong.

Johnson, 1968). These analysts divided aerospace industry knowledge and capabilities into three categories: *general, system specific,* and *firm specific. General* knowledge and capabilities are common to the entire industry and are necessary for entry into the industry. They run the gamut from basic science and mathematical knowledge to specialized skills, such as tool making and computer programming. All active aerospace prime contractors possess this general knowledge and these capabilities at least up to some minimum level necessary to remain active in the industry.

System-specific knowledge and capabilities are acquired by firms that engage in certain projects or tasks and that design, develop, and manufacture specific types of articles. All or most companies that develop the same item are likely to possess them. According to the RAND analysts, they comprise:

> ingenious procedures connected with a particular system, solutions to unique problems or requirements, and experiences unlike those encountered with other systems. (Hall and Johnson, 1968, p. 5.)

This concept suggests that not all aerospace prime contractors will possess the same level of system-specific knowledge and capabilities at any given time, because some firms will have knowledge and experience in specific types of systems, and others will not. According to this framework, some firms will be better than others at designing and developing bombers, for example, and will thus be more likely to win design-and-development competitions in their areas of specialization. These will be the leading contenders for contracts in any competition for a specific type of system.

But why does one company with system-specific knowledge win out over another company with system-specific knowledge, often repeatedly? This phenomenon is explained in part by the concept of *firm-specific* knowledge and capabilities. These are defined as those possessed by only one or at most just a few companies among all the companies that make the *same* item. These capabilities "cannot be attributed to any specific item the firm produces," but rather result "from the firm's over-all activities." (Hall and Johnson, 1968, p. 5.) Thus, even firms that develop and manufacture similar items may have different levels of knowledge and capabilities based on the totality of their overall experience base, their management and organization, corporate culture, and so forth.

As is shown by the examination of the historical record beginning in Chapter Two, the contractors that usually won R&D competitions for bombers were those with the greatest system-specific experience in bomber development. Clearly, system-specific capabilities are directly related to system-specific experience.

Later in this report, we argue that firm-specific knowledge is a critically important concept that plays a central role in the changes in leadership in the industry that take place during periods of great technological change. We conclude that, during periods of great technological change, firm-specific capabilities can be more important than system-specific capabilities.

Three Postwar Periods of Bomber R&D

For analytical purposes, this report divides the five decades since World War II into three broad periods of bomber development. Each period is characterized by different clusters of dominant technology challenges, military requirements, procurement environments, and attitudes toward the role and importance of the heavy bomber. These periods are summarized in Table 1.

Division of the postwar period into these three periods is only meant to serve as a broad conceptual guideline. There is no distinct begin-

Table 1

Three Broad Periods of Postwar Bomber Development

Time Frame	Doctrine and Bomber Role	Procurement Environment	Dominant Performance Goals	Technology Drivers
1940s–1950s	Massive retaliation, central role	Many R&D programs	Speed, ceiling, range	Aerodynamics, propulsion, materials
1960s–1970s	Flexible response, role in question	Few R&D programs, none completed	Low-level, high-speed penetration	Avionics, system integration
1970s–1990s	Flexible response, role in question	Few R&D programs, two completed	Stealth	Airframe shaping, materials, avionics

ning or end point for any of the three periods. Indeed, there is considerable overlap between one period and the next. Nonetheless, the periods are dramatically different in several respects and thus require separate treatment. The first period covers about 15 years, from the mid-1940s to the end of the 1950s. It is characterized by the central role of the bomber in U.S. military planning in the era dominated by nuclear weapons and the doctrine of massive retaliation. More importantly, it is a period of dramatic technological change and innovation, when the government funded large numbers of procurement and technology demonstration programs.

The second period stretches from the beginning of the 1960s into the mid-1970s. It is characterized by increasing doubts about the role and utility of the strategic bomber, as national leaders discarded the massive retaliation doctrine in favor of flexible response, with its greater emphasis on conventional operations. A combination of technology trends, the emergence of new weapon systems, skyrocketing R&D costs, dramatic changes in the government's procurement approaches, and changing doctrine led to a period of great uncertainty in bomber R&D. Not a single new bomber completed development during this period.

Finally, the third period, which extends from the mid-1970s to the present, is dominated by the stealth revolution. Similar to the first period, this period is characterized by dramatic advances in technology, which breathe new life into the strategic bomber and shake up the existing leadership ranks in bomber R&D among aerospace contractors.

CONCLUSIONS

Using the methodology discussed above, the remainder of this report carefully surveys postwar bomber development for insights into the importance of experience. A preview of our conclusions is presented below:

- Experience matters. Prime contractors tend to specialize and thus develop system-specific expertise. For most of the period under consideration, successful contractors built on a clear and uninterrupted progression of related R&D programs, as well as design and technology projects. A strong experience base in specific types of military aircraft R&D or in specific technology areas appears to have been extremely important. Special measures for maintaining the experience base may be critical for a viable aerospace industry capable of meeting future military requirements.

- The historical evidence indicates far less correlation between expertise in commercial transport development and successful bomber R&D than originally anticipated. However, there appears to be a strong link between expertise in fighter development and bomber R&D. Therefore, commercial aircraft development programs are unlikely to provide the necessary experience base for future military aircraft R&D programs.

- During periods of normal technological evolution, high intra-industry entry barriers prevent prime contractors from changing their areas of specialization, further suggesting the importance of system-specific expertise. During periods of radical technological change, however, entry and success in new areas of specialization take place, causing major changes in R&D leadership. This suggests that a dynamic military aircraft industrial base may require more than two or three prime contractors or specialized divisions.

- Over the last 50 years, dedicated military R&D conducted or directly funded by the U.S. government has been critical in the development of new bomber capabilities. Major new breakthroughs in bomber technology, design approaches, and concepts have come far more often from government labs than from the commercial sector. As a result, the contribution of "dual-use" technology to future military aircraft design and development may be limited.

ORGANIZATION OF THIS REPORT

Chapters Two through Four examine the historical record for each of the three periods of bomber development in detail. Included are specific notes on the role of experience—with new technologies as well as types of systems—and the influences of the then-current strategic environments. Chapter Five elaborates upon the conclusions noted above.

Chapter Two

THE 1940s AND 1950s: EVER FASTER AND HIGHER

The first era of bomber development stretches from the mid-1940s through the end of the 1950s. This was a period of revolutionary change made possible by turbojet engines. During this period, contractors developed America's first and second generations of jet fighters and bombers, while nearly all other military aircraft, as well as commercial transports, began transitioning from piston engines to jet or turboprop propulsion. The era was characterized by rapid technological evolution and considerable innovation, particularly in aircraft propulsion, airframe design, and materials. The government funded a remarkable array of fighter and bomber R&D programs, ranging from full-scale development of new operational aircraft to technology demonstration prototypes. Indeed, more military aircraft designs were developed and reached first flight during the 1950s than in all the following four decades combined. (Drezner et al., 1992, p. 28.)

Throughout most of the 1950s, President Eisenhower's heavy reliance on a deterrent policy of "massive retaliation" led to an emphasis on specialized strategic and tactical nuclear missions for the armed forces. The Air Force and—to a somewhat lesser extent—the Navy tended to seek fighters and bombers designed to operate in a theater or strategic nuclear environment, in support of offensive nuclear operations or defending against enemy strategic nuclear attack. As the key platforms for delivering strategic nuclear weapons, bombers enjoyed a high priority for R&D and procurement in defense budgets of the period. (See Coulam, 1977, p. 47; White, 1974, pp. 67–68.)

Doctrine thus dictated a set of missions that, along with the rapidly advancing state of jet aircraft engine and airframe development during this pioneering period, determined design requirements and performance goals. These tended to stress speed, ceiling, payload, range, and penetration capabilities over maneuverability and sustained sortie rates. As Tables 2 and 3 show, the speed and altitude capabilities of bombers and fighters increased dramatically during this period, while weight and cost also escalated. First-generation fighters, such as the Lockheed F-80, boasted performance characteristics that were only modestly superior to those of the most advanced piston-engine aircraft of the era.[1] But by the early 1950s, large advances in jet turbine engine power and efficiency, the advent of the afterburner, and resolution of the basic aerodynamic design problems posed by very-high-speed flight, led to an explosion in aircraft speed and altitude capabilities. Compared to first-generation jets, second- and third-generation bombers and fighters became ever faster, higher flying, heavier, and larger to meet the requirements of strategic doctrine and the nuclear battlefield.

The 1940s and 1950s were thus characterized by rapid technological advancement and change, as developers exploited the enormous increases in potential performance made possible by the jet engine. System-specific experience seems to have been very important during this period. The dominant jet bomber developers at the end of the period—Boeing, North American, and Convair—had also been leaders in bomber R&D at the beginning of the period, during the heyday of the propeller. Nonetheless, a significant change in leadership took place during this period, which illustrates the heightened importance of firm-specific expertise during a period of rapid technological change. Boeing had been the dominant developer of heavy bombers in World War II, followed by Consolidated (later Convair). Boeing continued to lead the pack during the early postwar period of

[1]For example, the top speed of early versions of the F-80 was only a little over 100 mph faster than the most advanced versions of the piston-engine North American P-51. Having experienced German jet fighters in combat, such as the Messerschmidt Me-262 near the end of World War II, the U.S. Army Air Force strongly supported jet fighter development and procurement in the immediate postwar era. The U.S. Navy, however, remained highly skeptical and did not vigorously pursue jet fighter development until Navy pilots confronted Russian MiG-15 jets over Korea after the outbreak of the war in 1950. (See Bright, 1978, pp. 11, 15.)

Table 2

Selected U.S. Air Force Jet Fighters, 1947–1962

Aircraft	First Flight	Cost ($000)	Empty Weight (lbs)	Maximum Speed (mph)	Ceiling (feet)
F-80C	1944	584	8,240	600	42,750
F-84G	1946	1,334	11,095	622	40,500
F-86F	1947	1,181	10,950	678	45,000
F-86D	1949	1,931	13,498	692	49,600
F-89D	1948	4,501	21,000	610	48,000
F-94C	1949	3,003	12,708	600	51,400
F-100D	1953	4,201	21,000	864	47,700
F-101B	1954	9,234	28,000	1,100	50,300
F-102A	1953	6,761	19,460	825	51,800
F-104C	1954	9,797	14,082	1,450	58,000
F-105D	1955	10,508	27,500	1,480	50,000
F-106A	1956	23,859	23,646	1,525	52,000
F-4C	1958	8,803	28,540	1,500	55,400
F-111A	1964	39,922	46,172	1,450	57,900
YF-12	1962	66,282–80,781	60,000	~2,200	84,000

SOURCES: Knaack (1978); Johnson (1960).

NOTE: Costs are unit flyaway costs, estimated for a 100-aircraft production run, based on 1993 dollars. The YF-12 was not deployed operationally.

Table 3

Selected U.S. Air Force Jet Bombers in the 1950s and 1960s

Bomber	1st Flight	Takeoff Weight (000 lbs)	Maximum Speed (knots)	Combat Ceiling (feet)
Medium				
B-45A	1947	92	496	32,800
B-47A	1947	157	521	44,300
B-57B	1953	57	520	45,100
B-66B	1954	83	548	38,900
B-58A	1956	163	1,147	63,000
Heavy				
B-36A	1946	311	435	38,800
B-52B	1952	420	546	46,600
XB-70A	1964	521	1,721	75,200

SOURCE: Knaack (1988).

bomber R&D, with its highly successful B-47 and B-52 aircraft. By the end of the first postwar period, however, North American and Convair had surpassed Boeing to become the industry leaders in cutting-edge strategic bomber technology and development. A key to understanding this change in leadership was the more extensive firm-specific capabilities and expertise that North American and Convair had developed in very-high-speed supersonic flight. With the continuing Air Force emphasis on speed and ceiling, this firm-specific expertise gave North American and Convair a considerable edge against Boeing in the bomber competitions of the 1950s. These points are elaborated upon below.

FIRST-GENERATION JET BOMBERS

Most observers in 1945 would have picked Boeing, Convair, North American, and Martin as the backbone of the U.S. bomber industrial base. Boeing and Convair (Consolidated Aircraft before 1943[2]) were the dominant designers and developers of U.S. heavy bombers during World War II. Boeing's legendary B-17 and revolutionary B-29, along with Consolidated's B-24, were the most important and successful American heavy bombers during the war.[3] Derived in part from extensive company-funded studies based on the XB-15 and B-17, Boeing's B-29 design beat out rival proposals from Consolidated, Lockheed, and Douglas in mid-1940. However, Consolidated's entry was deemed good enough to merit a prototype contract and was eventually developed and produced in small numbers as the B-32 Dominator. In 1941, the Army Air Corps selected another Consolidated design as the main follow-on to the B-29. This huge bomber first flew in August 1946 as the Convair XB-36. (Swanborough, 1963, pp. 84, 143, 488.) Neither Convair nor Boeing developed operational fighters or other smaller combat aircraft during the war.[4]

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[2]In March 1943, Consolidated Aircraft merged with Vultee Aircraft to become Convair.

[3]Although less well-known than Boeing's two famous bombers, Consolidated's B-24 Liberator was built in larger numbers for U.S. and foreign armed services than any other single type of American aircraft during World War II (see Swanborough, 1963, p. 132).

[4]Boeing worked on both fighters and bombers before the war. In the 1930s, Consolidated developed the most famous seaplane used extensively in World War II,

In the category of medium bombers, North American with its B-25 Mitchell and Martin with its B-26 Marauder were industry leaders during the war. North American also enjoyed the distinction of developing America's most famous World War II fighter, the P-51 Mustang.

It is not surprising, then, that these four companies played leading roles in the effort that began late in the war to develop America's first all-jet bombers. In late 1944, the Army Air Corps selected jet medium bomber designs from each of these companies for development as prototypes. Indeed, these were also the only four companies that responded with serious proposals. North American's B-45 Tornado was the first to fly, taking to the air on its maiden flight in March 1947. Convair's XB-46 and Martin's XB-48 flew shortly thereafter. Although it first flew over six months later than its most tardy competitor, Boeing's radical new design, the XB-47, was destined to win the competition because of its dramatically superior performance. (See Knaack, 1988, p. 61.)[5]

The prototypes developed by North American, Convair, and Martin were based on conventional straight-wing designs, which in concept were similar to first-generation jet fighters like the Lockheed F-80. Boeing's effort had been delayed by a revolutionary redesign of its original design proposal, which led ultimately to America's first second-generation jet bomber. The Seattle company's engineers developed the notion of placing the jet engines in pods hung under the wing, and fully exploited critical technical data on swept wings captured from the Germans by applying a 30-degree sweepback to their

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the PBY Catalina. Before the war, the company also concentrated on trainers and a heavy fighter (the P-30). Vultee developed a fighter, attack aircraft, and light bombers, which were primarily exported. Convair and Vultee did, however, produce experimental fighter prototypes during the war. See footnote 2.

[5]Another even more unconventional jet bomber prototype design also first flew around the same time. In 1945, the Air Corps authorized Northrop to convert its XB-35 flying wing prototype—which had nearly beaten the Convair B-36 for a production contract—to jet power. This effort resulted in the YB-49, whose maiden flight took place in October 1947. The prototype broke many performance records, but proved difficult to control, with both original test aircraft destroyed in accidents. The program was eventually canceled.

wing design. (See Jones, 1980, pp. 153–165; Gunston, 1993, pp. 25–31, 38–44.)[6]

North American's B-45 eventually won a small production contract, while Convair's and Martin's programs were canceled after flight testing of the prototypes. Boeing, however, received the first of many major production contracts in 1950 for the B-47, which launched this bomber on its way to becoming the backbone of the Strategic Air Command (SAC) throughout most of the 1950s. This is not surprising, since the B-47's advanced design made it faster and more maneuverable over 20,000 feet than virtually all operational fighters at the beginning of the 1950s. Following the outbreak of the Korean War, production was ratcheted up even further, with Lockheed and Douglas brought into the program to keep up with SAC's prodigious demand for ever greater numbers of B-47s. By 1957, SAC counted about 1,800 B-47s in its inventory. Well over 2,000 of the aircraft were ultimately manufactured.

Even more successful over the long term was Boeing's famous B-52, perhaps the most important and longest-lived heavy bomber of the postwar period. Yet at the beginning of this program, the B-52 was intended to have only a relatively short service life. More will be said on this later.

With the development of the high-speed, jet-powered, swept-wing B-47 medium bomber in the late 1940s, the Air Force began looking for a fast jet design for a new heavy strategic bomber to replace the relatively slow (200–225 mph) propeller-driven Convair B-36. The Air Force wanted a heavy bomber with nearly the same high speed as the B-47 (over 500 mph) but with more than twice its range and with a much larger bomb load. Originally, designers believed the speed re-

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[6]In early 1944, the Air Corps had also issued a requirement for an advanced attack aircraft. Late in the year, three design proposals were submitted: the Convair XA-44, the Martin XA-45, and the Curtis XA-43. However, the Air Corps altered and reissued the requirement in 1947, in part to make clear that the aircraft should be jet powered and should take advantage of German data on swept wings to achieve higher speed performance. Martin won the new competition with a modified XA-45 design, which included swept wings like the B-47 and three jet engines. The aircraft was latter redesignated as a light bomber and called the XB-51. First flown in 1949, the XB-51 performed quite well and was actually faster than any current fighter except the F-86. However, the program was eventually canceled, leading to eventual procurement of a foreign-designed light bomber, the B-57. (See Gunston, 1993, pp. 65–67.)

quirement could not be met because of the low thrust rating of existing turbojet engines. With a top speed of nearly 500 mph, Northrop's jet flying-wing bomber, the YB-49, was fast, but its unconventional configuration was not favored. Most engineers believed that a more standard configuration would require turboprops that could not meet the speed requirements.

The problem was solved by the development of the Pratt & Whitney JT3 (XJ57) jet engine, which pioneered the two-spool engine concept with separate high- and low-pressure compressors. In October 1948, Boeing engineers redesigned its turboprop XB-52 proposal to take advantage of the new engine, adopting the swept-wing and podded-engine configuration that was proving so successful for the B-47. Following the award of a prototype development contract at the end of the year, Boeing moved ahead rapidly toward a first flight, which took place on April 15, 1952. (Holder, 1975, pp. 11–13; Gunston, 1993, pp. 87–88; Jones, 1980, p. 175.)

Convair, however, refused to concede victory for the next strategic bomber to Boeing without a fight. The company adopted a strategy of selling the Air Force on a high-performance modification of its existing B-36, which would possess high commonality with the bombers already in the inventory. In early 1950, Convair began design studies on an extensively modified B-36 proposal intended to overcome the speed shortcomings of its existing bomber. Like the B-52, Convair's design had an all-new swept wing and used the revolutionary J57 turbojet mounted in pods under the wing. The Air Force approved prototype development in early 1951. The virtually all-new aircraft, now designated the YB-60, first flew in April 1952, three days after the YB-52. But with a top speed nearly 100 mph less than the YB-52, the Convair design was doomed to defeat. The Air Force soon ended the YB-60 flight-test program. Boeing had already received production orders for the B-52 after the outbreak of the Korean War in June 1950, and the YB-60's poor speed performance led the Air Force to devote all its procurement funds for heavy strategic bombers to production of the Boeing aircraft. (Gunston, 1993, pp. 103–105; Jones, 1980, pp. 202–204.)[7]

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[7]Korean War pressures also resulted in Air Force adoption of two modifications of existing medium tactical jet bombers. In February 1951, the British-developed English-Electric Canberra won a fly-off competition against the North American B-45

SUPERSONIC BOMBER DEVELOPMENT

Thus, by the early 1950s, Boeing had come to dominate both the medium and heavy strategic bomber markets for the U.S. Air Force. Yet this was a period of rapid technological advancement in jet aircraft, and no one expected Boeing's preeminent position to go unchallenged for long. Indeed, as early as 1946, Air Force planners had already begun to examine the prospects for supersonic medium and heavy bombers.

The Air Force had pushed rapidly ahead on the development of supersonic fighters. In October 1947, the Bell X-1 experimental aircraft broke the sound barrier for the first time. Less than three years later, the Air Force sent out requests for proposals (RFPs) for the development of a supersonic fighter-interceptor. Convair, Lockheed, and Republic won this competition in August 1951, but Convair's effort quickly became the most important development program, leading to the F-102 Delta Dagger and the improved F-106 Delta Dart. Republic proceeded with its F-103, although the program was later canceled. Even though the Air Force had refused to fund development of the Lockheed proposal, the company went ahead on its own, eventually winning funding in 1953 for development of the F-104. Several months after the original August 1951 selection, another initial loser, North American, received funding to develop its Sabre 45 proposal, a supersonic modification of the F-86. This development ultimately resulted in the F-100, America's first operational fighter capable of sustained, level supersonic flight.[8]

As early as October 1946, the Air Corps had launched its first major investigation of design approaches for a supersonic bomber, called the first Generalized Bomber Study, or GEBO I (Miller, 1985, p. 17). With Martin beginning to lose ground following lack of success of its XB-48 and XB-51, the three remaining World War II leaders in the

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and AJ-1, the Martin XB-51, and the Avro Canada CF-100 for procurement as a U.S. Air Force tactical attack bomber. A month later, Martin received a contract to modify and produce the British aircraft as the B-57. In June 1952, the Air Force ordered procurement as a medium tactical bomber of a slightly modified version of the Navy A3D Skywarrior nuclear bomber developed by Douglas. The resulting Air Force B-66 Destroyer was so heavily modified, however, that it virtually amounted to a new aircraft.

[8]For an in-depth discussion of the development of these fighters, see Johnson (1960).

field of bomber development—Boeing, Convair, and North American—became locked in an intense competition for development of the next-generation supersonic medium and heavy strategic bombers. Despite its dramatic successes with the B-47 and B-52 programs, Boeing eventually found itself at a distinct disadvantage. Boeing showed great strengths in large subsonic jet bombers, military transports, and commercial jet aircraft. But Boeing had not developed a production fighter or even a fighter prototype since the 1930s and did not appear to have good prospects for winning a new fighter R&D competition in the early 1950s. Yet development of supersonic long-range bombers posed even greater technological challenges than supersonic fighters. Many of the cutting-edge technology breakthroughs and design solutions related to supersonic flight were being generated in fighter and fighter-related R&D programs.

Convair and North American, on the other hand, had focused on the development of supersonic flight early in the jet age and had emerged in the 1950s as industry leaders in supersonic fighter R&D. Convair had received Air Corps support in 1945 to use German delta-wing data to examine supersonic fighter concepts.[9] By 1948, Convair had developed and manufactured the delta-wing XF-92A prototype in close cooperation with the Air Force and the National Advisory Committee for Aeronautics (NACA), forerunner of the National Aeronautics and Space Administration (NASA). Originally intended as a Mach 1.5 fighter interceptor, the XF-92A became a one-of-a-kind fighter technology test vehicle. Although soon handed over to the Air Force for further flight testing, the XF-92A formed the basis for Convair's successful entry in the 1951 supersonic fighter competition, which led to the F-102 and F-106 delta-wing fighters. Meanwhile, North American forged ahead at the beginning of the 1950s with its Sabre 45 supersonic fighter design derived from its

[9]As mentioned earlier, neither Consolidated nor Vultee developed a major production fighter during World War II. However, the two companies had been involved in advanced fighter technology demonstration programs. Late in the war, Convair developed and flight-tested America's first turboprop-powered aircraft, the XF-81, which was also equipped with a pure jet engine. Earlier in the war, Vultee had developed and flight-tested an unorthodox fighter design equipped with a pusher prop, designated the XP-54. Vultee also produced an uninspired conventional fighter that the Air Corps used in very small numbers during the war, called the P-66.

enormously successful F-86 jet fighter, ultimately resulting in the highly successful supersonic F-100.[10]

But Boeing remained very much in the running throughout most of the medium supersonic bomber competition. Convair's study experience was extensive, but Boeing had also done much work of its own. Soon after the end of World War II, Convair had won a major GEBO I study contract to investigate supersonic bomber configurations and design approaches and had examined about 10,000 configurations through the late 1940s. GEBO I ended in 1949 and was immediately followed by GEBO II, which specifically looked at medium supersonic bomber concepts. Convair, Martin, Douglas, Fairchild, and other companies took part in this and other related studies. For its part, Boeing had been conducting supersonic medium bomber studies as part of the XB-55 study program starting in late 1947. Convair and Boeing soon emerged as the leading contenders and, by late 1950, were the only serious competitors. Martin and Douglas submitted proposals in 1951, which were rapidly rejected. Apparently fully involved in its fighter development programs, North American did not even bother to submit a design proposal. (Miller, 1985, pp. 17–23.)

In early 1951, Convair and Boeing received follow-on study contracts for continued refinement of their proposals, including extensive wind-tunnel testing. By the next year, Convair's design was clearly viewed by the Air Force as superior. Nonetheless, another follow-on competitive design study was funded for the two contractors, with a final decision planned for early 1953. The Convair design proposal, designated the XB-58, was by far the most technologically daring of the two. It had evolved into a delta-wing configuration closely related to the XF-92 fighter technology demonstrator and the company's F-102 proposal—which had won the fighter design competition in August 1951—with four podded jet engines under the wing, similar to existing Boeing bombers. Boeing's XB-59 proposal was a conventionally configured design, which ironically called for four engines imbedded in the fuselage at the wing roots. Both designs were estimated to be capable of Mach 2 performance and ceilings over 50,000 feet.

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[10]For a detailed discussion of the XF-92A program, see Mendenhall (1983).

In late 1952, Convair won the design competition to develop America's first supersonic bomber. Some have claimed that the Boeing design was probably as good as Convair's submission but that selection of the B-52 and cancellation of the YB-60 around the same time may have influenced the decision on the supersonic bomber competition for industrial-base reasons (Gunston, 1993, p. 174). This assertion seems unlikely. Boeing's proposal was apparently clearly inferior in supersonic capability. According to the official Air Force history, the final design evaluation by the Wright Air Development Center had "left little doubt about the forthcoming decision." Air Force experts concluded that the Boeing design "would produce either an aircraft of small size with mediocre supersonic speeds or one so large as to almost preclude any supersonic capability." (Knaack, 1988, p. 363.) In addition, the Air Force determined that Convair was considerably further along in its design study than Boeing.

The apparent technical superiority of Convair's proposal is not hard to explain. Convair had more experience in investigating supersonic bomber concepts, beginning with the 1945 GEBO I study and flight testing of its proposed supersonic delta-design configuration with the XF-92 fighter demonstrator. Furthermore, Convair could take advantage of synergies between its F-102, F-106, and B-58 development programs. Indeed, by the time Convair won the supersonic bomber competition, its B-58 design proposal had evolved into a scaled-up and refined version of the F-102. The original B-58 design was substantially modified in accordance with the "area rule" concept discovered during the F-102 program in 1952. In another example, the leading edge of the B-58 wing was redesigned before first flight to incorporate the "conical camber" design concept also developed on the F-102 program. (See Miller, 1985, pp. 25–26; Johnson, 1960, pp. 20–21; Gunston, 1993, p. 175.)[11]

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[11]Boeing did have some experience developing supersonic airframes. In the late 1940s, the company developed the Ground-to-Air Pilotless Aircraft, an unmanned supersonic winged missile or drone with a range under 35 miles intended to shoot down enemy aircraft. The program was canceled, however, before the completion of R&D. In the early 1950s, Boeing started work on the much-longer-range Bomarc air defense missile, a Mach-2 hybrid rocket and pilotless plane. The first Bomarc prototype crashed almost immediately after launch on its first flight in 1954. Although the missile was eventually procured by the Air Force for continental air defense, the development program experienced many problems. (Serling, 1992, pp. 161–166.)

Because of the extremely harsh demands placed on aircraft structure, propulsion systems, and other areas by sustained flight at twice the speed of sound, development of the B-58 pushed the very frontiers of current knowledge on aerodynamic design, materials, engines, avionics, and many other areas. As in the case of the B-52, breakthroughs in engine technology had been critical to the development of the B-58. General Electric (GE) solved key engine problems related to supersonic flight with the development of variable-incidence compressor stator blades in 1951. In 1952, GE began development of what eventually became the J79 turbojet, which became one of the most widely used engines in fighters and bombers in the late 1950s and 1960s.

While one of the most important and technologically demanding bomber programs of the era, the B-58 was not the ultimate prize for bomber developers in the 1950s; rather, the Holy Grail for contractors remained the future heavy strategic bomber to replace the B-52. North American, Boeing, and Convair bitterly fought for this contract (along with other less likely candidates), while Martin attempted to remain alive in the bomber field with a new supersonic medium bomber. But Martin continued to fade, and after losing the B-58 competition, Boeing worked under the severe disadvantage of having no supersonic bomber or fighter projects on which to build its technological and design expertise. Meanwhile, Convair and North American continued to accumulate extensive experience on supersonic flight vehicles.

In the early 1950s, rapid advancement of technology and the explosive growth in potential performance capabilities continued. Because of these factors, the Air Force leadership expected the subsonic B-52 to remain in the inventory for only a relatively short time. In 1954, before the first flight of the first production B-52, SAC began looking at future heavy strategic bomber options. Two concepts emerged: Weapon System 110A, which called for a Mach 2+ bomber, and Weapon System 125A, which envisioned a nuclear-powered bomber. Weapon System 110A posed a demanding requirement indeed: essentially, the development of a bomber with the B-52's range and payload combined with the B-58's very-high speed. (Pace, 1984, pp. 9–10.)[12]

Convair and Lockheed won study contracts for the nuclear-powered bomber program. Convair even flew an operating nuclear reactor in a heavily modified B-36.[13] By the end of the decade, however, it became evident that such a bomber was not entirely practical. The Mach 2+ strategic bomber program elicited far more contractor interest, with numerous firms entering the fray. In July 1955, six companies were selected as finalists and received study contracts: North American, Convair, Boeing, Martin, Douglas, and Lockheed. Late in the year, the Air Force eliminated four of the contenders, leaving North American and Boeing alone to fight it out with follow-on study contracts.[14]

The technical problems facing the engineers were daunting, and the competition was fierce. With the loss of the medium supersonic bomber competition and no fighter projects on the horizon, this was a must-win for Boeing. Likewise, North American had to win to stay in the Air Force bomber business. To meet the range, payload, and supersonic dash requirements, both design teams resorted to "floating wing tips," large wing extensions with huge fuel tanks that would be jettisoned prior to supersonic dash to the target. The Air Force rejected both companies' proposals in early 1957, telling them to go back to the drawing board. North American then discovered a paper written by NACA aerodynamicists in early 1956 explaining their discovery of "compression lift," an aerodynamic phenomenon that was postulated to dramatically increase lift-to-drag ratios at high supersonic speeds. North American completely reworked its design

[12]Actually, the requirement originally asked for supersonic dash over the final 1,000 miles to the target.

[13]Convair received the original Air Force contract in 1951 to modify two B-36Hs to carry GE nuclear reactors. Although this contract was eventually canceled, flight testing of a modified B-36 used as a nuclear-reactor-shield test aircraft took place between 1955 and 1957. Convair, Boeing, Lockheed, and Martin all took part in design studies during this period on subsonic and supersonic nuclear-powered strategic bombers. (See Miller, 1983b, pp. 65–67.)

[14]It is surprising that Convair was eliminated, although the company was clearly fully occupied with the F-102, F-106, B-58, and nuclear-powered bomber programs. Little information is available in published sources on the criteria used for selection of the winners.

and ran new wind-tunnel tests in response to the paper's findings. These tests indicated that the new design could travel the full required mission radius at *Mach 3* without the absurd floating wing tips. Boeing was told to revise its proposal to incorporate compression lift concepts. Although the Seattle company extensively modified and improved its design, called the B-110 proposal, Boeing engineers remained skeptical about the compression lift concept and doubted North American's data.[15] Both teams submitted their revised proposals in the summer of 1957. (Pace, 1984, pp. 11–14; Gunston, 1993, pp. 220–221.)

On December 23, 1957, the Air Force selected North American as the winner to develop the XB-70 strategic bomber. Shocked at the loss, Boeing demanded and received a congressional investigation of the decision. The investigation concluded that the Air Force had chosen North American's proposal because it was technically superior, particularly in its incorporation of compression lift aerodynamic concepts. (Pace, 1984, p. 15.) According to the official Air Force history, the North American design had been found "unanimously to be substantially superior to that of Boeing" by a 60-member team representing the Air Material Command, the Air Research and Development Command, and SAC. (Knaack, 1988, p. 566.)

Furthermore, by the late 1950s, North American had clearly accumulated an extensive amount of experience in the design and development of advanced supersonic air vehicles, which undoubtedly contributed to the quality and credibility of its proposal. As early as 1946, the company had been selected as the prime contractor in one of the most important pioneering R&D efforts regarding supersonic flight, the Air Force X-10/SM-64 Navaho program. Unlike the much slower and more conventional Martin TM-61 Matador and Northrop SM-62 Snark cruise missile programs and the much-shorter-range Boeing Bomarc effort, this program sought to develop an unmanned intercontinental Mach-2.75 cruise missile to deliver strategic nuclear weapons over 5,000 miles against the Soviet Union. The first phase of this remarkably ambitious program aimed at developing the X-10 test vehicle intended to investigate supersonic cruise aerodynamics.

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[15]Boeing's supersonic wing design for the B-110 reportedly drew heavily on experience from developing the Mach 2 Bomarc air defense missile. See Footnote 11.

North American engaged in general design studies in the late 1940s and launched the specific X-10 design effort in 1950. The X-10 experienced a successful first flight in October 1953 and later achieved speeds of over Mach 1.8. Three X-10s and seven XSM-64 weapon systems were manufactured prior to the program's cancellation in 1957. (Miller, 1983b, pp. 81–85.)

North American's pioneering F-100 program, which included many technological and design innovations and led to the Air Force's first supersonic fighter, has already been mentioned. Yet perhaps even more relevant, the X-10/Navaho, with an empty weight of nearly 26,000 pounds, was in the same weight class as most of the Century Series fighters, and thus in many respects was similar to a Mach 2+ long-range fighter R&D program. The Navaho effort is clearly recognized as contributing significantly to the XB-70 design and development effort. (Jones, 1980, p. 214.) Indeed, early North American bomber design proposals submitted in 1956 were merely scaled-up versions of the Navaho. (Knaack, 1988, p. 563.) Following cancellation of the XSM-64, the Air Force continued to fund flight testing of the prototypes specifically to carry out further investigation of very-high-speed aerodynamics, system integration, and so forth, in support of the XB-70 program. (Miller, 1983b, p. 84.)

Another experimental aircraft program that clearly contributed to North American's credibility and experience was the X-15. NACA launched this program in the early 1950s to explore very-high speed, high-altitude flight at speeds of Mach 4 to 10. In 1954, North American, Douglas, Bell, and Republic submitted design proposals. NACA announced that North American had won the design competition in September 1955. The winning contractor further refined its design and began construction of the first aircraft in June 1956, a year and a half before the conclusion of the XB-70 competition. The first unpowered test flight of the X-15 took place just three months after North American won the bomber competition. Thus, North American would be flight-testing this very-high-speed rocket aircraft during the same period that it needed to refine its XB-70 design and launch full-scale development. The X-15 program would provide extensive information about materials, subsystems, and a myriad of other issues related to high-speed flight. (See Miller, 1983b, pp. 101–115.)

A final area of critical experience supporting North American's efforts related to the development of a very technologically advanced Mach 2 strategic bomber for the Navy. North American began work on this project in 1954. The Navy awarded a prototype development contract for the company's A3J design (later A-5) in September 1956; as the aircraft took shape, it showed that many novel developments in aerodynamics and systems had been incorporated. When North American won the B-70 contract, the company was only eight months away from first flight of the A3J. (Gunston, 1993, pp. 187–189.)

THE ROLES OF EXPERIENCE AND INNOVATION

Thus, by 1958, North American and Convair, having successfully drawn on their extensive participation in advanced bomber studies, supersonic technology development programs, and major supersonic fighter R&D efforts, seemed to be well on their way to becoming America's premier bomber developers. Their experience with Air Force fighter and bomber programs throughout the era, as well as with high-speed test aircraft and unmanned vehicles, was impressive, as is shown in Figure 1, which illustrates most major jet bomber, fighter, and related R&D programs in the 1940s and 1950s. These two contractors probably could be characterized by the late 1950s as with the foremost combat aircraft developers for the Air Force. No other companies could match the range and breadth of their fighter and bomber R&D. They possessed the unique combination of system-specific and firm-specific capabilities necessary to lead the field during this era.

Boeing's position in combat aircraft had been severely weakened by the end of the decade. Boeing's B-47 and B-52 were proving highly successful, but it did not seem likely that these bombers would remain in the inventory very far into the 1960s. Although it was the developer of the most famous heavy bombers of World War II, Boeing viewed its future in combat aircraft as rather bleak. It had lost the most important medium and heavy bomber development projects of the 1950s, at least in part because of its lack of experience in super-

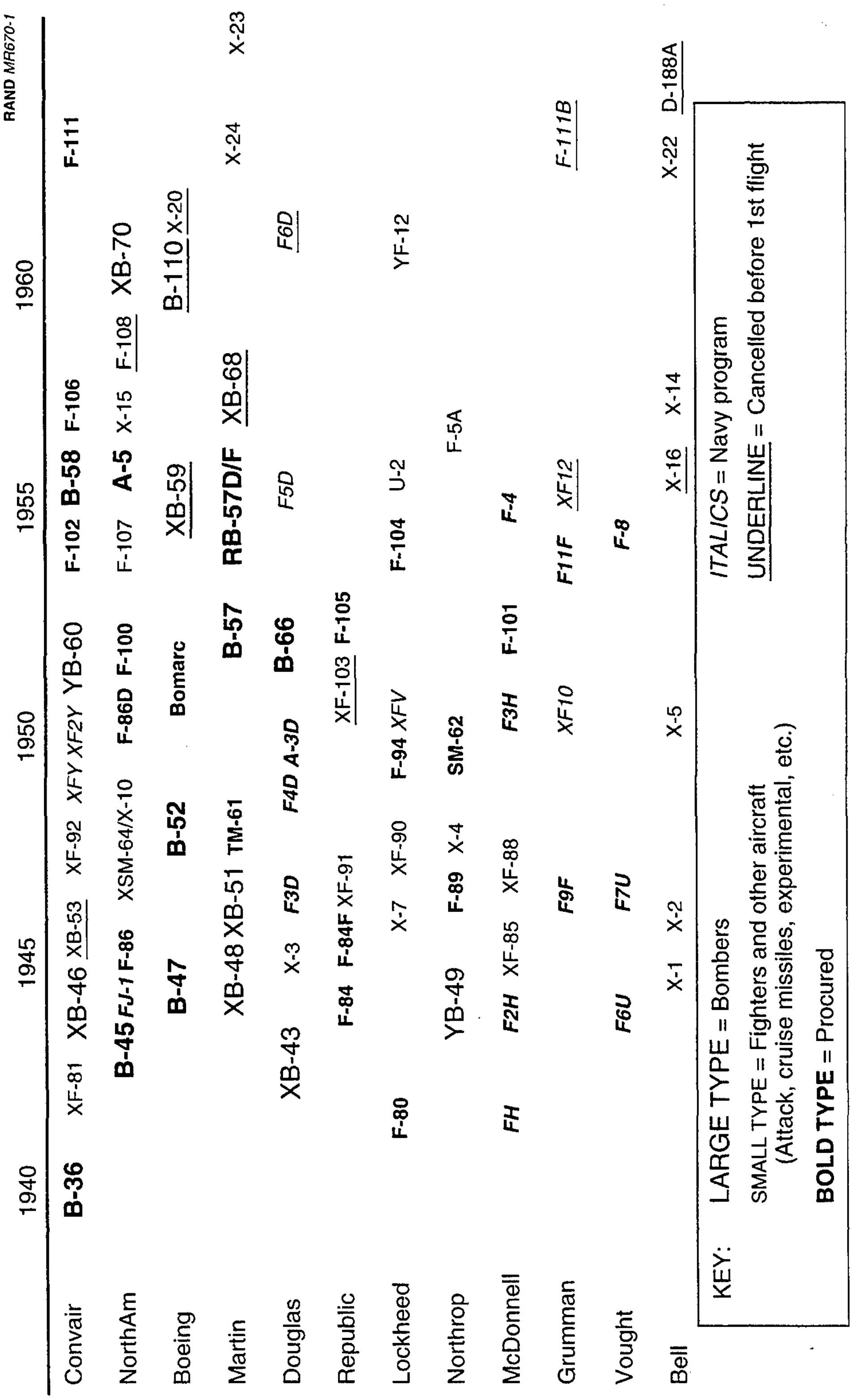

Figure 1—Jet Bomber, Fighter, and Related R&D Programs, 1940–1962

sonic fighter and other high-speed air vehicle development. Boeing turned increasingly toward civil transport development by kicking off the B.727 R&D program as a follow-up to its highly successful B.707, and sought to protect itself by diversification through the purchase of the Vertol helicopter company in 1960. Nonetheless, Boeing was still not out of the game. The B-52 was going through many major modification and upgrade programs, and an important program for the replacement of the main Air Force fighter-bomber, the Republic F-105, was on the horizon. Boeing intended to compete fiercely for that project.

Martin suffered far worse problems than Boeing. It had won no major fighter or bomber development projects since World War II and had accumulated very little experience with supersonic air vehicle development. The firm made one last attempt to remain in the bomber market with the Mach 2.5 XB-68 medium bomber project, which was approved by the Air Force in September 1956. But since the XB-68 was very similar to the B-58, the Air Force canceled the project only a few months later, in early 1957, before any significant work could be undertaken. Attempts to diversify into commercial transports and nonaerospace products did not fare well. Martin had more success moving into space, by building on its pioneering experience in developing the Titan ICBM beginning in 1953. In 1961, Martin merged with American Marietta, a nonaerospace conglomerate, and concentrated on space programs and subcontracting.

By around 1960, the bomber R&D leadership could be summarized as shown in Table 4. North American and Convair had become the industry leaders. Boeing had slipped by losing the two major competitions for supersonic bombers; this was related to its lack of supersonic fighter and other relevant firm-specific R&D experience. Although they had not won any major land-based strategic bomber competitions, Lockheed and Douglas probably possessed high potential capabilities because of their strong experience in fighters and other supersonic test vehicles, large aircraft, and medium bombers. Both companies had been serious contenders in several of the

Table 4

Firms with the Most Credible Bomber R&D Capabilities in 1962

Company	WWII	Jet Bombers	Supersonic Bombers	Jet Fighters	Commercial Jet Transports	Large Military Aircraft
Leaders						
North American	B-25	B-45	A-5 XB-70	FJ-1 F-86 F-100 F-107 F-108	—	—
Convair[a]	B-24 B-36	XB-46	B-58	F-102 F-106 F-111	880 990	NX-2
High Potential						
Boeing	B-17 B-29	B-47 B-52			B.707 B.720 B.727	KC-135 C-135
Douglas	A-20 A-26	XB-43 A3D B-66		F3D F4D	DC-7 DC-8 DC-9	
Lockheed				F-80 F-94 F-104 YF-12	188[b]	C-130[b] C-140 C-141 P-3[b]

[a]Later General Dynamics.
[b]Turboprop propulsion.

bomber competitions in the 1950s. Northrop and Grumman could also possibly be included in this list.

As Table 4 indicates, both system-specific and firm-specific capabilities combined in the 1940s and 1950s to produce the industry leaders in bomber R&D. The primary technology drivers of the two decades had been the revolutionary advances in propulsion systems and the development of very-high speed aerodynamics and the associated airframe materials and structures. Important synergies appear to have existed between fighter R&D and large jet aircraft development. Leading companies needed to have experience in bomber R&D, *as well as* firm-specific capabilities in high-speed aerodynamics, materials, and engineering. North American and Convair developed these firm-specific capabilities through participation in a wide variety of supersonic flight technology demonstration programs and through extensive R&D work on America's first generation of supersonic fighters. Boeing lacked the firm-specific experience in these areas. Martin not only failed to develop its firm-specific capabilities in these areas but saw its system-specific capabilities in bomber R&D erode as it failed to win any major bomber R&D contracts except the B-57, which was more akin to a licensed production effort of a foreign-developed aircraft than an *ab initio* R&D effort. Clearly, the firms that proved to be most successful were involved in the greatest number of relevant technology demonstration and full-scale development projects.

The overall situation in the late 1950s, however, would soon be significantly altered by a variety of forces. First, the full development and deployment of intercontinental and submarine-launched ballistic missiles, which began in the early 1950s, would soon displace the bomber from its central position as the primary means of delivering strategic nuclear weapons. Second, the entry into service of effective high-altitude long-range surface-to-air missiles (SAMs) would greatly reduce the survival benefits of high-speed, high-altitude bombers and indeed would further erode the perceived value of strategic bombers when compared to invulnerable strategic ballistic missiles. Third, the declining marginal returns and exploding costs of developing ever-faster and higher-flying bombers, combined with the growing effectiveness of SAMs, clearly required new approaches to performance and technology goals for future bombers. Finally, a major shift in national doctrine away from massive retaliation toward flexible response raised the priority of tactical bombers and fighter bombers compared to strategic aircraft. Some of these changes and their implications are discussed in more detail in the next chapter.

Chapter Three

THE 1960s AND 1970s: THE STRATEGIC BOMBER UNDER ATTACK

INTRODUCTION

The 1960s and 1970s witnessed major changes in the existing patterns of combat jet aircraft R&D and design leadership that had been established in the 1950s. These changes were caused by a dramatic decline in the number of new program starts for manned combat aircraft, prototypes, and technology demonstrators. This decline came about because of the continuing and relentless rise in the cost and complexity of fighters and bombers, the emergence of cost-effective strategic ballistic and tactical missiles, and changes in U.S. strategic and tactical doctrine. As a result, several prime contractors were, in effect, forced out of the mainstream fighter and bomber business. These companies sought new military aircraft niche markets, diversified into other areas inside or outside of aerospace, merged with competitors, or withdrew entirely from the market.

These were unhappy decades for strategic bomber R&D. During this second period of postwar bomber development, only one strategic bomber—the B-1A—entered full-scale development, and none completed R&D. One heavy tactical fighter-bomber completed development—the F-111—which was later modified into a long-range strategic bomber. No radical new technology developments emerged during this period that were comparable to the introduction of jet engines and the focus on high-speed supersonic aerodynamics in the 1940s and 1950s. Therefore, the relative importance of special firm-specific knowledge relevant to bomber R&D appears to have declined. However, system-specific experience seems to have remained critical. Rockwell, which had emerged from the 1950s as America's foremost strategic bomber developer, eventually won the contract for the B-1. Convair, which stood neck and neck with North American, won the F-111 contract, although its selection remained under a cloud of considerable controversy.

The Tactical Fighter, Experimental (TFX, later the F-111) program for replacement of the F-105, as modified by the incoming Kennedy administration in 1961, is a convenient symbol of the beginning of this new era in the postwar history of fighter and bomber development. Upon entering office, Kennedy's Secretary of Defense, Robert McNamara, almost immediately began implementing fundamental changes from the 1950s in doctrinal emphasis and procurement style. In the area of strategy and doctrine, the Kennedy administration placed increased emphasis on the importance of the "conventional option," stressing the ability of the armed forces to fight conventional and limited wars in a nonnuclear environment. McNamara and his "Whiz Kids" at the Pentagon were also determined to impose much greater discipline and rationality on the overall defense planning and budgeting process. The new Pentagon managers were particularly interested in reforming the process the services used to generate military requirements and procure new weapon systems. (See Art, 1968, pp. 30–34.)

The desire to rationalize the procurement process was in part a response to technology trends in the 1950s. The rapidly increasing speed, weight, and technical complexity of first- and second-generation fighters and bombers resulted in a dramatic escalation in R&D and procurement costs, as shown in Table 2. As jet aircraft engine and airframe technologies passed out of the early innovation stages and began to mature, each new increment of improvement in speed and altitude capabilities became increasingly challenging technologically and much more expensive.

With costs skyrocketing, defense planners realized that the large number of full-scale development and prototype technology-demonstration programs characteristic of the 1950s could no longer be financially sustained. The Pentagon sought to reduce what it considered to be inefficient duplicative R&D by the services. McNamara canceled numerous programs and encouraged the services to procure similar or identical aircraft, as in the case of the

TFX and the McDonnell F-4. The rising unit costs of military aircraft and the new emphasis on greater commonality of aircraft designs among the services tended to push requirements toward even smaller numbers of even more complex and expensive fighters designed to offer multirole and cross-service capabilities.[1]

For a relatively short period in the late 1950s, many observers predicted that the introduction of tactical and strategic missiles would soon make manned combat aircraft obsolete (Bright, 1978, pp. 18–19).[2] While this belief proved to be wrong, the deployment of land-based and submarine-launched strategic ballistic missiles clearly reduced the relative importance of strategic bombers in the view of U.S. military planners of the period. Indeed, no new strategic bomber design was fully developed in either the 1960s or the 1970s. At the same time, medium bombers essentially disappeared as a distinct category of aircraft, and their role was taken over by heavy multirole fighter-bombers, such as the F-4E, and tactical bombers, such as the F-111.

As a result of these cost, technology, and procurement trends, the 1960s and 1970s witnessed a significant decline in the number of new military manned aircraft R&D programs from that of the 1950s. By one accounting, a full two-thirds fewer military aircraft designs were developed and reached first flight during the 1960s than in the previous decade. The numbers declined even further in the 1970s. (See

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[1]Much of the fighter pilot community and a variety of defense reformers rebelled against this concept in the late 1960s, primarily because of the relatively poor showing in Vietnam of large, heavy multirole U.S. fighters, such as the F-4, against smaller, more-agile Soviet designs, such as the MiG-21. The F-15 and F-16 were subsequently designed as dedicated single-role air-combat fighters. But the same cost trends discussed here, combined with a variety of other factors, led the F-16 to evolve toward a heavier multirole fighter during development, and even the F-15 program eventually produced multirole attack versions.

[2]In Great Britain, the government issued a Defence White Paper in April 1957 that stunned the British aircraft industry. The White Paper reoriented British defense policy toward a heavy reliance on nuclear weapons and missiles. It called for the cancellation of all British fighter and bomber R&D programs then under way, predicting that within ten years all Royal Air Force missions would be carried out by unmanned missiles and vehicles. (See Gallois, 1957, pp. 453–456.) Although manned aircraft R&D programs continued for some years, nearly all national programs were canceled by the Labour government in the first half of the 1960s.

Drezner et al., 1992, pp. 29, 49.) Figure 2 shows some of the major fixed-wing, missile, and space projects of this period.

The 1960s and 1970s also witnessed shifts in the design emphasis and technology focus for new combat aircraft designs as a result of changes in doctrine and other factors. The technological focus on increasing speed and altitude that dominated the 1950s disappeared in the following decade. Rightfully considered by many as the most capable fourth-generation fighter, the F-15 nonetheless boasted approximately the same empty weight, ceiling, and top speed as its immediate predecessor, the F-4. Other highly successful fourth-generation fighters, such as the F-16 and F-18, actually weighed less empty, had lower top speeds, and had only modestly higher ceilings than did the last second- and third-generation fighters.

These changes came about because of the relative decline in the operational utility of ever greater speed and higher ceilings and because of the growing cost and technical challenges of achieving them. The doctrinal shift toward limited tactical warfare implemented under President Kennedy and the lessons learned from air combat experience in the early years of the Vietnam War, during the Indo-Pakistan War of 1965, the 1967 Arab-Israeli War, and later Middle East engagements led to new design and technological focuses for fighters. These emphasized maneuverability, agility, and advanced avionics. Air combat in Vietnam and in the Middle East revealed the inadequacies of early-generation long-range air-to-air missiles and showed the importance of maneuverability and agility in winning dogfights with guns or early-generation short-range missiles. The initial experience with ground attack missions in Vietnam indicated that fighter-bombers were vulnerable to SAMs and other ground-based air defenses and were unable to deliver ordnance with the required accuracy against ground targets. As a result, designers and engineers concentrated on increasing maneuverability for air combat success and on developing and integrating the avionics necessary to counter enemy threats and to deliver munitions more effectively.

BOMBER PROGRAMS ON HOLD

For its part, strategic bomber development entered a severe crisis period from which it did not fully recover until the era of stealth. New-generation air defense missiles and interceptors made bombers

RAND *MR670-2*

		1960	1965	1970	1975
Boeing	(M)	C-135* Minuteman X-20 *Lunar-Orbiters*	SRAM ARM/ AGM-7B	E-3A T-43 SCAD E-4A YQM-94	
	(C)	727	737 747 SST		757 767
General Dynamics	(M)	*Centaur* **F-111** Model-48 **RB-57F**		**YF-16**	**F-16** SLCM GLCM
	(C)		600-640		
Grumman	(M)	**A-6*** **E-2*** *Apollo* **F-111B** C-2	**F-14**	**EA-6B**	
Lockheed	(M)	P-3* **A-12** C-141 X-V4A **YF-12A**	C-5 SR-71 D-21 QT-2/ X-26 YO-3A S-3	**XST**	Trident I **F-117**
	(C)		L-100 L-1011		
McDonnell-Douglas	(M)	**F-4*** *Mercury/ Gemini* Missileer C-9	KC-10 **F-15**	*Skylab* Harpoon/ AGM-84A	**F-18** **AV-8B**
	(C)	DC-9	DC-10		MD-80
Northrop	(M)	X-21 F-5A/B	**F-5E**	P-530 X-27 **YF-17** **A-9A**	**THAP (?)** **F-20**
Republic	(M)		AV-23A *ATS-1*	**A-10** *ATS-6*	*ISEE-3*
	(C)		Merlin & Metro F-228		
Rockwell	(M)	AGM-28B YAT-28E *Apollo*	Hover-buggy OV-10A	**B-1** XFV-12A	HiMat Hellfire
	(C)		Aero & Lark	Sabre & Aero 112	
Vought	(M)	XC-142A **A-7**			

* Program began in late 50s.

KEY: (M) = Military
(C) = Commercial
NORMAL TYPE = X-planes, commercial aircraft, and misc.
BOLD TYPE = Fighter, attack, bomber
ITALICS = Space programs
UNDERLINED = Missiles

Figure 2—Selected Major Fixed-Wing Aircraft, Missile, and Space Programs, 1960–1980

vulnerable no matter how high and fast they flew, as the shooting down of an American U-2 spy plane over the Soviet Union in 1960 illustrated dramatically. At the same time, ICBMs, such as the Atlas and Titan, emerged, which were virtually invulnerable to enemy air defenses. Finally, the technology challenges for Mach 3 bombers, such as the XB-70, were so great that some observers began to doubt whether effective weapon systems could ever be developed at an acceptable cost. Although many believed the manned strategic bomber had reached the end of its usefulness, important elements within the Air Force and elsewhere struggled mightily to retain it as a viable option. Many years were spent trying to develop an effective doctrine and weapon system concept to save the manned strategic bomber. However, the problem was never really solved prior to the stealth era, in the sense that no widely held consensus in the defense and political establishments ever emerged.

Indeed, as early as 1958, the XB-70 program began coming under mounting pressure because of growing doubts about the bomber's survivability and high R&D costs. In September 1959, the program received a major blow when the Air Force canceled North American's Mach 3 fighter, the F-108, which had been intended to share development costs with the bomber on engines, escape capsules, and other areas. In 1959, President Eisenhower downgraded the effort to a prototype technology demonstration program, although full-scale development was briefly resuscitated during the 1960 presidential campaign. But in March 1961, President Kennedy once again reduced the project to the status of a technology demonstration program for investigating Mach 3 flight. Six years later, after many developmental problems and the crash and destruction of one of the two prototypes, the XB-70 program was terminated. (Knaack, 1988, pp. 566–573.)[3]

The B-58 program was also scaled back considerably at the beginning of the 1960s for similar reasons. As early as 1958, the program was almost canceled because of range shortcomings and a myriad of other technical problems. In July 1959, the Air Force canceled procurement of the B-58B, the low-level strike version of the aircraft that

[3]In May 1966, the second prototype reached and sustained a speed of Mach 3 for more than 30 minutes.

was intended to increase survivability. A year and a half later, the planned buy of B-58As was slashed substantially. In 1965, only a few years after initial operational capability, Secretary McNamara directed phaseout of the entire B-58 force by 1970. (Knaack, 1988, pp. 379–389.)

With advanced strategic bombers coming under increasing attack in the late 1950s and several fighter programs canceled, many contractors looked ahead hopefully to new programs for a future Air Force tactical fighter bomber, a Navy fleet interceptor, and a close-air-support (CAS) aircraft. Following the election of President Kennedy, however, Secretary McNamara sought to combine these replacement requirements—minus CAS—into a single aircraft, as reflected in the TFX RFP issued in September 1961. Calling for a 60,000 lb gross takeoff weight and low-level supersonic dash capability for the delivery of nuclear and conventional weapons, the TFX requirement asked for a large multirole fighter-bomber in the same weight class as medium bombers, such as the B-57 and B-66. (See Knaack, 1978, pp. 223–224.)

Not surprisingly, the traditional bomber developers for both the Air Force and the Navy, as well as the fighter developers, fought hard for this contract in an environment of declining new program starts. General Dynamics,[4] North American, Boeing, Lockheed, Douglas, Grumman, Chance-Vought, McDonnell, and Republic all responded with serious proposals. This would be Boeing's last chance to win a bomber-related R&D program for some time, and the Seattle firm was determined to win. Indeed, the Air Force Selection Board and Navy representatives selected the Boeing design in January 1962, but the Air Force Council rejected it. Boeing and the runner-up—General Dynamics—then received follow-on study contracts. In June, the Air Force once again selected the Boeing proposal, but the Navy refused to approve. Refined proposals were received in September, and once again the Air Force selected the Boeing design. To Boeing's great consternation, however, McNamara overturned the decision of the uniformed services and gave the contract to General Dynamics. (Knaack, 1978, p. 225.)

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[4]Electric Boat and Canadair merged in 1952, forming General Dynamics. In 1954, General Dynamics acquired Convair. However, the main Fort Worth facility was still routinely referred to as Convair until the early 1960s.

The Secretary of Defense's decision caused a huge political scandal. Since General Dynamics was based in Ft. Worth—in the home state of Vice President Johnson—and was in serious financial trouble because of the major cutback in the B-58 program that had been decided on in December 1960, many observers felt the General Dynamics design had been selected over a superior Boeing design merely to save the Ft. Worth company from going out of business. Extensive congressional hearings were held on this issue, but no definitive conclusions were reached.

For our purposes, the most interesting information to come out of the hearings was the evidence of the technical strengths and weaknesses of the two proposals and the nonpolitical rationale for McNamara's decision. Three key factors behind the secretary's decision were that the General Dynamics proposal showed more commonality between the Air Force and Navy versions, that the Texas firm's technical approach was more conservative and credible, and that General Dynamics' cost estimates appeared more reliable and believable. The second two factors appear to be a reflection of General Dynamics' far greater experience in the development of high-performance, supersonic combat aircraft. Although Boeing's design promised slightly greater performance on paper, General Dynamics' proposal—in the view of the Office of the Secretary of Defense (OSD) and many Air Force engineers—showed a much more realistic appreciation of the challenges of supersonic aircraft development.

Indeed, analysis of the two proposals suggested that only General Dynamics' design would be capable of sustained low-level supersonic dash. OSD engineers thought that Boeing's use of top-mounted engine air inlets and maneuvering thrust reversers in its design was particularly unrealistic on a Mach 2 fighter-bomber. Finally, General Dynamics was teamed with Grumman. Although Boeing had begun design studies on variable-geometry (VG) swing wings of the type to be used on the F-111 considerably earlier than General Dynamics, Grumman had actually designed, developed, and flight-tested a VG fighter prototype in the 1950s, the F10F. Grumman also had extensive experience in the development of other fighter aircraft for the Navy. In short, it is certainly arguable that General Dynamics won the competition because of its greater technical realism, which was based on its extensive experience in development of supersonic combat aircraft.[5]

The F-111 victory assured General Dynamics continued central role in bomber development, although the R&D program would generate enormous unwanted controversy. The radical scaling back of the XB-70 program and Boeing's bitter defeat on the F-111 left both North American and Boeing hungry for a new bomber contract. After all, something had to be procured to replace the subsonic B-52, which had already been in the inventory much longer than expected. The Air Force was willing to oblige, but the type of bomber to procure—now that "higher and faster" had fallen into disrepute and now that the very concept of manned strategic bombers was under attack—remained in doubt. It had already become clear by the end of the 1950s that the only hope for bombers to penetrate enemy air defenses successfully was at high speed at very low altitude. In many respects, this requirement placed even greater technological demands on bomber contractors than high-altitude supersonic flight did, as the F-111 R&D effort eventually showed.

Between 1961 and late 1963, the Air Force conducted at least four major studies of future strategic bomber concepts. In November 1963, the Air Force sent a new bomber RFP to North American, General Dynamics, and Boeing. McNamara soon pulled most of the budgeted money out of the effort, which evolved into an inconclusive design study. In July 1964, the Air Force reconfigured the bomber requirement into a new study called Advanced Manned Strategic Aircraft (AMSA),[6] which envisioned a long-range heavy strategic bomber with a 2,000-mile low-level dash capability and high-altitude supersonic speed. The three contractors undertook a variety of AMSA studies throughout the 1960s, but McNamara continued to block the program from advancing beyond the concept-formulation stage despite strong Air Force protests. Instead, the secretary authorized the development of the FB-111, a pure bomber version of

[5]Indeed, General Dynamics was well aware of the unhappy consequences of technological overoptimism from its F-102, F-106, and B-58 programs and would suffer the consequences again on the F-111. For an exhaustive discussion of these issues, see Art (1968, pp. 115–132), and Coulam (1977, pp. 62–65).

[6]Also said by some to stand for "America's Most Studied Airplane."

General Dynamics' new fighter-bomber. (Knaack, 1988, pp. 576–579.)

The contractor studies, however, resolved several important issues for future strategic bomber development after examining over 300 design configurations. The airframe and engines would be largely conventional, but swing wings were necessary for supersonic low-level dash. Combining this with the high-altitude supersonic requirement meant using VG air inlets and affected the type of engines selected. But on the whole, the airframe-and-engine combination was envisioned to be fairly technologically conventional by the standards of the day, in marked contrast to the B-58 and XB-70. The greatest technological challenges would come in the areas of the integrated electronic warfare system, other complex avionics, and overall system integration. (Gunston, 1993, p. 268.) Recognizing the importance of this challenge, the Air Force awarded avionics concept study contracts in 1968 to IBM and the Autonetics Division of North American Rockwell.[7] However, once again, McNamara blocked full-scale development of a new bomber.

THE BOMBER TEMPORARILY REVIVED: B-1A DEVELOPMENT

President Nixon's entry into the White House in early 1969 resulted in a new administration far more sympathetic to strategic bomber development. Melvin Laird, the new Secretary of Defense, drastically cut back procurement of the FB-111, the bomber version of General Dynamics' swing-wing aircraft, and accelerated AMSA study efforts. Before the end of the year, a new RFP went out to the three AMSA contractors plus Lockheed. In June 1970, the Air Force announced the selection of Rockwell to develop the new bomber, now designated the B-1. According to the official Air Force history, the Rockwell submission won because of "superior technical proposals, as well as lower cost estimates." (Knaack, 1988, p. 581.) In a stark contrast to their reaction to the outcome of the TFX/F-111 competition, Boeing officials reportedly recognized that the Rockwell

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[7]In 1967, North American merged with Rockwell Standard, an industrial conglomerate, becoming North American Rockwell.

design was clearly more responsive to Air Force requirements than their company's submission (Serling, 1992, p. 202).

Boeing's poor showing on the B-1 competition combined with the experience of the commercial SST competition from the mid-1960s may provide additional interesting insights into the issues of supersonic R&D experience and the relationship between bombers and commercial transports. As far back as 1957, Boeing had begun investigating commercial supersonic transport (SST) concepts.[8] Early in the Kennedy administration, the Federal Aviation Administration had begun pressing for a government-supported R&D program for an SST. The Air Force had opposed this effort, because it feared that such a program could threaten the XB-70 program, but Congress approved a government-funded program early in the Johnson administration. The major competitors were North American, Boeing, Lockheed, and Douglas. Douglas soon withdrew from the competition, and surprisingly, North American was eliminated later. According to the industry press, the Lockheed design was heavily favored to win. This was in part because the Boeing design proposed a swing wing, which most industry observers—as well as the other three competing prime contractors—believed would be too heavy and too complex and would cause configuration problems for any future SST. The purpose of the swing wing was to permit slower landings speeds to reduce noise. Like North American, Lockheed had proposed a delta-wing design that was not dissimilar to that of the XB-70.

To the great surprise of most industry observers, Boeing won the competition in December 1966. The airlines simply had more confidence in the Seattle company and liked the low-noise feature. The problem was that Boeing had proposed a swing-wing design concept "that simply was beyond the state of the art." (Serling, 1992, p. 273.) As Boeing engineers launched into detailed design development, they encountered more and more problems. Eventually, the Seattle firm dropped the swing-wing design and adopted a delta-wing configuration like its competitors. But as time passed, mounting environmental objections to SST development and cost-growth problems fatally undermined the program. Congress ended funding in May

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[8]This account of Boeing's SST program is taken from Serling (1992, pp. 267–278).

1971, just as Boeing was about to begin cutting metal for the first prototype.

The SST program is interesting because it appears to illustrate both the differences between bomber and commercial aircraft development and the importance of experience. North American was clearly the most experienced developer of large military supersonic aircraft. But few airlines or other officials believed it would be the best choice to develop a commercial airliner. As the premier developer of commercial transports, Boeing was handed the job. Yet its lack of experience in the design and development of supersonic aircraft—particularly large ones—led it to promise a technological solution that was impractical and beyond the state of the art.

North American's B-1 design proposal had many advanced and novel features and was intended to produce a strategic bomber with performance capabilities that far surpassed those of the B-52. Yet the El Segundo firm had a strong experience base in bombers and supersonic fighters on which to build and did not need to worry about the commercial requirements that drive civilian transport development. Equipped with VG wings, variable inlets, and GE F101 turbofans with afterburners providing a very-high thrust-to-weight ratio, the B-1 would be able to take off from short runways, fly out at supersonic speeds, cruise at high altitude at over Mach 2, and approach enemy targets at very low levels at near-supersonic speeds. Nonetheless, the basic B-1 airframe-engine combination could not be considered groundbreaking in the same sense as the B-58 and XB-70, in that it did not push out the boundaries of aerodynamic or engineering knowledge. Many of its design features, such as swing wings, variable inlets, and blended-body wing design, had been incorporated on other aircraft.

The importance of related R&D experience and the close relationship between fighter and bomber R&D continued on the B-1. Rockwell clearly drew heavily on its experience from the XB-70 and other earlier programs. The variable air inlet design and the under-wing engine configuration and pods were patterned after those developed for the XB-70 effort. (Jones, 1980, p. 239.) The low-altitude ride-control system was also derived from the same aircraft. (Godfrey, 1970, p. 53, and 1975, p. 62.) The B-1's blended-body wing configuration owed much to the extensive design work and wind-tunnel testing Rockwell had conducted to develop the losing advanced fighter design it submitted for the F-X (F-15) competition in the late 1960s (Gunston, 1993, p. 270.)

The greatest technological challenges facing the B-1 program, however, would come from avionics development and integration. The early 1970s witnessed the beginnings of an explosion in computer, sensor, radar, and other electronics technologies. Electronics took the place of aerodynamics and engines as the area of most rapid technological advance. Sophisticated sensors, avionics, and other major electronic subsystems, such as automatic terrain-following radar and integrated electronic warfare suites, would be critical for the effectiveness and survivability of the B-1. The technical challenges and complexity of developing and integrating the necessary avionics would be great. Avionics costs would grow to nearly half the R&D costs of modern combat aircraft.

Recognizing the growing risk and complexity of avionics development, the Air Force separated B-1 avionics into offensive and defensive functions for the purpose of selecting contractors for avionics integration. As an indication of the high technological demands made by the program requirements, only five contractors responded out of 27 companies solicited for offensive avionics integration. In April 1972, Boeing received the contract for developing the offensive avionics and integration of avionics subsystems. Boeing's selection may have been related to the major avionics upgrades and integration efforts that it was involved with in the early 1970s on the B-52.[9] Only two companies responded out of 23 for the defensive avionics, an extremely complex system development effort. Airborne Instrument Laboratory eventually won the contract. These avionics were not fully developed, however, before the entire B-1 program was canceled. (See Bodilly, 1993.)

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[9]With the cancellation of the XB-70 and the long delays in the AMSA program, B-52s soldiered on with numerous structural and avionics upgrades in the 1960s and 1970s to improve their low-level penetration capability. Some of the largest upgrade programs in the early 1970s included provision for the Boeing AGM-69A short-range attack missile (SRAM), beginning in 1970; the Electro-optical Viewing System (EVS), introduced in 1973; and the Phase VI ECM upgrade, which included 17 major avionics units.

A military and political consensus supporting the need for a new penetrating strategic bomber failed to coalesce in the 1970s. The doubts that had first arisen in the late 1950s about the basic role and cost-effectiveness of the manned bomber lingered on. In addition, antimilitary sentiment flourished in Congress in the wake of the Vietnam War, while the B-1 R&D program experienced cost overruns and schedule slippage. In 1977, President Carter canceled the program after three prototypes had been built, in part because he expected development of the stealthy Advanced Technology Bomber (ATB).[10] Continued flight testing of B-1 prototypes verified the basic design of the engine-airframe combination, but the avionics were not fully developed and tested. (Bodilly, 1993, pp. 4–5.)

THE LONG HIATUS OF THE 1960s AND 1970s

Thus, as the 1970s drew to a close, it became increasingly clear that a full two decades would pass without the development of a single new strategic or dedicated medium bomber. Strategic bomber development had never recovered following President Eisenhower's decision in 1959 to downgrade the XB-70 effort to a prototype demonstration program. Fighter-bombers, such as the McDonnell-Douglas F-4E, and dedicated CAS aircraft, such as the Republic A-10, had taken over the role of dedicated medium bombers, although the General Dynamics F-111 and FB-111 could legitimately be considered to be medium bombers in the pre-1960s sense. But with the cancellation of the XB-70 and the B-1, no new strategic bomber would emerge fully developed in the 1960s and 1970s. Instead, the B-52, whose original design dated from no later than 1948, remained in service decades longer than originally anticipated and was continually upgraded and modified with new equipment and munitions. Indeed, the development of air-launched cruise missiles (ALCMs), which provided the B-52 with a long-range stand-off capability, was one reason opponents of the B-1 argued that no new strategic bomber was needed.

At the end of the 1970s, Rockwell appeared to stand out as the most credible, if not the *only* credible, bomber developer and seemed to

[10]A fourth prototype was under construction.

have few real competitors. With its XB-70 and B-1 programs, it was the only company to have demonstrated system-specific capabilities by having worked on strategic bomber development throughout the 1960s and 1970s. Indeed, Rockwell had evolved increasingly into a contractor specializing in heavy bombers and spacecraft, since it failed to win any new fighter contracts following the cancellation of the F-107 and the F-108 in the late 1950s. Since this was a period of less-revolutionary change in airframe and propulsion technology than in the 1940s and the 1950s, system-specific capabilities were of particular importance.

General Dynamics could claim with some accuracy that it had continued the Consolidated and Convair traditions of bomber development and that it thus maintained system-specific capabilities—at least in the area of medium bombers—with the F-111 and FB-111 programs. At the same time, General Dynamics remained very prominent in the area of fighter development, having produced the F-16 aircraft in the early 1970s, which would become the most numerous fighter type in the Air Force inventory. Although Boeing worked on several large aircraft programs and developed numerous new commercial transports, it appeared to be pretty much out of the game with no new bomber or fighter development programs since the early 1950s.

All of this was to change dramatically, however, with the emergence of a revolutionary new technology approach to military aircraft in the late 1970s and early 1980s.

Chapter Four

THE 1970s THROUGH THE 1990s: THE STEALTH REVOLUTION

NEW TECHNOLOGY, NEW INDUSTRY LEADERS

The stealth era, which got fully under way in the mid-1970s behind a wall of strict secrecy, rescued the manned penetrating strategic bomber from probable extinction. No new strategic heavy bomber design had been fully developed since the B-52 in the early 1950s, as doubts continued about the survivability of bombers against improving air defenses. The deployment of first-generation Soviet SAMs had helped kill the XB-70 program, and continuing improvements in Russian SAMs, radars, and fighter-interceptors, as dramatically demonstrated in the later phases of the Vietnam War and during the 1973 Arab-Israel conflict, had led to President Carter's cancellation of the B-1A.

Stealth technology aims at enhancing survivability by reducing as much as possible the radar, infrared (IR), acoustic, and visual signatures of combat aircraft to avoid detection by the enemy. The highest priority and the most challenging aspect of stealth is achieving a low radar cross section (RCS). This is because radars can detect aircraft out to 200 miles or more, providing ample warning time for defenders, while IR, acoustic, and visual sensors usually have much shorter detection ranges in most situations.[1] Stealth became increasingly of interest to Air Force and Department of Defense (DoD) planners in the 1970s as the continuing development

[1]At very high and very low altitudes, IR suppression becomes increasingly important. (See Bahret, 1993, p. 1377.)

of a variety of technologies increased stealth's appeal as a cost-effective means of countering rapidly improving Soviet counter-air capabilities. In the case of the strategic bomber, stealth appeared to be the only way to ensure the survivability, and thus the continued existence, of penetrating manned bombers into the 1980s.

The key technologies for achieving low-RCS manned combat aircraft that are operationally useful included the development of advanced composite materials and fabrication processes for large load-bearing aircraft structures and engine structures; advanced radar absorbing materials (RAMs) and application processes; measurement devices and methodologies for accurately measuring RCS; high-capability computers and advanced computer-assisted design processes to assist in shaping the aircraft structure; and advanced fly-by-wire (FBW) computer-operated electronic flight-control systems to provide flight stability for aerodynamically unstable low-RCS designs. (See Pace, 1992, pp. 219–220.) Later, engineers also had to develop fire-control radars and avionics that reduced detectable emissions, such as low-probability-of-intercept radar. Most of these technologies had been under development in the 1970s or earlier for a variety of applications, but Lockheed and Northrop first brought them all together in an effective way for stealth combat aircraft.

The stealth era exhibits several general characteristics in common with the first postwar period of great technological innovation in the 1940s and 1950s. Like the earlier period, the stealth era witnessed a significant amount of technological change in basic airframe and air vehicle development that had the effect of leveling the playing field for several aerospace prime contractors. In terms of Hall and Johnson's categories, unique firm-specific experience and capabilities once again increased dramatically in importance relative to bomber system-specific capabilities. Indeed, it can be argued that, in the case of bombers during the stealth period, firm-specific experience became more important than system-specific experience.

Periods of major technological innovation and change can provide enhanced opportunities for new entries into specialized areas among the prime contractors. In the 1950s, the turbojet engine revolution permitted a company like McDonnell, which was founded in 1939 and had no major development contracts in World War II, to come out of nowhere and become a leading developer of both Navy and Air

Force jet fighters. Boeing, the dominant heavy-bomber developer of World War II, slipped behind North American and Convair in the mid-1950s because of its relative lack of experience in the rapidly advancing technologies associated with supersonic flight. Likewise, the stealth revolution permitted two companies—Northrop and Lockheed—which had specialized in niche areas and had not been the leading fighter and bomber developers in the 1960s and 1970s, to take over a clear leadership role in stealth combat aircraft in the 1980s. Conversely, the dominant fighter and bomber developers of the middle period (McDonnell-Douglas, General Dynamics, and Rockwell), which had built their leadership on their substantial expertise in conventional combat aircraft development, ended up losing most of the competitions for the new stealth combat platforms. Figure 3 shows many of the major bomber, fighter, missile, and space vehicle programs of this period.

Lockheed's strong position as a leader in stealth appears to be partly due to good fortune related to firm-specific capabilities acquired from its niche specialties in the 1950s and 1960s. For its part, Northrop appears to have made a strategic corporate decision as far back as the 1960s to concentrate on stealth as part of a strategy to break out of its second-tier position among combat aircraft contractors by increasing its unique firm-specific capabilities.[2]

The F-104 began development in the early 1950s—this was not only Lockheed's last fighter, which was procured by the Air Force, but its last figher fully developed and procured by any service. After this point, Lockheed continued to compete for numerous fighter and bomber programs, but failed to win them. The company increasingly specialized in large aircraft (military and commercial transports, and Maritime patrol aircraft), as well as top-secret highly specialized reconnaissance aircraft developed at its famous Skunk Works facility in Burbank.

Aircraft designed for covert strategic reconnaissance missions are, of course, intended not to be detected. Launching development of

[2]Most of the details about the history of stealth R&D are still shrouded in secrecy. The account presented here has been pieced together from a variety of open sources, which may not be accurate and often tend to be sketchy. A full and accurate account of this period will have to await the declassification of substantially more information.

their U-2 reconnaissance aircraft in 1954, Lockheed designers sought to ensure survivability and avoid detection by making the aircraft small and providing it with very-high-altitude capabilities. Some studies were conducted on reducing the U-2's RCS, but they did not meet with great success. The follow-on to the U-2, however, was the first aircraft designed from its inception to reduce RCS. Eventually known as the SR-71 Blackbird, this remarkable aircraft was approximately the same size as the Convair B-58, flew at speeds over Mach 3 and at altitudes above 80,000 feet, but had the RCS of a small private aircraft. (Rich and Janos, 1994, pp. 23–24.) Selected as the developer of this U-2 follow-on in 1959, Lockheed configured the aircraft from the beginning with low RCS in mind. In addition, the firm employed RAMs for structural edges and radar-absorbing coatings for the fuselage to achieve the first stealthy military aircraft.[3]

In developing the stealthy SR-71, Lockheed apparently drew heavily on earlier government research efforts. Although not widely known until recently, much of the pioneering theoretical and applied research on reducing radar signature was conducted at the U.S. Air Force Avionics Laboratory at Wright-Patterson Air Force Base in the 1950s. Efforts to determine and measure aircraft RCS accurately started at the beginning of the decade. As engineers developed better models for measuring RCS, interest in reducing RCS increased. The echo characteristics of specific aircraft were examined in a special measurement range built for the purpose. By the mid-1950s, engineers had begun to investigate what elements of an aircraft shape and configuration contributed most to radar echo and how the

[3]Lockheed and Convair competed for this top-secret project, which was sponsored by the Central Intelligence Agency. Convair submitted designs for a small aircraft launched from the B-58 that would use ceramics to achieve a low RCS and heat resistance. In addition to fuselage shaping, Lockheed's design incorporated radar-absorbing plastic materials on the leading-edge flaps and control surfaces, as well as ferrous coatings and other composite materials on the fuselage. North American did not know it at the time, but the go-ahead for the Lockheed Blackbird contributed directly to the cancellation of North American's Mach-3 F-108 Rapier, as well as rejection of proposals to save the XB-70 program by modifying the bomber into a strategic reconnaissance aircraft. Briefly considered as F-108 replacements, several Blackbirds were modified into a fighter-interceptor configuration called the YF-12. (See Rich and Janos, 1994, p. 24; Lynch, 1992, p. 23; Sweetman and Goodall, 1990, pp. 13–14.)

RAND MR670-3

Company		Programs (1975 → 1990)
Boeing	(M)	ALCM, **A-6F**, SRAM II, E-767, *Space-Station*, ASTOVL
	(C)	757, 767, 7J7, 777
General Dynamics	(M)	**F-16**, SLCM, GLCM, **F-16XL**, MRASM, ACM, **A-12**
	(C)	
Grumman	(M)	X-29, E-8/JSTARS
Lockheed	(M)	Trident I, **F-117**, Milstar, *Hubble*, Trident II, **YF-22**, AC-13OU, P-7A, **F-22**, THAAD
	(C)	
McDonnell-Douglas	(M)	**F-18**, **AV-8B**, C-17, **A-12**, SLAM
	(C)	MD-80, MD-11, MD-90
Northrop	(M)	THAP (?), **F-20**, **B-2**, TR-3A, TSSAM, **YF-23**
Republic	(M)	*ISEE-3*, Mini-Drone
	(C)	340A
Rockwell	(M)	HiMat, Hellfire, *Shuttle*, **B1-B**, X-31, AC-130U, AGM-130, *NASP*
	(C)	
Vought	(M)	SIM, T-46

KEY: (M) = Military
(C) = Commercial
NORMAL TYPE = X-planes, commercial aircraft, and misc.
BOLD TYPE = Fighter, attack, bomber
ITALICS = Space programs
UNDERLINED= Missiles

Figure 3—Selected Major Fixed-Wing Aircraft, Missile, and Space Programs, 1975–1990

configuration could be changed to reduce radar echo. In 1955, a major effort was launched to develop a RAM to apply to aircraft structures. By the late 1950s, a Lockheed T-33 had been coated entirely in a RAM and tested extensively. Screens for air inlets and masking of exhaust pipes had been developed on two B-47 test-bed aircraft. Early on, this research had demonstrated that aircraft shape and configuration were the most important contributors to radar echo and that significant reduction in RCS required full application of RCS concepts to the basic aircraft design from the beginning of development. These results clearly influenced Lockheed's design approach to the SR-71.[4]

Lockheed's experience with developing low-RCS configurations and materials grew in the 1960s as the Skunk Works continued its specialization in covert reconnaissance aircraft. Early in the decade, Lockheed began development of a stealthy reconnaissance drone, which was originally intended for launch from the SR-71. Called the D-21, the drone entered a flight-test program in 1966. Shaped like an SR-71 nacelle with blended wings attached, the small unmanned stealth vehicle had amazing performance: Weighing only 13,000 pounds loaded, it reportedly had an intercontinental range and could attain speeds of nearly Mach 4 and altitudes of 100,000 feet. Basic research on materials, aerodynamics, and other areas continued at Lockheed's Rye Canyon laboratories. (Rich and Janos, 1994, pp. 22–23; Sweetman and Goodall, 1990, p. 15.)

Other companies worked on various aspects of stealth in the 1960s. Ryan Aeronautical Company produced a wide variety of stealthy reconnaissance drones beginning in 1960 that included fuselage shaping and RAM (see Wagner, 1982). General Dynamics, the loser in the U-2 contest, built an extensive RCS range and tested its TFX designs there. The firm later built another major range for the Air Force. Apparently, Northrop began concentrating on stealth research in the mid-1960s and gained important experience during this period on stealth, although few details are publicly available. According to one account, Northrop's research focused on attaining

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[4]A fascinating account of early Air Force research on stealth can be found in Bahret (1993).

very low RCS without compromising aerodynamic performance capabilities. (Sweetman, 1992, p. 18.)

Maintaining good aerodynamic capabilities and maneuverability had always been viewed as a problem in shaping airframes for stealth and may explain why so many years passed before serious attempts were made to develop very-low-RCS fighters and bombers. At one point, Lockheed officials considered offering a modification of the D-21 to the Air Force as a stealthy attack aircraft. But fighter design in the 1960s was moving away from high-speed characteristics to enhanced maneuverability and agility. The fuselage shaping and added weight of RAM treatments thought necessary for low RCS would reduce the aerodynamic qualities designers sought. An aircraft with very low RCS might not even have been controllable, given the flight-control technology of the 1960s. By the early 1970s, however, many of these problems appeared more amenable to solution. General Dynamics had developed a sophisticated analog FBW flight-control system for the YF-16. Progress was being made in RAM materials and the development of lightweight composite materials for structural use.

In 1974, the Defense Advanced Research Projects Agency (DARPA) awarded competitive study contracts to Northrop, McDonnell Douglas, and three other contractors to develop design concepts for a very-low-RCS combat aircraft. The winner of the competition would be awarded a contract to develop and fly two technology-demonstration prototypes. Lockheed joined the competition in 1975.[5] Its engineers developed a highly unconventional faceted design nicknamed the Hopeless Diamond, which contained only two-dimensional flat surfaces. This was because RCS could only be calculated with high precision for two-dimensional surfaces, given the state of knowledge and the capability of computers at the time. Northrop proposed a more conventional delta-wing stealth design with the air inlet on top, which used a combination of angular and rounded surfaces. (Sweetman, 1992, p 23.) In October, DARPA selected the Northrop and Lockheed designs as the finalists. The two

[5]Pentagon officials had not sent out the original RFP to Lockheed, because they were unaware of the firm's pioneering stealth work on the highly classified SR-71 and D-21 programs conducted for the Central Intelligence Agency. Each of the original five contractors received $1 million, but Lockheed had to finance its effort with corporate funds. (See Rich and Janos, 1994, p. 22–25.)

companies built models of their designs, which were tested in a competitive "fly-off" in early 1976 on a fixed pole at the Air Force's radar range in New Mexico. In April, DARPA informed Lockheed that it had won the competition.

Under a program code-named Have Blue, jointly sponsored by the Air Force and DARPA, Lockheed received a new contract to build and flight test two manned prototypes to be called experimental stealth technology test beds (XSTs) to demonstrate and validate its stealth technologies and design. Except for their shape and materials, these test vehicles were largely conventional, using mostly off-the-shelf components and subsystems, such as a modified version of the GD F-16 FBW flight-control system. The Lockheed XST first flew in December 1977. Flight testing continued through July 1979, at which time the program ended when the second prototype was destroyed in an accident.[6]

EMERGENCE OF THE ADVANCED TECHNOLOGY BOMBER PROGRAM

Northrop's loss to Lockheed for the XST did not end its pioneering efforts in stealth. In 1976, the Air Force and a variety of government agencies were supporting several contractor studies to examine operational applications of stealth technology to different mission areas and types of air vehicles. A government "Blue Team" was also looking at similar issues. These studies led to recommendations to the Air Force encouraging the development of low-RCS fighter, attack, and bomber aircraft, as well as cruise missiles and unmanned aerial vehicles (UAVs). In response, the Air Force initiated the Covert Survivable In-weather Reconnaissance and Strike (CSIRS) program, which led to a decision to develop a stealthy tactical attack fighter and a tactical reconnaissance platform. Lockheed then went on to base the F-117 stealth attack fighter on its XST prototypes. The F-117 would later become America's first operational very-low-RCS combat aircraft. According to unconfirmed press accounts, the Air Force also

[6]The first XST prototype had been destroyed in May 1978 in another accident. The most extensive account of Have Blue and F-117 development can be found in Rich and Janos (1994).

moved ahead with studies for a stealthy Tactical High-Altitude Penetrator (THAP) reconnaissance platform.[7]

Unverified press reports claim that the Air Force supported a major THAP R&D program. Northrop's THAP design allegedly was the leading submission in the CSIRS program. In 1976, the Air Force began RCS and wind-tunnel tests of the Northrop proposal. Late in 1978, Northrop supposedly won a contract to build and flight-test a prototype technology demonstrator based on its THAP design. The first flight of the experimental prototype is claimed to have taken place in mid-1981 at about the same time that flight testing began on the first full-scale development Lockheed F-117 prototype derived from the XST. The piloted THAP demonstrator was allegedly about the size of a fighter-bomber, such as the F-18, and had a maximum takeoff weight of 55,000 to 60,000 pounds and a wingspan of 56 feet. In marked contrast to the XST and the F-117, the Northrop THAP is claimed to have rejected the use of two-dimensional faceting and instead adopted a rounded manta-ray shape (or triangular spanloader concept) with extensive use of RAM. The aircraft supposedly more closely resembled the Northrop XST submission or even a flying wing than the Lockheed "Hopeless Diamond" concept. After a successful flight-test program, Northrop is claimed to have received a follow-on contract in 1981 for the development and manufacture of 30 operational versions of its stealthy reconnaissance aircraft prototype. Press accounts assert that this led to an even larger aircraft called the TR-3A, which allegedly has a wingspan of 63 feet; a length of 42 feet; a maximum weight of 62,000 pounds; and a range in excess of 3,500 miles. (See Scott, 1991c, p. 20; Baker, 1994a, pp. 143–144.)

Meanwhile, in 1978, Lockheed received a two-year concept-formulation contract to study the development of a stealthy medium tactical bomber in the F-111 class, which could be based on a scaled-up version of the F-117. Over time, the Lockheed design evolved toward a flying wing concept, because such an approach provided low RCS and good wing efficiency for long range and a large payload. Later, Northrop also began proposing bomber designs and received its own design study contracts. If the THAP program indeed existed,

[7]This discussion of the THAP and TR-3A programs is based on speculative and unverified press accounts (see Scott, 1991b, p. 20).

Northrop could have drawn on the experience from this prototype technology demonstrator, which was allegedly under development at the time. Eventually, Northrop developed its N-14 design, a flying wing that had many design approaches in common with the claimed THAP and TR-3A designs. (Rich, 1994, pp. 302–307; Baker, 1994a, p. 144.)

The ATB program had clearly evolved into a high-stakes competition between the two leaders in stealth technology: Lockheed and Northrop. In early 1981, at DoD urging, the two contractors sought out team partners to provide more resources to support such a potentially large program. Lockheed teamed with Rockwell, and Northrop with Boeing and LTV. These were ideal teams from the perspective of experience. Lockheed of course was the pioneer developer of the first stealth fighter, and Rockwell was the leading bomber developer of the last two decades. Northrop also benefited from Boeing's long experience with bombers and its vast knowledge of large-aircraft development. Its lack of experience in supersonic fighter and bomber development was, of course, irrelevant, since the stealth bomber would be subsonic. In addition, both Boeing and LTV were industry leaders in the design and manufacture of composite materials, particularly in the area of large load-bearing structures.

As in the case of the XST several years earlier, the Air Force organized a "shoot-out" between models of the two competing designs in May 1981 at a radar range to determine which had the lower RCS. The Air Force also conducted wind-tunnel tests to determine lift-to-drag ratios to calculate potential range. In October, the Air Force formally awarded the ATB development contract to Northrop. Ben Rich of Lockheed claims that his company's design tested out with a lower RCS. However, the Lockheed proposal called for a considerably smaller aircraft than the Northrop submission, with inferior range and payload capabilities. (Rich, 1994, pp. 309–311.)

Northrop's greater experience in directly related design and technology areas may have been the key to its victory in the competition. As one published account notes, developing the ATB bomber entailed significant technological risks relating to the aircraft's "complex curvatures, exotic materials, and other stealth methods." (Scott, 1991a, pp. 7–8.) Unknown to Lockheed in 1981, Northrop may have already been flying its prototype THAP spanloader for many months at the time it won the ATB competition. Clearly, Northrop would have accumulated significantly more experience than Lockheed in designing and developing the large curved and rounded flying-wing stealth designs necessary for long-range heavy bombers, if THAP actually existed.[8] Indeed, Rich recounts that, when Lockheed's chief executive officer complained about the ATB decision to Vernon Orr, Secretary of the Air Force, he shot back that "not only was Northrop better than you, they were *much better* than you." (Rich and Janos, 1994, p. 311.)

The R&D program proceeded reasonably well, culminating in a first flight in 1989. The new bomber, eventually called the B-2, went through a major redesign in 1983 when the Air Force changed some critical requirements. Originally, the B-2 had been intended to penetrate enemy airspace at high altitude. Improvements in Soviet air defense capabilities led the Air Force to request the added capability of low-level penetration. This required extensive structural changes, which led to a significant change in the wing design, resulting in a delay of at least a year in the program. (Scott, 1991a, p. 14.)

Northrop reportedly hired significant numbers of engineers away from Rockwell who had extensive bomber R&D experience from their work on the B-1 bomber. LTV also appears to have acquired important experience on earlier programs that was critical for its contributions to the B-2 effort. Of particular importance were two science and technology programs in the 1970s aimed at developing design methodologies and advanced manufacturing processes for large aircraft composite structures. These programs provided data that were of significant importance to the design of the B-2 wing and that permitted extensive use of composite materials on the B-2's very large wing structures.[9]

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[8]Available sources claim that Northrop's flying wings from the late 1940s—the XB-35 and YB-49—provided few data and insights relevant to the ATB development effort. This was because most engineers involved with the earlier efforts had long since retired, and Northrop had great difficulty locating test data that had been recorded during the earlier programs. However, engineers and test pilots did consult extensively with pilots who had flown the YB-49. (See Scott, 1991a, pp. 9, 60.)

[9]For example, see Gunston (1993, pp. 301–307).

THE ROLE OF EXPERIENCE DURING THE STEALTH ERA

The critical importance of experience in advanced composites and other stealth technologies in the development of large, stealthy flying-wing or delta-spanloader designs may be illustrated by the problems encountered on the Advanced Tactical Aircraft (ATA), or A-12, program. The ATA program was launched in the early 1980s to provide a stealthy carrier-based attack aircraft to replace the aging Grumman A-6. Later officials decided that a modified version of the ATA would also replace the Air Force F-111 in the tactical bomber role. In November 1984, two contractor teams won preliminary concept development contracts for the ATA: McDonnell-Douglas–General Dynamics and Northrop-Grumman-LTV. Both teams won follow-on contracts in June 1986 to refine their design proposals in anticipation of the selection of one of the teams to lead full-scale development. Northrop's team proposal envisioned a larger and heavier aircraft than did its competitor, with a projected development cost $1.1 billion more than that for the design that the McDonnell-Douglas–General Dynamics team submitted. (House, 1992a, p. 186.) The Navy selected the McDonnell-Douglas–General Dynamics team. Unfortunately, by mid-1990, the A-12 program was at least $1 billion over the cost estimate and 18 months behind schedule. In January of the next year, Secretary of Defense Cheney canceled the program.

The cancellation of this program caused great controversy and acrimony between the contractors and the government. Clearly, however, the R&D program had run into serious problems when cancellation occurred, and many of these problems appear to have been caused by the contractor's lack of experience in critical composite technologies related to stealth. In the words of the "Beach Report," the official administrative inquiry into the A-12 fiasco:

> The primary problem encountered during FSD was weight growth due to the thickness of the composite material necessary for the structural strength required to support the stress and loads experienced by carrier-based aircraft. *Both contractors have limited experience in building large composite structures* and, in large measure, have had to develop the technology as the program progressed. (House, 1992b, p. 244; emphasis added.)

Apparently this was an especially difficult problem for General Dynamics, which had never developed an aircraft that incorporated large load-bearing structural components made out of composites. According to one DoD expert, General Dynamics encountered such severe problems in manufacturing large load-bearing composite structures that it sought to off-load as much of the work as possible to McDonnell-Douglas (House, 1992a, p. 204). Indeed, the contractors later sued the government for allegedly failing to transfer composite and stealth technologies to them that were necessary to develop the aircraft and that, by implication, these companies clearly did not possess in house. According to one press account, the contractors claimed that the government failed to provide technical data on stealth technology from the F-117, B-2, and other stealth projects:

> such as the types of composite materials necessary to cloak aircraft from enemy radar.... Lacking that information, McDonnell and General Dynamics say, their engineers flailed away for many months. Using heavier materials, they ultimately increased the plane's weight by almost one-third. The cost zoomed skyward. (Mintz, 1992.)

The early Navy assessment of the original contractor proposals also seems to bear out a lack of experience at the contractor level. The Navy study concluded that the cost projections in the McDonnell-Douglas–General Dynamics proposal were at least $500 million too low. Assuming the contractors did not purposely underbid, this very-low bid could reflect a lack of understanding of the complexity and difficulties involved in developing and manufacturing an air-frame composed almost entirely of composite materials. Investigators also determined that the original McDonnell-Douglas–General Dynamics weight estimates were unrealistically optimistic. The Navy selected the McDonnell-Douglas team anyway, because, even after adjusting for optimistic cost estimates, the Northrop proposal was still much more expensive, in part because Northrop had proposed a larger aircraft. (House, 1992a, p. 186.)

Interestingly, the Navy assessment of the Northrop proposal resulted in virtually the same cost numbers and weight estimates that the contractor provided. This could indicate a greater realism on Northrop's part, which was due to experience. Northrop may have recently completed development of the THAP and TR-3A triangular spanloader designs—if indeed these programs actually existed—which were very similar in concept to the A-12, and the firm was of course deeply involved in B-2 R&D. Combined with Grumman's experience with the A-6 and many other Naval aircraft, and LTV's expertise in composite structures and Naval aircraft, the Northrop team in retrospect probably would have been a less risky choice as developers of the A-12.

Thus, by the early 1990s, Northrop and Lockheed had clearly emerged as the industry leaders in military aircraft because of their expertise and growing experience with stealth platforms and related technologies. Indeed, these two firms had won the leadership positions in late 1986 for the two contractor teams developing demonstration prototypes for the most important military aircraft effort of the period, the Advanced Tactical Fighter (ATF) program, which the Lockheed team later went on to win. Since the ATF would be a fighter with low RCS and would have an airframe largely composed of advanced composite materials, it is hardly surprising that these two contractors led the R&D effort. Interestingly, McDonnell-Douglas and General Dynamics, the leading developers of both Air Force and Navy fighters in the 1960s and 1970s, never appear to have been in serious contention for a leadership position on the ATF program. (Baker, 1994b.)

In marked contrast to the previous two decades, when not a single new strategic bomber design was fully developed, the 1980s and 1990s witnessed the full development and deployment of an all-new strategic bomber and the revival of an older program, the B-1. In October 1981, President Reagan resurrected the B-1 program to provide the Air Force with a modern "interim" bomber pending full development and deployment of the B-2 ATB. Although sold to Congress as a relatively low-risk development program based largely on the existing B-1A prototypes, the effort actually called for extensive modifications that would lead to a new version called the B-1B. Compared to the B-1A, the new version was planned to penetrate at a substantially lower altitude—although at a reduced subsonic speed—and to incorporate stealth technology to lower its RCS to 1 percent of the B-52's. The B-1B would also have greater range, a larger payload, wing hard points for external stores, a capability to launch cruise missiles, and much-more-capable avionics. These new requirements necessitated major structural modifications to the airframe, redesign of the air inlets, changes in the engine, and extensive avionics development. The first true B-1B flew in October 1984. Many problems were encountered during development, but production was approved, and the first squadron was declared operational in 1986. The last of the planned 100 aircraft was delivered in 1988. (See Bodilly, 1993, pp. 6–10, 20–26, 33–37.)

Thus, in certain respects, the 1980s represented a major revival in U.S. bomber R&D capability. Not since the 1950s had more than one bomber been under development at the same time. Indeed, the 1980s were unique: This was the only decade since World War II in which two heavy strategic bombers were under development simultaneously. By the end of the decade, Northrop and Rockwell had clearly built up a substantial amount of additional experience in bomber development and associated technologies. Rockwell had added to its long tradition of system-specific leadership in the area of supersonic bombers, while Northrop had emerged as the leader of the new era of stealth bombers.

Lockheed also could be added to this list. Following its successful development of the F-117 and its victory in the ATF contest, Lockheed's leadership position in stealth technology and combat aircraft development remained unquestioned. It is also possible that Lockheed maintained significant stealth bomber development capabilities in the 1980s. According to unconfirmed press reports, Lockheed—later teamed with Boeing—won a major competition in 1983 involving seven contractors to develop a highly classified replacement for the SR-71 spy plane. Called the "Q" program in the aviation press, this effort was intended to produce a stealthy, high-altitude, subsonic, unmanned reconnaissance vehicle. According to press speculation, the Q aircraft was nearly as large as the B-2 bomber and may have been directly derived from Lockheed's losing bomber design from the ATB competition with Northrop. Supposedly, the program was canceled in 1992 because of its high costs in a declining budget environment. Later, Lockheed and Boeing were awarded a development contract for the stealthy "Tier III-minus" UAV, which replaced the Q aircraft. If this story is true, Lockheed may have built up considerable capability in the area of very large stealth aircraft, which could be directly applicable to stealth bomber development.[10]

Finally, Boeing and LTV clearly gained significant experience in the design and manufacture of very complex composite airframe structures for bombers by their participation on the B-2 program. Indeed, Boeing and LTV combined produced a much greater share of the aircraft—70 percent—than Northrop. If Boeing took part in the so-called Q program, its experience would even be greater. Finally, Boeing also developed considerable experience in bomber avionics integration by managing major programs for the B-1B and various B-52 upgrades.

In short, American prime contractors are ending the decade of the 1990s with a level of experience in bomber development unparalleled since the 1950s. What can the historical record tell us about the prospects of preserving this experience in the coming years of declining defense budgets and few major R&D programs?

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[10]For example, see Boatman (1994, pp. 1–2).

Chapter Five

CONCLUDING OBSERVATIONS

Great caution must be exercised in drawing definitive conclusions from the type of broad and general historical overview presented here. Nonetheless, certain observations based on the U.S. historical experience seem justified. These are briefly surveyed below.

THE IMPORTANCE OF EXPERIENCE

The central role of experience in ensuring the successful design and development of new bombers can be inferred from the tendency of aerospace prime contractors to specialize. Specialization comes about because firms tend to develop competitive advantages in specific product areas by building up experience and focusing on R&D directly relevant to these areas. This experience results in system-specific capabilities—using the terminology of Hall and Johnson—which are not possessed by other leading contractors in the industry that have little experience with bomber R&D. This in turn makes it more likely that the contractors with system-specific capabilities based on experience will win a new R&D competition in that specific area, which results in such firms gaining even more experience and thus acquiring an even greater competitive edge.

The concepts of system- and firm-specific knowledge and capabilities appear to be highly relevant to the case of postwar bomber development and help bring into relief the central importance of experience that arises from specialization within an industry. At the end of World War II, at least 14 prime contractors that developed fixed-wing military aircraft were competing for future government R&D programs. In all likelihood, virtually all these companies possessed the general industry-wide knowledge necessary to develop new bomber aircraft. Yet only four firms possessed, or were perceived as possessing, a credible level of system-specific knowledge and capabilities necessary to develop the next generation of bombers successfully. Clearly, this perception of credible system-specific capabilities was founded squarely on the experience of the firms in question. During the war, these four companies—Boeing, Convair (General Dynamics), North American (Rockwell), and Martin—dominated land-based bomber development and production. Although Martin had withdrawn from the prime contractor role for bombers by the end of the 1950s, the other three firms continued to occupy the dominant leadership roles in bomber R&D well into the 1960s, further building up their system-specific knowledge and capabilities.

However, firm-specific knowledge and capabilities seem to have also played an increasingly important role as the 1950s progressed. Boeing's position as a designer and developer of new bomber designs began to fade after the early 1950s, while North American and Convair played an increasingly central role. This seems to have been at least in part due to the firm-specific capabilities in supersonic flight developed by North American and Convair because of their heavy involvement in fighter R&D and other very-high-speed platforms. Boeing did not build up nearly the same experience base as these two companies in this area in the late 1940s and early 1950s, and it failed to win either follow-on bomber development contracts or fighter contracts.

During the 1960s, Rockwell increasingly specialized in supersonic heavy bomber development and other high-speed vehicle programs, such as the X-15 and Apollo. General Dynamics turned more toward tactical fighter-bombers and lightweight, highly maneuverable fighters with the F-111 and F-16. By the late 1970s, Rockwell remained the only experienced developer of new strategic bomber designs, while General Dynamics slipped to a distant second with its FB-111. Rockwell remained in a leadership position through the end of the 1980s with B-1B development, but was joined by the apparent anomaly of Northrop as a new entrant into bomber R&D during the same decade. Nonetheless, Northrop reportedly drew heavily on engineering personnel from Rockwell's B-1A program.

Thus, throughout the 50 years spanning the beginning of World War II through the end of the 1980s, North American Rockwell maintained a nearly continuous experience stream of bomber design and development and related R&D with the B-25, B-45, A-5, XB-70, B-1A, and B-1B programs. General Dynamics had a similar record through the end of the 1960s with its B-24, B-36, XB-46, NX-2, B-58, F-111, and FB-111. After its highly successful B-47 and B-52 designs, Boeing failed to win follow-on bomber development contracts and concentrated on upgrades of existing designs. Put another way, no prime contractor won a major bomber development program during World War II or later that did not have significant and recent bomber design and development experience—with the one major exception of Northrop in the 1980s, the implications of which are discussed later. Thus, system- and firm-specific knowledge and capabilities—which are derived largely from experience—seem to matter.

If experience is as important as might be inferred from the historical record, clearly the DoD needs to consider options that will help maintain experience levels during long periods when no major R&D programs are under way. Such a strategy could focus on prototyping or technology demonstration. However, other types of military R&D programs may also contribute considerably to maintaining bomber R&D capabilities.

THE RELATIONSHIP OF BOMBER R&D TO OTHER TYPES OF SYSTEM DEVELOPMENT

The historical record indicates that successful bomber development is aided by system-specific capabilities based on experience. As suggested above, firm-specific capabilities also appear to have been particularly important, especially in the 1950s and during the stealth era in the 1970s and 1980s. Four firms had system-specific experience in bomber development in the late 1940s, but only two—North American and Convair—became heavily involved early on in the development of supersonic fighters and other high-speed platforms. Boeing had been the leading heavy bomber developer for World War II, which contributed to its success in winning both of the initial postwar jet bomber development contracts for the B-47 and B-52. But when the Air Force began seeking supersonic bombers, Boeing fared less well. Convair, successfully building on its F-102 and F-106 supersonic fighter experience, won the B-58 program. In a like manner, North American exploited the skills and capabilities developed on the F-100, F-107, and Navaho programs to help win the XB-70 contract.

Northrop's victory in the ATB competition seems at first glance to be one of the great anomalies of the postwar period. Northrop had never developed an operational heavy bomber and had not flown a prototype bomber design since its YB-49 flying wing in the late 1940s. Yet, in the 1970s, Northrop had accumulated significant firm-specific knowledge and experience in the key new technologies for the ATB: large composite structures, rounded fuselage shaping, and other stealth methodologies. The only other firm with a comparable level of firm-specific knowledge in stealth technologies was Lockheed. Yet Northrop had more closely related system-specific capabilities; it may have developed the large THAP reconnaissance aircraft, allegedly based on a rounded triangular planform design with heavy use of composite structures and RAMs. Lockheed had developed the XST and F-117, but these were based on the flat, two-dimensional "faceted" approach to shaping and used less composite structural material. The only firm with significant system-specific capabilities in bombers at this time was Rockwell. But that company had far less firm-specific knowledge in stealth technologies and approaches. Northrop also had more recent and extensive experience in fighter and other combat aircraft development than did Lockheed or Rockwell, with its F-20, YF-17/F-18, and earlier A-9 prototype.

Overall since the 1940s, companies that combine system-specific bomber R&D capabilities with critical firm-specific capabilities, often derived from fighter aircraft and other combat aircraft development, seem to have done particularly well. On the other hand, expertise in large commercial or military transports does not appear to be as relevant as fighters and other combat aircraft for bomber development. In fact, there almost appears to be an inverse correlation. Boeing has long been a leader in commercial transport development, but stopped developing new bomber designs after the early 1950s. Boeing won the commercial SST competition, but lost the XB-70 and B-1 competitions. Furthermore, its lack of experience with large supersonic aircraft appears to have contributed to the failure of the SST program. Convair made a strong bid for commercial jet transport leadership in the 1950s, but failed. North American was never a key player in large commercial transports but was a prominent fighter developer well into the 1960s. Although Rockwell never won a fighter contract after the cancellation of the F-108, it continued to maintain a major fighter design and development capability and vigorously competed for nearly all fighter contracts well into the 1980s. In the 1970s and 1980s, it was involved in two major fighter technology demonstration programs that included flying prototypes: HiMAT and X-31. Finally, Northrop has never been a developer of large commercial transport designs.

In short, the historical record suggests that, in the future, many firm-specific skills and capabilities related to bomber development may be maintained through other types of military aircraft programs, particularly fighters. On the other hand, commercial and military transport development does not appear to have been as closely correlated to bomber development as might have been thought.

THE EFFECT OF NEW TECHNOLOGY PARADIGMS

During the overall era under consideration, two periods of radical change in technology took place: in the 1940s and 1950s, with the introduction of jet propulsion, and in the 1970s and 1980s, with the introduction of stealth. Revolutionary changes in technology may drastically shake up the current hierarchy of capabilities and skills in the aerospace industry. This is because companies with high levels of system-specific capabilities have developed their skills on the old-technology aircraft, while other companies with eclectic firm-specific capabilities that may be highly relevant to the new types of aircraft may suddenly find themselves thrust into a leadership role.

It is widely recognized among scholars that the entry barriers into the aerospace industry are very high. This report has argued that significant capability barriers exist even within the industry, making it difficult for a firm to change its specialization and move into a new system area. A period characterized by a new technology paradigm may dramatically lower these intra-industry barriers.

One of the best examples of this phenomenon for the earlier period is McDonnell. In 1945, this company had no experience in developing an operational fighter or bomber, but the company had experimented during the war with unusual experimental prototypes.

Grumman was the dominant developer of Navy fighters at the time. Yet in this period of dramatic technological change, McDonnell succeeded in convincing the Navy that it possessed the new skills and capabilities necessary to develop jet fighters. The St. Louis company went on to develop the Navy's first jet fighter, the FH-1 Phantom, and soon won an Air Corps contract for another jet fighter. By the late 1950s, McDonnell had become the leading fighter developer for the Navy. Two decades later, it had become the leading fighter developer in America.

During the stealth period, the change in technology paradigm caused an even greater shake-up of leadership roles. Northrop and Lockheed had been marginal players in the area of fighters and bombers since the 1950s. They had ended up specializing in niche areas. But their unique firm-specific knowledge helped catapult them into leadership roles during the dawn of the stealth era. Lockheed was able to draw directly on its niche specialty in spy planes, which had long emphasized stealth. Northrop apparently drew on in-house study efforts launched in the 1960s. Gaining early entry into the stealth game, these two companies rapidly built up their firm-specific and system-specific capability advantages. Exploiting their unique positions, these companies were able to defeat and replace the dominant leaders in fighters and bombers from the 1960s and 1970s: McDonnell-Douglas, General Dynamics, and Rockwell.

This situation seems to suggest that system-specific experience may count considerably less in periods of dramatic technological change. But it is difficult to predict when these periods will take place and what firm-specific skills will suddenly be more important. This may imply, however, that it is important to support a significant number of companies—or at least divisions—engaged in a wide variety of different specializations and system-specific development. Northrop kept itself alive in the 1960s and 1970s in part through its own efforts to develop and sell an export fighter. After failing to win any major U.S. military aircraft development programs, it could have just as easily withdrawn from the prime contract market, as Martin and LTV did. Likewise, Lockheed failed to win any significant fighter or bomber contracts for decades after the F-104, which itself was a disappointment from the Air Force perspective. Lockheed would not have developed its unique expertise without its highly specialized niche area of spy planes dating back to the 1950s.

In short, the dramatic downsizing and consolidation of the aerospace industry currently under way may have major unanticipated long-term technology consequences if aggressive and entrepreneurial niche companies can no longer be maintained as in the past.

THE IMPORTANCE OF GOVERNMENT MILITARY TECHNOLOGY RESEARCH

A final observation that emerges from the historical record is the importance of basic and applied research funded by the government and performed in both government labs and industry. At various times over the past 50 years, key technological breakthroughs that (at least at the time they were performed) were uniquely applicable to military applications emerged from Air Force and NASA labs and the industry teams they supported. This seems to have been particularly true during periods of revolutionary technological change, such as in the 1940s and 1950s, and the 1970s and 1980s.

For the first period, some of the basic science that permitted supersonic flight was developed through the X-plane programs and associated activities in government labs. Large supersonic bombers, such as the B-70, and swing-wing technology, later used in the F-111 and B-1, were made possible through theoretical advances achieved by government researchers and engineering design concepts developed by industry.

As revealed only recently, much of the basic science and technology that made genuinely stealthy combat aircraft possible was generated through a sustained program of research in both government and industry labs in the 1950s and 1960s. Similarly, technological breakthroughs covering the spectrum from active phased-array radars to thrust vectoring and new materials were achieved through sustained government support of basic and applied research focused on military applications.

These observations suggest that a heavier dependence on "dual-use" technology development in the commercial sector and further cutbacks in government-funded science and technology may be risky for future military aircraft development. The importance of dual-use technology, except possibly in electronics and on the parts level, may be grossly exaggerated. The basic methodologies and technologies behind radical new developments in military capabilities ranging from stealth to supermaneuverability are unlikely to have ever emerged from the commercial marketplace.

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