Chapter 3

Prototyping-Plus

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INTRODUCTION

A challenge facing the Nation in the aftermath of the cold war is to reduce the size of the U.S. defense technology and industrial base (DTIB) while preserving key defense-related design and manufacturing teams, maintaining technological innovation, and giving the armed forces options from which to make future weapon-system and force-structure decisions. One approach to this problem, called "prototyping-plus,') would involve the continuous development of prototypes and, in selected cases, limited production for operational and field testing. In the event of a need to replace obsolete systems or the emergence of a new military requirement, some of the prototype systems could be further developed for quantity production.

Prototyping refers to the development and testing of working models—from computer simulations through operational hardware-to explore concepts and demonstrate specific design and operational objectives, thereby reducing technological uncertainties and risks. (See box 3-A.) The current weapons-acquisition process is based on the assumption that prototype development will lead in most cases to a design produced in quantity for the operational inventory. This assumption severely constrains the number of technological options that can be explored. A prototyping strategy, in contrast, would involve the exploration of a variety of system, subsystem, and component options *without the* assumption of proceeding to quantity production,

Greater reliance on prototyping at the expense of quantity production, as recommended by the Department of Defense (DoD), would have both benefits and costs. It would advance systems technology (e.g., systems design, not laboratory R&D), keep design teams intact, and support deployment of the most advanced equipment—assuming planners can see far enough into the future to begin production in a timely way. But it would sacrifice active forces and hot production lines, including large manufacturing teams. It is therefore necessary to define a new strategy that overcomes these drawbacks.

Defenders of the status quo often overlook the fact that the current acquisition system neglects the development of new manufacturing technologies, and that without a fundamental restructuring of the process, reduced procurement will further erode the DTIB. The prototyping-plus approach would avoid simply putting new technologies "on the shelf and allowing the manufacturing base to atrophy.[1] Instead, design teams would hone their skills and know-how by developing and testing a series of prototypes, some of which could then be manufactured in limited quantities for field testing. By working out the major bugs in the manufacturing process, limited production would make it easier to negotiate the transition to quantity production—if and when such a decision is made. This approach could mitigate the effects of reduced procurement by replacing the boom-and-bust development cycle of the cold-war era with a more deliberate process, structured to preserve the full range of critical design, manufacturing, and support skills.

This chapter examines the feasibility of a prototyping-plus strategy and suggests how it might be implemented. The discussion addresses some frequent criticisms of this approach, such as the difficulty of moving from prototyping to quantity production; the unprofitability of prototyping; the problem of maintaining an adequate vendor base in the absence of significant production; the cost of prototyping; and the ability of a prototyping-plus strategy to preserve critical elements of the DTIB and its effects on jobs, skills, and training. The chapter also describes the larger restructuring of the DTIB that would be necessary for a prototyping-plus strategy to serve the Nation's future defense needs and to be profitable to all tiers of defense contractors.

THE PROTOTYPING SPECTRUM

Prototypes are useful in different ways depending on their role in the weapons-development process.[2] Figure 3-1 shows the different categories of proto-

[1] David Silverberg, "Acquisition Rule Irks Industry, " *Defense News, vol. 7, No. 6,* Feb. 10, 1992, p. 10.

[2] I.C. Oelrich, Donald D. Weidhuner, and Frederick R. Ridden, *Small Turbine Technology Review,* IDA Paper P-1840 (Alexandria, VA: Institute for Defense Analyses, July 1985), p. 13.

Box 3-A—Traditional Functions of Prototyping

Prototyping has long served a number of functions in the weapons-acquisition process.

Hardware prototypes can fine and reduce technological uncertainty in the development of a new system.~ If the technological risks of a design are large and cannot be reduced by alternative techniques such as computer modeling or scale-model testing, construction of a working prototype is necessary. For example, vertical-takeoff-and-landing (VTOL) aircraft have complex aerodynamic and propulsion characteristics that are difficult to predict with analysis alone, so a prototype is needed to test performance predictions.

Prototypes can identify design flaws before a system enters full-scale development, also known as engineering and manufacturing development (EMD). A prototype nearly always reveals fictional flaws in a design so that corrective action can be taken early. It is therefore possible to avoid the high costs and delays caused by engineering changes late in the development process or after production has begun.[2] During testing of the YA-10 prototype in 1974, for example, Fairchild discovered that during maneuvers at high angles of attack the flow of air through the engine inlets was disturbed by turbulence from the fuselage-wing root area causing the engines to flame out. The contractor used the prototype to develop and test a correction. In the absence of a prototype, this defect might not have been detected until the first production aircraft flew, when it could have caused a major crisis.[3]

Prototyping tests systems integration and exposes problems with electromagnetic interference and compatibility (EMI/EMC) and software. General Dynamics first bench-tested the M1A2 tank's digital mapping system and other electronic subsystems individuality. They were then integrated in a laboratory, tested in a technology demonstrator, and finally put in a prototype tank Even so, it took months of testing to correct operational discrepancies and to debug the software.[4] It is not enough to test various subsystems in the laboratory; in many cases, they must be integrated in a prototype and tested under realistic conditions.

Prototyping can help define how to accomplish a given military mission before a production decision is made. Prototypes can test out different approaches to performing a given mission (e.g., ballistic-lnissile defense). The experience gained in prototyping can then lead to faster and lower cost completion of development and production.

Competitive prototyping can help to select a prime contractor, Competitive prototyping led the Army to select a different contractor for the AH-64 attack helicopter than it would have chosen based on the original paper proposals. During the paper competition, many program personnel believed that Bell Helicopter had abetter design. But in the prototyping phase the Hughes Aviation prototype outperformed Bell's, and conceptual differences between the two designs were resolved in Hughes' favor. As a result, the Army awarded Hughes the contact.[5]

Prototyping tests the soldier/system interface for the first time. The man in the loop remains the most essential ingredient of successful hardware/software development. In some cases, problems in the soldier/system interface cannot be identified and corrected early without prototyping.

1 B.H. Klein, T.K. Glennan, Jr., and G.H. Shubert, *The Role of Prototypes in Development,* RM-3467/1-PR (Santa Monica, CA: RAND Corp., April 1971), p. 10.

2 Robert Perry, *A Prototype Strategy for Aircraft Development,* RM-5597-1-PR (Santa Monica, CA: RAND Corp., July 1972), p. 9.

3 G.K. smith et al., *The Use of Prototypes in Weapon System Development,* R-2345-AF (Santa Monica, CA: RAND project Air Force, March 1981), p. 58.

4 Interview with William F. Cody, corporate director of Land systems, General Dynamics, Washington office, Nov. 13, 1991.

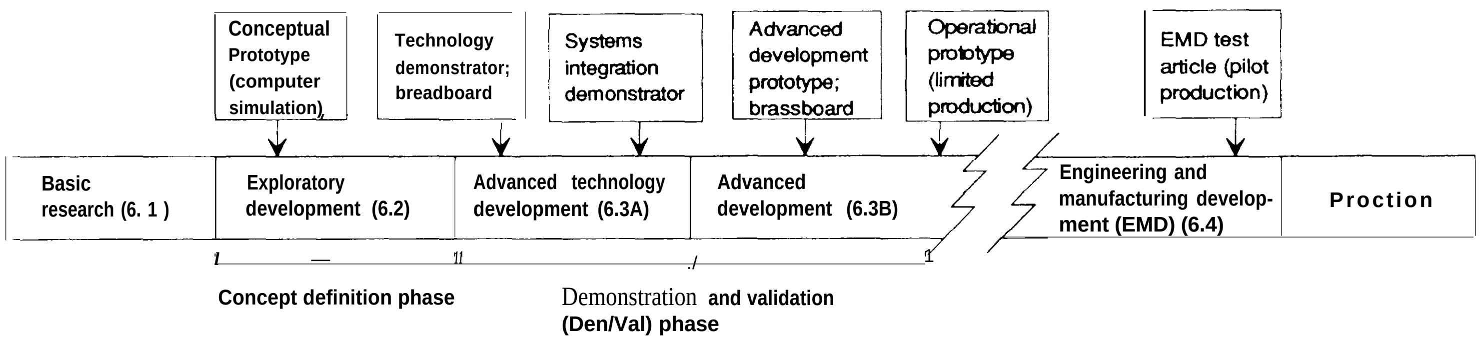
5 Smith *et al,* op. cit., footnote 3, p. 166.

types, positioned along a spectrum from the concept-definition phase to the engineering and manufacturing development (EMD) phase. Each kind of prototype is discussed in detail in the following sections.

Conceptual Prototypes

Conceptual prototypes are computer simulations of hypothetical systems. During exploratory development, simulation can emulate the capabilities and properties of an aircraft or a tank that exists only in the computer's memory. (See box 3-B.) Simulators generate dynamic visual environments that are impressively realistic, enabling military users to practice aerial dogfights or tank engagements, complete with simulated terrain, smoke, and enemy vehicles. The Defense Advanced Research Projects Agency (DARPA) has developed a Simulation Network (SIMNET) consisting of 120 computer-controlled and networked simulators of MIA1 tanks, Bradley infantry vehicles, helicopters, and fighter-bombers located at military bases throughout

Figure 3-I—The Prototyping Spectrum



SOURCE: Office of Technology Assessment, 1992,

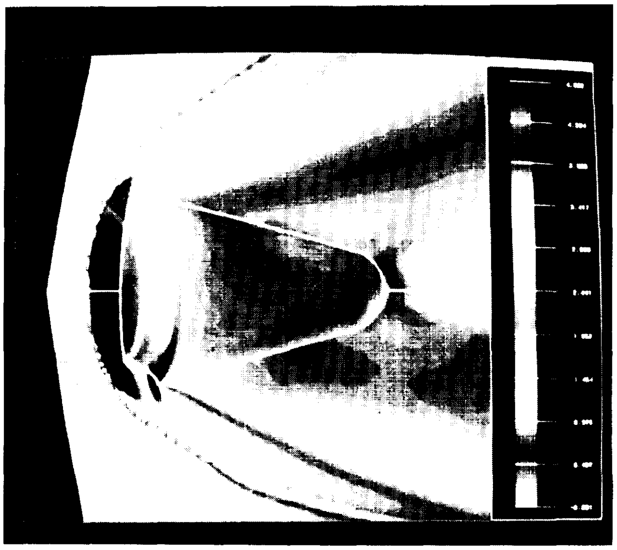


Photo credit: Rockwell International

Computational fluid dynamics (CFD) simulates the aerodynamics of reentry of a proposed single-stage-to-orbit rocket.

Photo credit: DoD

A Lockheed technician models vari ɔus aircraft concepts on a computer-graphics generator.

the United States and Europe. These interlinked simulators can be used to fight imaginary war games.

Interactive computer simulations can also inform and focus the definition of new military systems in advance of hardware development by evaluating the effects on military performance of proposed design changes. Such models can help planners sort through various threat scenarios and assess which new technologies and capabilities would provide the greatest payoff on the battlefield. For example, DARPA has sponsored the development of an interactive simulation called Project Odin, which reconstructs a pivotal tank battle during the Gulf War between the U.S. Army and the Iraqi Republican Guard. The simulation is highly detailed, including the characteristics of the weapon systems on both sides, as well as sight lines, damage, and casualties.[3] Parameters of friendly and enemy weapon systems can be altered interactively to assess the impact on the outcome of the battle if, say, the Iraqi tanks had been equipped with thermal sights, or U.S. tank guns had had 20 percent more range. (The latter simulation might reveal, for example, that increasing the firing range of U.S. tank guns would offer no operational benefit unless they had improved thermal sights that could acquire targets at greater distances.)

Conceptual prototyping his limitations. Some types of aerodynamic behavior are so complex that a physical prototype must be tested before a design concept can be validated. Other tasks exceed the capabilities of computer simulation, such as integrating multiple subsystems in:0 a platform or using new materials with unknown aging and fatigue characteristics. There are also unknown unknowns' —phenomena whose existence: is unsuspected until they emerge in testing. Further, interactive simulation often does not account for training, morale, or unexpected enemy tactics.[4]

Technology Demonstrators

A *technology demonstrator is* a functional vehicle (or test rig) that is built and tested to answer a few important technical questions as cheaply as possible. It can provide the proof-of-principle of an enabling technology or design configuration, or explore in a preliminary way the characters tics of a new systems

[3] F. Clifton Berry, Jr., "Re-creating History: The Battle of 73 Easting,'' *National Defense, vol.* 76, No. 472, pp. 6-9.

[4] After World War II, Admiral Nimitz commented on war pl tig: ''We had war-gamed every single possibility of how and what the Japanese would do in the Pacific, and we were ready for it . . . . All except one: we never expected them to use the kamikaze tactic. '

Box 3-B-Computer Simulation as an Analytical Tool

In earlier years, computers were used to speed analytical calculations during system design and to process data derived from empirical studies. Today, however, computers also have begun to replace drawing boards and wind tunnels for purposes of design and analysis. Most aerospace engineers use computer-aided design (CAD) for drafting, and an increasing number rely on computer-aided engineering (CAE) for structural and physical analysis.

CAE uses computational models to simulate the behavior of hypothetical systems. For example, finite element analysis models the stresses in a complex structure, like an aircraft wing, by representing the object as a collection of discrete elements with specified properties. Computational fluid dynamics (CFD) simulates the flow of air or water over a body (e.g., a plane or submarine). It can greatly reduce the time devoted to costly wind-tunnel testing. Finally, computer simulations can integrate 'human-factors engineering' into the design, manufacture, operation, and maintenance of weapon systems to improve compatibility between people and machines.[1]

In a growing number of cases, computer simulation can dispense with the need for a complex test article to emulate real-world conditions. For example, CFD is more accurate than wind-tunnel testing for the simulation of unsteady flow conditions within a jet engine or for a jet fighter flying at high angles of attack. Computers can also simulate velocities and environments of hypersonic flight vehicles that cannot be duplicated by traditional wind-tunnel studies,[2] Yet computer-based simulation tools are far from perfect. While supercomputers can simulate the aerodynamic behavior of a hypothetical aircraft, the simulations are only as good as the computational model on which they are based. Further, computational complexity tends to increase costs as software models become more elaborate.

The limitations of computer simulation often make hardware prototyping necessary. Such prototypes have advantages in testing an overall system and identifying manufacturing problems. They can also allow engineers to verify computational models like CFD by correlating them with red-world physical phenomena. Moreover, before engineers simulate an entirely new phenomenon such as stealth, a prototype can help build a database on how radar and detection technologies are affected by different shapes, textures, aspect angles, and electromagnetic properties.

One strategy for reducing total development costs in the future smaller DTIB would be to combine computer simulation with limited hardware prototyping. Cost constraints already require the use of computer simulation during tactical-missile development. A software program first simulates the engagement between the missile and target, and tests the performance of the missile's seeker and guidance computer. Then a limited number of hardware prototypes are fired against a set of targets selected to verify the computer model.[3] Once verified, the model can be used with confidence to explore system performance throughout the engagement envelope. This approach could be applied to other systems in development, quite apart from any decision on production.

1 William B. Scott, ''Computer Simulations Place Models of Humans in Realistic Scenarios,'' *Aviation Week & Space Technology, vol.* 134, No. *25,* June *24, 1991,* pp. 64-65.

2 Dean R. Chapman, "A Perspective on Aerospace CFD,'' *Aerospace America,* vol. *30, No.* 1, January 1992, pp. 19,58.

3 Telephone interview with Donald Putnam, corporate director of Contracts and Technical Analysis, General Dynamics, Jan. 2211992.

concepts Technology demonstrators are also built for subsystems, such as the thrust-vectoring engine nozzle developed by Pratt & Whitney. A technology demonstrator of an electronic subsystem, built and tested in a laboratory, is known as a *breadboard.*

The best-know technology demonstrators are the series of experimental ''X' vehicles, built intermittently by U.S. aerospace companies since the late 1940s for the Air Force, NASA, or DARPA. (See table 3-1.) An X-plane is often little more than an airframe, engines, and flight controls, without the specialized electronics and integrated armaments required for an operational weapon system. The *X-3* 1 demonstrator, for example, was developed to explore new technologies to enhance fighter maneuverability and does not include many subsystems required for a combat-capable aircraft. Technology demonstrators incorporate a few custom-built elements essential to the concept or technology being

[5] According to the DoD, advanced technology transition demonstrators (ATTDs) are intended to test "integrated technologies in as realistic an operational environment as possible to assess the performance payoff or cost-reduction potential of advanced technology before program-specific prototyping begins. ' Under Secretary of Defense for Acquisition *Department of Defense Directive No. 5000.1*, Feb. 23, 1991, p. 5-C-2.

Table 3-l—The X-Aircraft and Missiles, 1946-1991

X-plane	Company	Ist flight	Mission
x-1	Bell	01/25/46	Identify dynamic fllght chalacteristics of supersonic aircraft.
X-1A	Bell	02/14/53	Investigate aerodynamic phenomena at speeds greater than Mach 2 and altitudes above 90,000 feet.
X-IE	Bell	12/12/55	Explore potential performance improvements to Mach 2.5.
x-2	Bell	06/27/52	Build swept-wing version o X-l to achieve higher speeds and altitudes, investigate aerodynamic heating.
X-3 Stiletto	Douglas	10/20/52	Explore high-speed flight with takeoff and landing under own power, and low-aspect-ratio wings.
X-4 Bantam.	Northrop	08/18/50	Test aircraft deslgn wlthout horizontaltall attrans-sonic speeds.
x-5	Bell	06/20/51	Investigate aerodynamics of variable-sweep-wing aircraft.
X-6	Convair	canceled 1953	Investigate operational feasibility of nuclear propulsion systems prior to commitment to prototype military nuclear-powered aircraft.
X-7A, B	Lockheed	04/26/51	Build testbed for supersonic: and hypersonic ram jet engine.
X-8 *Aerobee*	Aerojet	11/24147	Develop inexpensive upper-a atmospheric research vehicle/ sounding rocket with parachute recovery system.
X-9 Strike	Bell	04/28/49	Build simplified testbed for air-to-surface missile to obtain data on aerodynamics, stability, propulsion, and servo and guidance systems.
x-lo	North American	10/14/53	Build aerodynamic and systems testbed for the *Navaho* cruise-missile program.
X-n	Convah	06/11/57	Develop single-stage ballistic rocket to obtain design data for the planned *Atlas* intercontinental ballistic missile.
X-12	Convair	07/09/58	Build high-performance one -and-a-half stage ballistic missile to prove systems and hardware configuration for production version of the *At/as* missile.
X-13 *Vertijet*	Ryan	12/10/55	Explore feasibility of building a pure jet vertical-takeoff-and-landing (VTOL) fighter.
X-14/A, B	Bell	02/17/57	Study experience of a pilot ı lying a VTOL aircraft from a normal crew station using standard aircraft flight references.i
X-15/X-15A-2	North American	06/08/59	Investigate problems of atmospheric and space flight at very high speeds and altitudes (Mach 6.6 and 250,000 feet).
X-16	Bell	canceled 1955	Build high-altitude, long-range reconnaissance aircraft carrying various sensors. (Replaced by Lockheed u-2.)
X-17	Lockheed	04/17/56	Build multistage rocket to transport various reentry-vehicle configurations to very high altitudes for testing.
X-18	Hiller	11/24/59	Assess feasibility and practicality of large, tilt-wing VTOL aircraft.
X-19	Curtiss-Wright	11/20/63	Demonstrate tilt-propellor VTOL configuration for transition from hover to f orward flight.
X-20 *Dyna-Soar*	Boeing	canceled 12/10/63	Provide a manned, maneuverabfe vehicle to collect data on controlled reentr y from orbital flight.
X-21A	Northrop	04/18/63	Explore feasibility of full-scale boundary-layer control on large, subsonic aircraft.
X-22A	Bell Aerospace Textron	03/17/66	Evaluate dual-tandem ducted propellor configuration for V/STOL aircraft.
X-23A Prime	Martin Marietta	12/21/66	Test configurations, control systems, and ablative materials for hypersonic lifting-body type reentry vehicles.

(continued on next page)

Table 3-l—The X-Aircraft and Missiles, 1946-1991--Continued

X-plane	Company	1st flight	Mission
X-241A-C	Martin Marietta	04/1 7/69	Explore low-speed flight characteristics of maneuverable lifting-body design.
X-25/A,B	Bensen	01/23/68	Build small, ultralight aircraft to provide emergency egress capabilities beyond those of a conventional parachute.
X-26B	Lockheed	07/67	Develop quiet plane to carry dedicated sensors over enemy territory to obtain real-time intelligence during the Vietnam War.
X-27 *Lancer*	Lockheed	canceled 1971	Build prototype of advanced, lightweight fighter to replace F-1 04, with potential for both U.S. and foreign sales.
X-28A Osprey	Pereira	08/1 2170	Explore potential usefulness of a small, single-seat seaplane for civil police patrol duty in Southeast Asia.
X-29A	Grumman	12/14/84	Assess benefits and costs of forward-swept wing, relaxed static stability, and related technologies.
X-30A *NASP*	Rockwell	1999 (est.)	Build hardware testbed for National Aerospace Plane (NASP) with single-stage-to-orbit capability.
X-31A	Rockwell/MABB	1 0/11 /90	Break the so-called “stall barrier” to permit close-in aerial combat beyond normal stall angles-of-attack.

SOURCE: Jay Miller, *The X-Planes: X-1 to X-31* (Arlington, TX: Aerofax, 1988),

demonstrated, but make extensive use of off-the-shelf hardware. Thus, more than 50 percent of the X-31 consists of government-furnished equipment from other aircraft.[G]

The other Services have also built technology demonstrators. The Army’s Advanced Composite Airframe Program demonstrated that primary aircraft structures could be made of composite materials and led to the use of composites in the V-22 Osprey aircraft. In the mid- 1980s, General Dynamics Land Systems Division developed the Tank Test Bed, an experimental armored vehicle that featured an unmanned gun turret operated by remote control. Currently, General Dynamics is developing the Composite Armored Vehicle, which will explore radically new armors and manufacturing methods.[7] Navy technology demonstrators have included a quiet torpedo-launching system and a stealthy warship design to reduce vulnerability to enemy radars and guided missiles.[8]

There are two other kinds of technology demonstrators. A *technology integration demonstrator* assembles available, off-the-shelf subsystems to perform a unique mission. For example, the Advanced Fighter Technology Integration (AFTl) program in 1983-84 modified an F-16 to demonstrate technologies that could improve fighter maneuverability. A *production retrofit demonstrator* is an upgrade of an existing platform that incorporates some new capability. For example, earlier models of the F-15 were used to test new subsystems that were incorporated into the F-l SE.

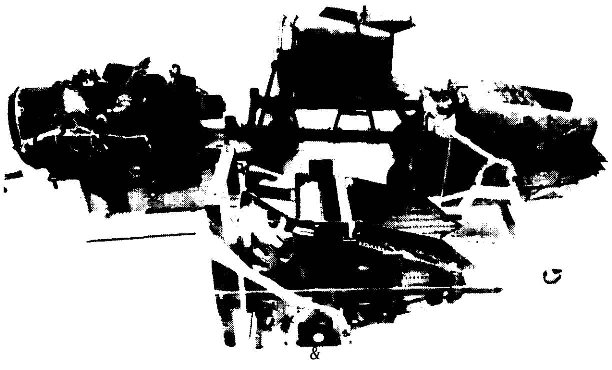
The history of the X-aircraft shows that technology demonstrators can provide a leg up on next-generation systems, often in a serendipitous manner. Table 3-2 indicates technologies from six X-aircraft programs that found their way into weapon systems, although many of the design concepts were so revolutionary that they were not applied for decades. Similarly, Northrop developed a number of “flying wing” technology demonstrators in the late 1940s.[9] Although the flying-wing program was later cancelled, flight-testing of the prototypes gave Northrop an extensive database on the aerodynamic coefficients, stability, and range/payload characteristics of these exotic designs. When Northrop

6 Off-the-shelf subsystems in the X-31 include the General Electric F404 engine, the canopy and windscreen from the F-18, the landing gear from the F-16, the wheels and brakes from the Cessna Citation III, and derivatives of existing Honeywell computers. Brian Wanstall and J.R. Wilson, “Air Combat Beyond the Stall, ” *Interavia Aerospace Review, No. 5,* June 1990, p. 406,

7 Telephone interview with Otto Renius, chief scientist, General Dynamics Land Systems Division, Sterling Heights, Michigan, Dec. 10, 1991.

8 Robert Holzer and Neil Munro, “Navy Invests Over $1 Billion in Stealth Ship, ” *Defense News,* vol. 7, No. 4, Jan. 27, 1992, p. 1.

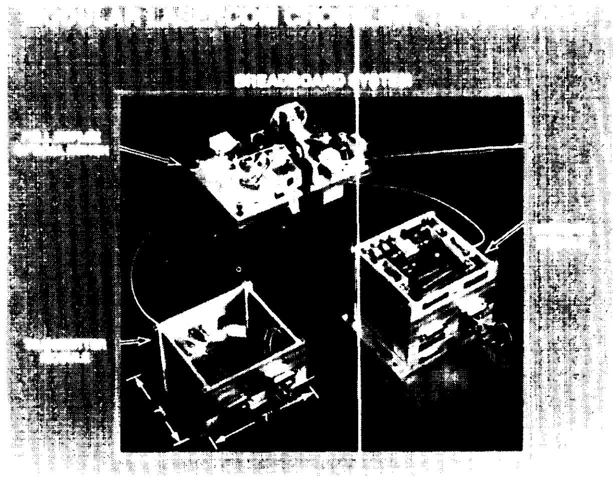
9 A propellor-driven version called the XB-35 was first flown in June 1946, and a jet-powered version called the YB-49 was first flown in October 1947. Christopher Chant, *Aircraft Prototypes* (Seacaucus, NJ: ChartWell Books, 1990), p. 8.



‘9 S

Photo credit: Pratt & Whitney

Technological evolution of a thrust-vectoring jet engine nozzle. A “boiler-plate” nozzle (left) provided basic mechanical and thermal data, which were incorporated into a durability demonstrator (top center). Initial flight testing was performed with a techrtology demonstrator (right). Finally, lessons learned in manufacturing and flight testing were applied in an advanced-development prototype (bottom *center).*



Phc to credit: Lincoln Laboratories

“Breadboard” version of a modulal laser-communications systems was built for lab testing It can be developed further into an advanced-develcpment prototype, or “brassboard,” for operational testing.

Table 3-2—Technological Spinoffs of X-Aircraft Programs

X-aircraft	1st flight	Program goal	Beneficiary program/date
x-l . . . . ,	01/25/46	Supersonic flight	F-1OO (1953)
x-4	08/1 8/50	Tailless aircraft	F-102 (1953) F-106 (1956)
x-5	06/20/51	Variable-sweep wings	F-1 11 (1964) F-14 (1970) B-1 (1974)
X-15	06/08/59	Hypersonic flight and spaceflight	SR-71 (C. 1964) Space Shuttfe(1981)
X-23124	12/21/66	Hypersonic lifting-body concept and materials	Space Shuttfe(1981)
X-29	12114184	Relaxed stability, mmposite wings, forward-swept win{is	ATF (mid-1990s)

SOURCE: Rockwell International, “X-Planes: Aeronautical Research Tools Have Paid Big Dividends in U.S. Aviation Leader: hip: A Perspective.”

decided in 1979 to use a flying-wing configuration for the B-2 strategic bomber because of its superior stealth characteristics, the company turned to the technical database collected some 30 years earlier.[10]

A technology demonstrator sometimes achieves a major breakthrough in performance that spurs a procurement decision that would not otherwise have been made. Historical cases include the U-2 and the SR-71 reconnaissance aircraft, developed secretly by the Lockheed Skunk Works for the Central Intelligence Agency. A more recent example is the Lockheed HAVE BLUE stealth-technology demonstrator, sponsored by DARPA. This $43 million program demonstrated the use of a faceted airframe design to minimize radar reflections, (The design was faceted rather than curved because of limits on computing power at the time.) The HAVE BLUE program built two small, nonmissionized technology demonstrators that weighed only 12,000 pounds fully loaded and used many components from existing aircraft. The first of the two prototype

10 Telephone interview with George J. Friedman, vice president for Engineering and Long-Range Planning, Northrop Corp., Dec. 16, 1991.

Photo credit: Northrop Corp.

"Flying wing" technology demonstrator, the YB-49 *(left)*, was first flown by Northrop in 1947. Three decades later, the company applied flight-test data from the YB-49 to develop another flying wing, the B-2 bomber *(right)*.

aircraft flew in early 1978, after 20 months of development; both were flight-tested for 18 months Lockheed demonstrated that the faceted configuration could fly and that the aircraft's radar signature was as low as predicted, although both HAVE BLUE aircraft crashed during flight testing.[12] In December 1978, the Air Force moved the program directly into the engineering and manufacturing development (EMD) phase. Lockheed then implemented the stealth technologies developed for HAVE BLUE in an operational fighter-attack aircraft, the F-1 17.

Although the initial 28 aircraft in the X-series had their first flights between 1946 and 1970, there was a hiatus of 14 years, from 1970 to 1984, between the X-28 and the X-29. (The HAVE BLUE was not officially an X-aircraft, although it met the same criteria.) In 1986, the President's Blue Ribbon Commission on Defense Management (the Packard Commission) expressed concern about the drop in the number of demonstrator programs. The Commission recommended "a high priority on building and testing prototype systems to demonstrate that new technology can substantially improve military capability, and to provide a basis for realistic cost estimates prior to a full-scale development decision.[13]

Since the early 1980s, there has been a modest resurgence of interest in experimental aircraft. The Grumman X-29 demonstrator, which first flew in December 1984, sought to enhance fighter maneuverability by integrating forward-swept wings, canards, composite structures, and flight-control software for inherently unstable aircraft. The Rockwell-MBB X-31, which first flew in October 1990, also tried to improve fighter maneuverability through the use of integrated control systems and a thrust-vectoring engine.

Since technology demonstrators are designed primarily to provide information, they are of most value if they give clear positive or negative answers

[11] Bill Sweetman, "Lifting the Curtain: Stealth Techniques Detailed, " *International Defense Review,* vol. 25, No. 2, February 1992, p. 159.

[12] While neither crash was the result of the low-observable technology, a hazardous design flaw was detected and *removed.* Jack S. Gordon, Lockheed Advanced Development Co., personal communication.

[13] The President's Blue Ribbon Commission on Defense Management, *A Quest for Excellence: Final Report to the President,* June 1986. Reprinted in U.S. Congress, House Committee on Armed Services, *Defense Acquisition." Major U.S. Commission Reports (1949-1988), Volume I* (Washington, DC: U.S. Government Printing Office, Nov. 1, 1988), p. 937.

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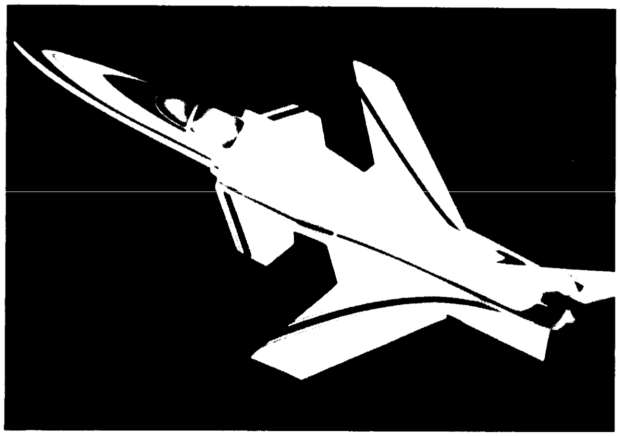


Photo credit: DoD

X-29 technology dernonstrator explored the use of forward-swept wings, canards, and an inherentfy unstable configuration to enhance fighter rnaneuverability.

Box 3-C—Submarine Prototypes

The 1950s saw rapid inovation in submarine design and construction. Submarines changed from being primarily surface boats that submerged occasionally to being capable of nearly unlimited endurance under water. Prototyping played a major role in this evolution. The USS *Albacore* (commissioned in 1953) was a technology demonstrator that tested a streamlined hull shape and novel steering devices. The first two nuclear-powered submarines were advanced development prototypes built for operational deployment. The *Nautilus (commissioned* in **1954)** had a reactor cooled with water, whereas the original *Seawolf* (commissioned in 1957) had a reactor cooled with liquid sodium. The watercooled reactor was eventually judged superior; all U.S. naval reactors since then have been water-cooled

Technological innovations were integrated into 7 different submarine prototypes built between 1956 and 1%0, all of which entered the operational fleet. Most U.S. submarines, however, were produced in multiple copies, including 4 Skate class, 6 *Skipjack class, 14 ThresherlPermit* class, 37 *Sturgeon class,* and 55 Los *Angeles* class. Since the new SSN 21 Seawolf will be canceled after production of only one, or possibly two or three units, this submarine will effectively be a prototype. It will join the operational fleet and serve as an R&D test bed The Navy's proposed *Centurion* a candidate next-generation attack submarine, is envisioned as a low-cost, modular system.[1]

1 Barbara Starr, "Lone Seawolf to join USN fleet," *Jane's Defence Weekly,* Feb. 29, 1992, p. 33).

to functional, operational, or manufacturing questions. Nevertheless, many useful defense technologies were not developed for specific applications or were applied in ways that the original inventors did not imagine. A good example is laser-based guidance, which was initially developed by the U.S. Army Missile Command for antitank missiles. The Army became disenchanted with the technology and transferred it to the Air Force, which applied it to the development of the laser-guided bomb in the 1960s.[14] Future demonstrator programs might therefore seek a balance between "technology push," or the pursuit of technological innovation for its own sake, and "technology pull, ' or more focused development efforts disciplined by a clear mission application and schedule requirement.

Advanced-Development Prototypes

During the demonstration and validation (dem/val) phase, *advanced-development prototypes are* often built to determine whether the chosen configuration can meet program objectives in terms of performance, cost, or operational suitability. Even negative answers are useful, since they can help to avoid technological dead-ends.[15] Advanced-development prototypes of electronic subsystems, called *brassboards, are* designed to be tested in an operational environment. Large weapon systems have sometimes been prototype as single units, which were later deployed as operational combatants. During the 1950s, for example, the U.S. Navy developed several one-of-a-kind prototypes of submarines (box 3-C), as well as nuclear-powered cruisers and aircraft carriers.

Whereas a technology demonstrator seeks to answer a basic technical question, an advanced-development prototype is the first physical representation of a potential operational system. There are two reasons for building an advanced-development prototype: to demonstrate through testing that the product has the required capabilities, and to estimate the time and cost of producing the system, along

14 peter deLeon, The *Laser-Guided Bomb:* Case *History of a Development,* R-1312 -1-PR (Santa Monica, CA: RAND Corp., June 1974), pp. 6-10.

15 Karen W. Tyson, et al., *Acquiring Major Systems: Cost and Schedule Trends and Acquisition Initiative Effectiveness,* IDA Paper p-2201 (Alexandria, VA: Institute for Defense Analyses, March 1989), p. VIII-l.

with its manufacturability and maintainability.[16] The validation of manufacturing processes and cost may require extrapolating from the prototyping experience into the actual production environment, using factory personnel and equipment. A novel approach to this problem is to develop computer simulations of manufacturing.

In sum, the information generated by a software or hardware prototype depends on its role in the development process. A computer simulation or technology demonstrator usually evaluates some limited design parameters, whereas an advanced-development prototype offers greater fidelity to the final production system but costs much more. The closer a prototype corresponds to the production model, the more it is locked into assumptions about the nature of military threats-assumptions that may be called into question in the future. Thus, the choice of which class of prototype to build is determined by such factors as the maturity of product and manufacturing-process technologies, the degree of **uncertainty in** the security environment, and the need to preserve technical competence and to maintain production capacity.

ASPECTS OF A PROTOTYPING-PLUS STRATEGY

A prototyping-plus strategy would involve the following elements, as illustrated in figure 3-2.

Increased development of prototypes. Prototyping would maintain the U.S. edge in defense technology for major systems (ships, aircraft, tanks, etc.) despite cuts in production and new program starts, Analyses of emerging military threats and computer simulations would identify new capabilities that might provide a clear performance advantage at an acceptable cost. A technology-demonstrator program could then be launched without a formal military requirement or the assumption of an eventual procurement.

Building a technology demonstrator might involve only one design team, or might involve competition between two or more industrial teams. In competitive prototyping, at least two technologically distinct systems would be built for testing, and one would then be chosen for further development or

Photo credit: DoD

Two advanced-development prototypes of the F-22 Advanced Tactical Fighter during flight testing.

production. Competition in selected areas might make each firm or industrial team more productive and hence improve quality and contain costs; competitive prototyping that considers dissimilar designs might also hedge against new technologies and threats. Nevertheless, funding constraints may restrict the use of competition to relatively inexpensive demonstrators rather than advanced-development prototypes.

Production of operational prototypes. Firms might manufacture a limited number of operational prototypes of one design to validate performance, manufacturing processes and controls, and projected costs. These systems would be designed for producibility and would include enough armaments, fire-control, and other subsystems to give them some operational capability. Military users would then put the prototypes through trials, since a new military capability cannot be realized until servicemen test it out under realistic field conditions.

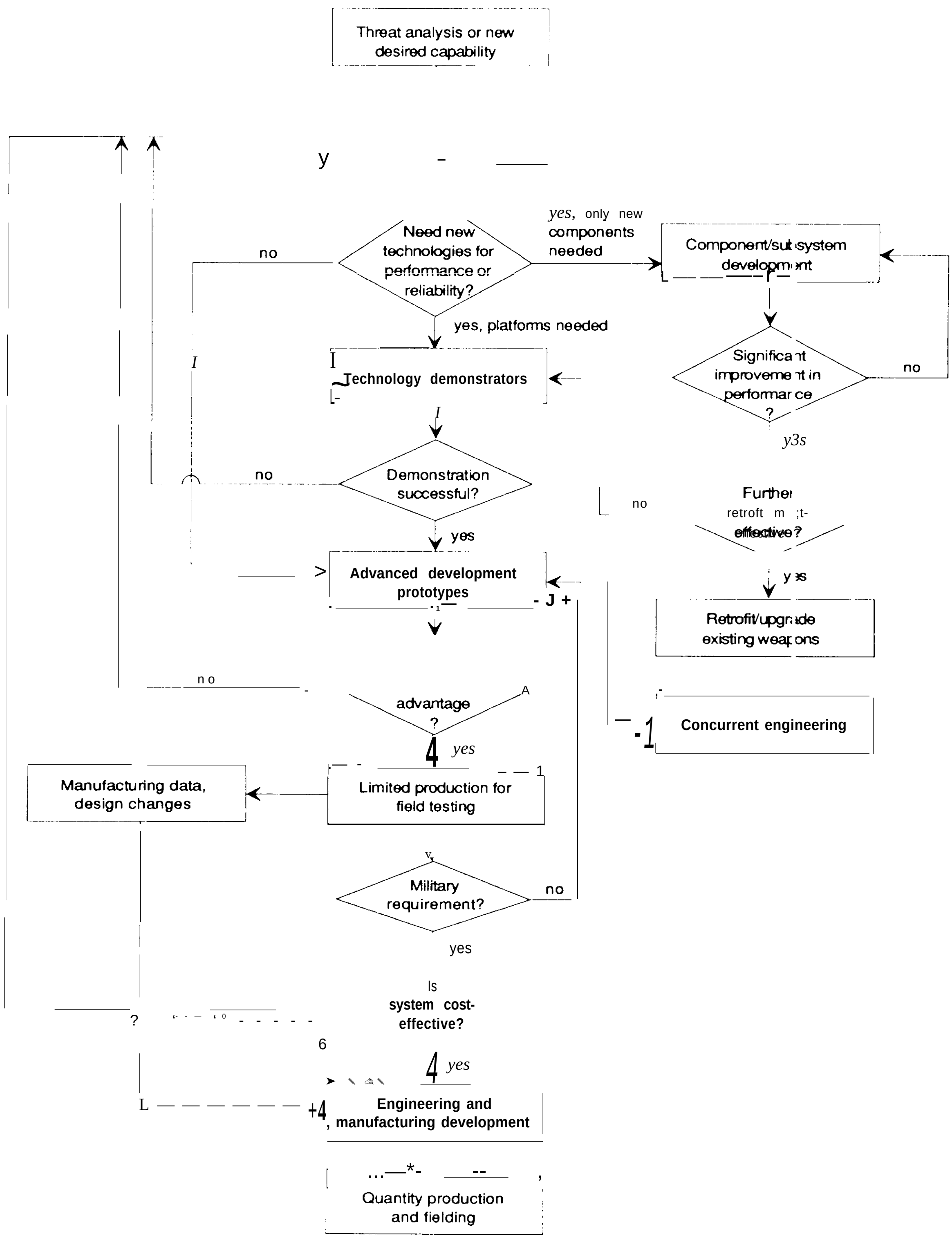
Enough operational prototypes would be produced to enable military customers to

1. develop tactics and doctrines;
2. perform reliability, maintenance, and live-fire testing; and
3. provide feedback to the development team on improvements needed to free-tune the system and compensate for operational shortcomings.[17]

16 Defense Systems Management College, *Department of Defense Manufacturing Management Handbook for Program Managers,* 2d ed. (Fort Belvoir, VA: Defense Systems Management College, July 1984), p. 3-5.

17 Gordon R. England, ''Statement Before the House Armed Services Committee Structure of U.S. Defense Industrial Base Panel' Oklahoma City Field Hearing, Nov. 1, 1991, pp. 7-8.

Figure 3-2—Prototyping-Plus Strategy



SOURCE: Office of Technology Assessment, 1992.

For these purposes, it might be sufficient to build a platoon of tanks or a squadron of aircraft.[18]

Limited production of prototypes would also provide some preliminary manufacturing data, increasing industry's ability to produce the system when needed, in sufficient quality, and at a target cost. Since long production runs would not be available to improve poor designs, a prototyping-plus strategy would emphasize designing for producibility, moving forward production issues that currently are not addressed until much later in the development process, Thus, a prototyping-plus strategy **would achieve a marriage** of R&D and manufacturing, with the goal of supporting both.

Limited production of prototypes raises the issue of how a small number of unique systems would be supported logistically in the field. In the past, the Services have provided logistical support for small numbers of complex systems, including the U-2 and SR-71 aircraft and various "testbed' vehicles fielded by the Army's Ninth Infantry Division. Logistical support could be contracted to the same firm that produced the prototype, rather than breaking out spare-parts production for competitive bid. This approach would minimize the impact of limited production on the DoD's logistical system. But it would require modifying the current procurement regulations mandating ' 'free and open competition, ' as discussed in chapter 4.

Selective replacement of major systems. Prototypes would preserve the *potential* to move into quantity production when needed, although only a fraction of all prototypes would enter the engineering and manufacturing development (EMD) phase. Quantity production could be ordered when

1. a radically new technology is developed (e.g., stealth) that cannot be retrofitted into a current platform;
2. a new or emerging threat warrants a new deployment; or
3. the current system has aged to the point where replacement is more cost-effective than an upgrade.[19]

Togo to full production, the Services would need to demonstrate a real requirement. The production contract could either be awarded to the same firm that designed the prototype, or opened up for competitive bid.

Systems v. Components

A prototyping-plus strategy could consist of two parallel but interlined tracks, one focused on components and subsystems and the other aimed at new platforms. Although the discussion of prototyping has concentrated largely on platforms, it would be more cost-effective to emphasize the development of improved subsystems (such as cockpit displays, mission computers, night-vision sights, and airborne radars), which could be retrofitted at regular intervals into fielded platforms to achieve improvements in performance. Component or subsystem development could be accompanied by development and validation of the manufacturing processes needed to produce them.[20]

In considering a prototyping-plus strategy, the DoD should strive for an optimal balance between upgrading fielded weapons and developing new systems for the next century. There is a need to change the mentality in the R&D community to make product improvement the first priority. At the same time, the new platform prototypes could make maximum use of the improved components and subsystems being developed on a second track. For example, several new components and subsystems could be integrated into a new system prototype, setting the stage for force modernization if and when a requirement for the new item emerges. To this end, the Services might jointly develop modular subsystems to be inserted into different weapon systems. An example of this approach is the Joint Integrated Avionics Working Group (JIAWG), a tri-Service office created to develop common avionics modules for the Air Force's Advanced Tactical Fighter, the

18 A U.S. Army platoon has 5 tanks. A U.S. Air Force wing typically consists of 3 squadrons, each containing between 18 and 24 aircraft (depending on type).

19 For example, in the case of the F-15 fighter, one could argue that neither the age of the aircraft nor the threat warrants near-term replacement with a more modern fighter. Stealth technology might justify a wholesale replacement, but only if it were a critical factor in the execution of F- 15 missions. Thus, the current absence of a significant threat and the reduced wear on the F-15 force in the post-cold-war era may provide a sufficient basis *not* to produce a follow-on weapon system for several years.

20 John D. Morrocco, ' 'Dangers Cited in Implementing New Pentagon Acquisition Strategy, " *Aviation Week& Space Technology, vol. 136, No.* 10, March 9, 1992, p. 21.

Navy's A-12 strike aircraft, and the Army's Comanche helicopter.[21]

A prototyping-plus strategy **would be compatible** with either an evolutionary or revolutionary approach to weapons development. The lack of a large-scale military threat to U.S. security gives the Nation the freedom to emphasize either the acquisition of knowledge and technology for future advances in military performance, reliability, and maintainability, or the evolutionary upgrading of fielded systems. Thus, a frost-generation prototype aircraft might focus on demonstrating incremental improvements in maneuverability or target acquisition, while the next-generation system could aim at entirely new capabilities such as stealth. When prototypes do not go into full production, the technology they embody could be recycled into other systems.

Profitability of Prototyping

A prototyping-plus strategy would require a significant change in attitude from both government and industry. When procurement budgets were large, companies were generally willing to break even or even lose money on R&D in the expectation of making profits on a follow-on production contract. As a result, the DoD could get private firms to provide a large share of the development funding. The result was to understate the true cost of design and development.

At present, defense firms are unable **or unwilling to invest their own money and engineering resources in prototypes that may not enter quantity production for years, if ever. The** case of the Army's proposed Mobile Protected Weapon System, a light tank to be deployed by parachute from a transport aircraft, indicates why. In 1980, the Army announced it would buy 300 of these tanks and invited industry to propose systems that met its specifications. Three U.S. producers of armored combat vehicles—FMC Corp., Teledyne's Continental Motors Division, and Cadillac Gage—responded by each building prototypes at their own expense, at a cost of $20 to 25 million per prototype. Subsequently, the Army cancelled the program.[22] Although Cadillac Gage sold a modified version of its prototype to Thailand, the ether two firms had to write off their investments.[23]

Since private-sector firms lack economic incentives to finance prototypes on their own, the government will have to bear most if not all the costs of prototyping. Prototyping-plus would be compatible with a U.S. defense: industry made up of fewer companies. These firms would have to downsize significantly while maintaining their core R&D and manufacturing capabilities, including design teams. Nevertheless, prototyping-plus would not be sufficient to preserve the defense production base. Since prototyping involves relatively little manufacturing, other measures would have to be taken to preserve manufacturing know-how. Moreover, manufacturing firms cannot be expected to survive entirely on prototyping contracts done. A prototyping-plus strategy would **only be viable in conjunction with an integrated restructuring of the** DTIB, including low-rate production, retrofits, and greater integration with the civil sector.

IMPLEMENTING THE STRATEGY

A prototyping-plus strategy should

1. keep design teams intact and technologically competitive by continually updating their skills;
2. help preserve essential manufacturing know-how;
3. facilitate the transition from prototyping to quantity production when a procurement decision is made, given sufficient lead-time and adequate funding;
4. help preserve the subtier subcontractors and suppliers that are an essential element of the DTIB; and
5. keep costs under control.

Each of these issues is examined below.

21 Michael I. Keller, consultant, personat communication, Mar. 16, 1992.

22 Telephone interview with Gen. Philip L. Bolte (U.S. Army, ret.), former program manager, Bradley Fighting Vehicle System, Nov. 19, 1991.

23 The requirement for this type of vehicle remained, however, and over a decade later the Army changed the name of the program and again requested bids for an Armored Gun System. The three companies invested additional funds and offered their prototypes in response tc a new Request for Proposal (RFP). One company and its suppliers maybe selected to produce this vehicle and recoup part of the prototype costs. If none of the three are selected, however, all will have lost not only their original prototype investment but the additional costs of upgrading and bidding again on the Army's RFP.

Preserving Design Teams

Design teams are important because the development of major weapon systems is as much an art as a science. Data alone cannot create a manufacturing capability; the other essential ingredients are people, infrastructure, knowledgeable management, and shop practices. As production budgets shrink, it will be essential to preserve the right design and manufacturing people to retain diverse approaches to defense systems work. Moreover, in order for design teams to be effective, they must work on real systems that may be actually built and tested.[24]

Preserving design teams means keeping them supplied with interesting and challenging work, Given the new financial constraints, however, the number and size of design teams involved in prototyping will have to be reduced from the current level. Over the past few decades, the increasing complexity of defense systems has led to the rapid expansion of design teams. At General Dynamics Convair Division, for example, the Tomahawk cruise-missile program started out with 8 to 10 people working on a small conceptual study and peaked at 300 to 400 engineers and other professionals at the start of EMD. At the Lockheed Skunk Works, the F-117 stealth fighter program involved a core team of about 300 throughout the development effort, but doubled in size to about 600 during the demonstration and validation phase. The EMD phase for a combat aircraft typically involves a staff of 3,000 to 7,000 people. On average, a fighter design team numbers about 1,000 people and costs about $100 million a year to maintain.

The current array of design teams will have to be consolidated into fewer, high-quality teams through streamlining, mergers, or strategic alliances. One approach is the ''agile manufacturing' concept developed by the Iacocca Institute, which focuses on teaming arrangements. Companies form temporary consortia to bring together a critical mass of skills or resources for responding to a particular market opportunity, and then disband to restructure for the next demand.[25] There is no reason why Service laboratories could not participate in such arrangements. National laboratories such as Lawrence Livermore and Los Alamos might also play an engineering support and training role.

In addition to cutting back the number of design teams, the size of the teams will need to be reduced. Two current trends should facilitate this process. First, modern management systems, supported by advances in computer-aided design (CAD) and computer-aided manufacturing (CAM) technologies, can reduce the size of design teams by increasing the efficiency of the development process. One example has been the development of new techniques for converting CAD models directly into three-dimensional hardware mockups (box 3-D). Another important advance has been the use of a single, integrated computer database to store all of the information needed to design, build, and support a weapon system. It might contain, for example, a geometric model of the more than 100,000 engineered parts that go into a combat aircraft, including cable runs, wiring harnesses, and hydraulic systems, Such models reduce the need to build expensive full-scale physical mockups to obtain insights into a system's appearance and internal layout.[26]

A centralized computer-integrated manufacturing (CIM) database can link together the functional departments of a company and its subcontractors and suppliers (figure 3-3). Since these different groups can work from the samne information, it is possible to carry out a complex project with a smaller, more dispersed staff. Another advantage of an integrated database is that engineers can update the digital blueprints continually so that the latest version of the design is available to all users of the system. Moreover, design changes made at an engineer's desk can be communicated to a host of subcontractors in a matter of hours, rather than the days or weeks formerly required to print and mail them.

Although many integrated databases are still experimental, they have been used successfully for the development of the B-2 bomber, the YF-22 fighter, and the Boeing 777 commercial airliner.[27] It

[24] Paul H. Richanbach et al., *The Future of Military R&D: Towards a Flexible Acquisition Strategy,* IDA Paper P-2444 (Alexandria, VA: Institute for Defense Analyses, July 1990), p. 16.

[25] Roger Nagel and Rick Dove, *21st Century Manufacturing Enterprise Strategy* (Bethlehem, PA: Iacocca Institute, Lehigh University, 1991).

[26] In some cases, however, mockups still provide an economic way to determine hydraulic line runs, engine fit to fuselage, and maintenance requirements.

[27] "Computer System Design Reflects B-2's Complexity, " *Aviation Week & Space Technology,* Nov. 28, 1988, pp. 26-27.

Box 3-D—Rapid Prototyping

Computer-driven tools are increasing the ability to move rapidly from designs to prototypes and thence to production. For example, a new technique known as *stereolithography* uses computer-aided design (CAD) data to produce three-dimensional solid models from a vat of photosensitive chemicals, which Polymerize and solidify into plastic as they are irradiated with a laser beam. As a result, a design engineer can complete a design and produce an accurate physical model of a complex component in a single day, for technical and presentat on mockups as well as prototypes. Quickly produced models of components can check fit against adjacent parts before expensive machining.

Stereolithography cuts the time needed to produce a mockup of a part by more than 90 Percent.[1] For example, the Air Force Manufacturing Technology (MANTECH) Program used the technique to redesign the brake pedal on the B-52 bomber. A CAD representation of the redesigned pedal was converted by stereolithography into a plastic model, which was test-fitted into a B-52 cockpit. The pedal's dimensions were found to be incorrect, so the CAD design was modified and used to generate a second prototype, which fitted correctly. Turnaround time between discovery of the original design flaw to creation of the second prototype was about 7 days, a time savings of 6 to 8 weeks over conventional machining methods. According to the Air Force, the fact that the problem was identified and corrected early, before manufacturing began, yielded a substantial cost savings.[2]

The National Science Foundation and a group of private companies are currently supporting research to make rapid prototypes from CAD models using a full range of materials, from steel to ceramics. One approach involves using a printer nozzle to squirt a binder chemical onto a bed of powdered ceramic or metal, after which the part is solidified by firing in a furnace. This method can be used to produce solid parts, dies, or ceramic molds for metal casting. While technical obstacles remain to be overcome, this approach may eventually enable manufacturers to produce small lots of customized metal or ceramic parts directly from CAD models, without casting or machining.[3]

1 Alan S. Brown, "Rapid Prototyping: Parts Without Tools," *Aerospace America*, vol. 29, No. 8, August 1991, pp. 18-23.

2 "Rapid Prototyping Program Supports B-52 Brake Pedal Redesign," USAF *Manufacturing Technology Program Status Report* (Wright-Patterson Air Force Base, OH: Wright Laboratory MANTECH Program, December 1990), p. 5.

3 Gary Stix, "Desktop Artisans," *Scientific American*, vol. 266, No. 4, April 1992, Pp. 141-2.

might be possible in the future to use computerized databases to develop a new design, upgrade it at regular intervals as new technologies become available, and build it when the need arises. Preliminary designs and manufacturing plans for such "mobilization prototypes" could be developed for rare contingencies such as Arctic warfare, special-operations needs, or future mobilization requirements.[28]

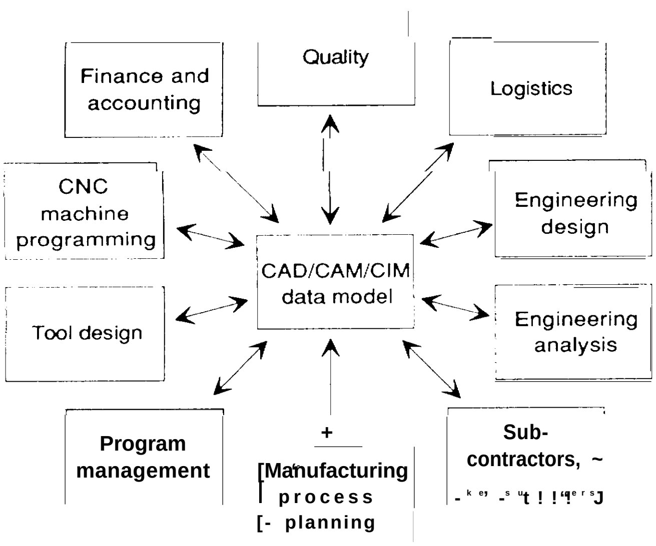
A second trend should also make it easier to rationalize the prototyping process. **Design teams are increasingly being restructured into multidisciplinary development teams that develop products and manufacturing processes simultaneously, an approach known as "concurrent engineering" or "integrated product development."**[29] Specialists are brought together at the beginning of the design process to exchange and define the information needed to manufacture and support the desired product. During development, this multidisciplinary team flows through multiple program assignments and is backed up with needed specialist support.[30] In the automobile industry, multidisciplinary development teams generally break up at the end of each development program. A prototyping-plus strategy, however, would seek to keep teams together between projects—an objective requiring a continuous flow of new prototyping projects. One approach would be to stagger prototyping efforts in time, so that some systems are in the conceptual design phase while others are in technology demonstration or limited production.

28 Leonard Sullivan, System Planning Corp., personal communication, Jan. 22, 1992.

29 Although concurrent en@@* is the more common term, it is a misnomer because the process involves more than engineering.

30 Robert I. Winner et al., The Role *of Concurrent Engineering in Weapons System Acquisition,* IDA Report R-338 (Arlington, VA: Institute for Defense Analyses, December 1988), pp. 91-92.

Figure 3-3—Centralized Database Concept



SOURCE: Office of Technology Assessment, 1992.

Maintaining Manufacturing Technology

Prototyping is a manufacturing activity—albeit one that differs from quantity production.[31] Technology demonstrators or advanced-development prototypes are usually built in special facilities, with little emphasis on durability, reproducibility, maintainability, or the suitability of the design for quantity production. Prototype construction is small-scale, flexible, and usually involves a small number of engineers or technicians working in stationary assembly booths or short, slow assembly lines. In contrast, an operational weapon system should be designed for efficient production on an assembly line and a long lifetime in the field. Quantity production is highly organized, requires a larger and more specialized workforce, and may entail the participation of several firms.

Given the different characteristics of prototype construction and quantity production, the transition from an advanced-development prototype to the final production item has traditionally been difficult and costly. In particular, it has been necessary to work out major bugs in the manufacturing process before production begins to run smoothly. For example, it took Martin Marietta 14 months to eliminate problems in the fabrication of its LANTIRN night-vision and targeting system. In the cases of the AMRAAM missile and the B-2 bomber, the transition from development to production has taken years. Industry officials argue that if they merely hand build a prototype or perform a limited production run, they will encounter serious problems in the transition to quantity production.

A possible solution to these problems lies with concurrent engineering, in which the design of a product and its manufacturing process are developed in parallel. By integrating manufacturing issues into the design process, concurrent engineering lowers the number of costly engineering changes needed after a system has entered production, significantly lowering total acquisition costs.[32] Boeing, for example, expects that concurrent engineering will reduce the development costs of its 777 passenger aircraft by as much as 20 percent.[33] For concurrent engineering to work, however, design and manufacturing engineers must share the same information. Organizational barriers must be broken down to permit the early release of preliminary design information to production staff and the feedback of manufacturing information to designers. Concurrent engineering is said to be ‘‘a people and communications issue, not an engineering technology one.’’[34]

The defense industry can learn from advanced civilian manufacturing in this area. Toyota and Honda, for example, make extensive use of prototypes to identify and solve design and manufacturing problems at an early stage of product development.[35] Some U.S. automobile companies have also implemented concurrent engineering on specifilc projects.

31 The term ‘‘quantity production’’ is relative. Most defense products are built in small volumes compared with most mass-produced products.

32 The traditional sequential approach t. development results in the need to make many costly design changes before a system can be manufactured efficiently. During the full-scale development of the Bradley fighting vehicle, for example, FMC Corp. made a total of 60,000 engineering change orders costing an average of $2,000 each. Sec John A. Alic, ‘‘Computer-Assisted Everything? Techniques and Tools for Design and Production,’ manuscript, p. 20.

33 Dori Jones Yang, ‘‘Boeing Knocks Down the Wall Between the Dreamers and the Doers,’ *Business Week,* Oct. 28, 1991, p. 120.

34 Joseph T. Vesey, ‘‘Speed-to-Market Distinguishes the New Competitors,’ *Research-Technology Management, vol. 34,* No. 6, November-December 1991, p. 36.

35 Kim B. Clark and Takahiro Fujimoto, *Product Development Performance: Strategy, Organization, and Management in the World Auto Industry* (Boston, MA: Harvard Business School Press, 1991), pp. 179-180.

Chrysler developed its new $55,000 Viper sportscar with an 85-person multidisciplinary development team, about a tenth the size of most U.S. automotive design teams. The team included 6 technicians who built all of the Viper prototypes. To transfer the manufacturing lessons learned from prototyping to production, the same 6 technicians were put in charge of assembly teams at the manufacturing plant, where 120 skilled production workers build the cars.[36] Since the Viper is a low-volume, high-value product that is largely hand assembled, it has much in common with defense systems like fighter aircraft.

Some defense contractors are beginning to address manufacturing and producibility issues during the demonstration and validation phase. In developing the X-31 demonstrator, for example, Rockwell International fielded a core multidisciplinary team of 50 to 60 design, manufacturing, and quality engineers who were retained throughout the various phases of the program. This approach resulted in better continuity of knowledge and institutional memory. Similarly, in developing the M1A2 tank prototype, the management of General Dynamics' Land Systems Division decided to have the prototype hardware built by workers in a production facility rather than by engineers in a specialized project shop. Although this approach initially sparked resistance, it promoted greater manufacturability by forcing designers and manufacturing engineers to work together.

The higher up-front costs associated with concurrent engineering are generally recouped during the production phase through a greatly reduced number of design changes and lower life-cycle costs, Nevertheless, the DoD has been reluctant to invest in manufacturing process development without a high probability of quantity production, even though some level of investment is warranted simply to maintain skills and improve manufacturing technologies. The dilemma is that whether a prototyping program will culminate in production is not usually known at the outset, because the decision depends on the outcome of the prototyping process itself. DoD and Service leaders must therefore weigh the early costs of concurrent engineering against its benefits in easing the potential transition to quantity production. Nevertheless, even if only a small fraction of prototypes lead to a design that is produced in quantity, the savings achieved through concurrent engineering—and the concomitant benefits to the manufacturing **technology base—may be great enough to warrant using this approach for most prototyping programs.**

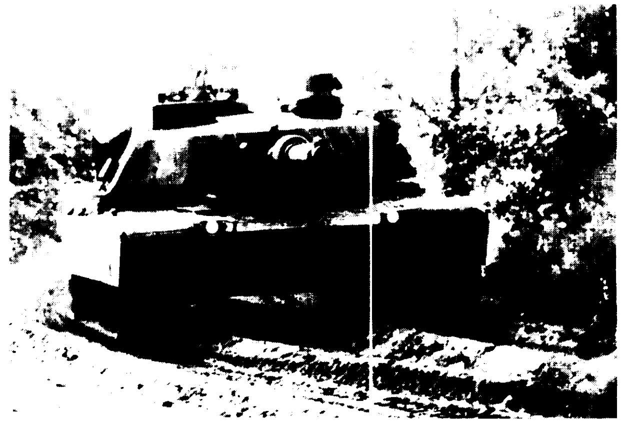


Photo credit: U.S. Army

Operational prototype of a MI A2 Abrams main battle tank undergoes field trials. An upgrade of the MI AI tank, it has a better cannon, armor, electronics, and communications.

Alternatively, OSD and Service leaders could examine a prototype at multiple decision points during the development process and assess the probability that it will lead to a design that is produced in quantity. In this way, **the extent of investment in manufacturing process development and preproduction planning during prototype development could be calibrated to the probability that the system will enter quantity production.** Other factors that may influence the extent of investment in concurrent engineering during a prototyping effort include program goals, changes in the military threat, foreign technological advances, available funding, performance requirements, and acceptable levels of technological and financial uncertainty.

Some critics contend that a prototyping strategy would be incompatible with concurrent engineering. Ongoing advances in manufacturing, they argue, would render a finished but shelved design either obsolete or incompatible with new manufacturing processes by the time it entered production years later.[37] One way of addressing this problem would

36 David Woodruff, "The Racy Viper is Already a Winner for Chrysler," *Business Week*, Nov. 4, 1991, p. 36.

37 Donald Christiansen, "Design, Don't Build?" *IEEE Spectrum*, vol. 29, No. 3, March 1992, p. 23.

be for multidisciplinary design teams to update a prototype design periodically to keep up with significant improvements in product and process technologies. Limited production of selected prototypes would also make it possible to work out the major bugs in the manufacturing process.

Tooling is another important element of prototype construction. Fabrication and assembly tooling can be either "hard" or "soft," depending on its durability and the extent to which it is amenable to change. Hard tooling refers to metal dies and jigs that are sufficiently specialized, resistant, precise, and efficient to permit quantity production.[38] Soft tooling, in contrast, is designed for low-rate manufacturing and includes standard tools, improvised rigging and clamping, dies made of malleable materials such as zinc alloys, manual forming and welding processes, and the use of machined parts rather than precision forgings. In the automobile industry, for example, prototype body panels are formed slowly on soft dies, whereas production panels are stamped on high-speed, high-power press machines fitted with hard-metal dies.[39] Soft tooling is easier, faster, and cheaper to manufacture, but it is suitable only for short or low-rate production runs and results in greater variability in production.

With smaller U.S. forces and a reduced requirement for new weapons, it should be possible to rely more on soft tooling, which would be sufficient for low-volume production. For example, although Northrop and McDonnell Douglas built only two prototypes of the YF-23 fighter with soft tooling, they claim that they could have used the same tooling to manufacture 50 of these aircraft, or more than enough for field testing.

Soft tooling also provides the flexibility to modify a design from time to time, In future weapon systems, subsystems will be upgraded at regular intervals and structures may be modified; for example, the F-1 17 airframe was refined repeatedly to reduce its radar signature. As a result, more flexible tooling and frequent design changes may become the rule, not the exception. Given the expected declines in production over the next decade, industry could use prototype construction on soft tooling to solve manufacturing problems at an early stage, and to produce operational prototypes in limited quantities for field testing. The challenge will be to build prototypes with soft tooling because of its flexibility and low cost, while simultaneously maintaining the capability to make a successful transition to hard tooling for quantity production.

In the event of crisis or war, prototype production could continue on soft tooling while manufacturing engineers prepared the hard tooling required for quantity production. This approach is not new: between the World Wars, the United States developed 37 prototype tanks but produced none in quantity. After the outbreak of World War II, it took industry about 2 years to begin turning out large volumes of tanks. Although the more sophisticated weapon systems in today's arsenals would require a longer lead-time to reach high rates of production, the length of time required **for a major new threat to emerge would still provide enough warning to gear up production of major weapon platforms such as tanks and bombers.** Deputy Defense Secretary Donald Atwood has said, "We talk now of a warning time of a major land war in Europe of something like 1 to 3 years. That's plenty of time to reconstitute an entire new [industrial] plant, an entire new supplier base. '[40] While short-warning regional conflicts would require a surge production capacity for munitions and other battlefield consumables, such wars would be fought mainly with forces-in-being. (See ch. 4.)

In the future, the definition of soft tooling may change as manufacturing systems become more versatile. Indeed, the long-term goal may be to increase the flexibility of manufacturing systems to the point **where hard tooling becomes obsolete.** It is already possible to download some types of CAD data to computer numerically controlled machine tools, so that a part can be designed and manufactured electronically without creating a paper drawing. Using this technique, it is possible to machine complex parts in 5 days, compared with the 40 days previously required. As computer-aided manufacturing technology matures, it should become possible to fabricate prototype components with the same machine **took as** quantity production, to build prototypes on assembly lines designed for multiple products, and to achieve a rapid transition

38 In the electronics industry, however, hard tooling refers primarily to specialized test equipment.

39 Clink and Fujimoto, *Product Development Performance,* op. cit., footnote 35, p. 180.

40 Atwood, quoted in 'New DoD Weapon-Buying Approach Has Industry Crying 'Uncle '," *Armed Forces Journal International,* March 1992, p. 12.

from prototyping to quantity production. To date, however, neither military nor civil manufacturers have absorbed the most advanced production technology.

Limited production of prototypes would mean foregoing many of the cost-efficiencies that result from moving down a production learning curve. Nevertheless, some analysts argue that the largest gains in efficiency result from production of the early units, when the major bugs are worked out of the manufacturing process.[41] If this assumption is true, then even the limited production of prototypes designed **for manufacturability would significantly reduce the** risks involved in the transition to quantity production. In sum, greater use of concurrent engineering in prototyping and limited, intermittent production of prototypes for operational testing would help preserve key manufacturing skills while facilitating the transition to quantity production when necessary.

Preserving the Vendor Base

Even if prime contractors agree to prototype new systems, where will the necessary parts and components come from? Without full production lines, the number of subcontractors and component suppliers at the lower tiers of the DTIB may continue to erode, and skilled machinists and other manufacturing tradesmen may be lost. Thus, for a prototyping-plus strategy to work, the survival of the vendor base must be assured.

Given some ongoing production, there is no reason to expect that lower-tier suppliers will be reluctant to supply prime contractors developing system prototypes. Indeed, vendors often seek out **such programs because it helps them to pursue their own advanced-technology development efforts. The** United States will continue to have some production programs under way in most defense areas for the forseeable future, including low-rate production of current systems, overhauls, and retrofits. Throughout the 1990s, for example, production lines for three major combat aircraft may be active at any given time. While some industrial sectors such as tanks might be without production for a time, they are the exception rather than the rule.

To attract vendor participation, **however, it will be necessary to reform the acquisition process.** First, the government may have to provide substantial amounts of R&D funding and probably some guarantee of future military orders. Morever, vendors may refuse to accept R&D contracts because of the government's insistance on ownership of all technical data developed with public funding. (See ch. 2.) It will therefore be necessary to resolve the data-rights issue. Further, since many of the larger vendors sell primarily to commercial markets, convincing them to stay in the (defense business may require modification of procurement regulations and military specifications.

In addition to these general approaches, there are some other options:

1. **The DoD could fund programs to retrofit and upgrade current platforms, ordering the improved componens in sufficient quantities to make their development and manufacture profitable for subtier suppliers. The** government might also support, on a cost-plus basis, development of the tooling needed to manufacture essential components. Further, the DoD might pay prime contractors to integrate several new subsystems and components into technology demonstrators or advanced-development prototypes.
2. **The subtier base will need to be consolidated. Prime** contractor! could protect their own workforce from layoffs by moving the production of key subsystems and components in-house. Alternatively, subtier Firms might be consolidated into a smaller number of diversified companies, which would be linked to prime contractors through strategic alliances. Indeed, Total Quality management (TQM) precepts call for the use of fewer, but high-quality and efficient, suppliers. Although market forces will result in consolidation, Federal Acquisition Regulations mandating "free and open competition' may need to be changed to permit long-term supply relationships between primes and subtiers.
3. Subcontractors **and suppliers might play a more active role in cooperating with prime contractors on prototype development and engineering.** For example, representatives of key suppliers and subcontractors might participate in concurrent engineering teams. This approach would broaden the training base and

[41] Linda Argote and Dennis Epple, ''Learning Curves in Manufacturing, ' Science, vol. 247, No. 4945, Feb. 23, 1990 pp. 920-924.

improve timely response to emerging military requirements.

4. The role of foreign suppliers should be **considered.** Foreign sources often have a lock on subcomponent technologies (such as materials, semiconductors, and optics) that will be critical to any future systems. To ensure access to these technologies, the DoD may have to make defense contracts available to foreign vendors on more or less the same terms it offers domestic producers. Alternatively, the DoD could invest more money to develop or expand an onshore (North American) production capability, using Title III of the Defense Production Act.

Time and Cost of Prototyping

On average, an advanced-development aircraft prototype can be built for 25 to 30 percent of the total development cost of the system. But the actual cost of a prototyping-plus strategy would depend on several factors:

1. the type of system, desired military performance; and extent to which it is a radical departure from current systems;
2. the number of contractors (and development teams) building prototypes;
3. the number and category of prototypes to be built (e.g., breadboard, brassboard, or fieldable operational prototype);
4. the amount of time a contractor is allowed for early development models;
5. the extent to which prototype design and manufacturing data must be documented for storage or recycling; and
6. the producibility of the design and its fidelity to the final production model, including the extent of systems integration.

Because of these numerous factors, the cost and time involved in prototyping can vary enormously. Whereas the 10 prototypes of the M1A2 tank (an upgrade of the current Ml A 1) are said to have cost about $15 million apiece, a radically new tank design (based on novel composite materials) could cost as much as $200 million. Similarly, while an austere technology demonstrator like the X-3 1 was developed under a cost-plus contract totaling about $200 million (of which the U.S. share was $135 million),[42] four advanced development Prototypes of the Advanced Tactical Fighter (ATF) cost a total of about $5 billion to develop.

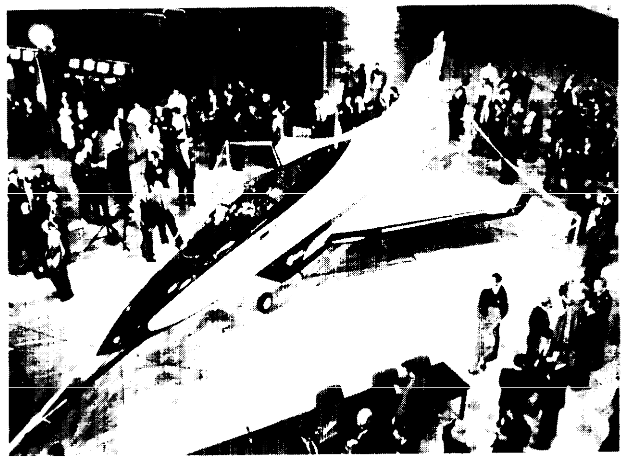


Photo credit: DoD

X-31 technology demonstrator was unveiled in March 1990. Two of the aircraft were developed and built jointly by Rockwell and the German firm MBB.

The cost of developing a prototype was not a major issue when it was just one step in a process culminating in quantity production. For tactical aircraft programs, for example, prototyping represented only a small percentage of total acquisition costs: the YF- 16 prototype cost about $100 million out of a $30 billion program; the A-10 prototype cost about $100 million in a $5 billion program; and the AV-8B prototype cost $150 million out of a $10 billion program.[43] But the economics are very different when prototyping is no longer an integral step in a sequence leading to quantity production. Without production to spread R&D and overhead costs over time, all equipment and associated costs must be borne during the development phase. The result will be an apparent rise in defense R&D) costs.

There are, however, some options for reducing prototyping costs. For technology demonstrators, one approach is to build unmanned, remotely operated systems that are easily reconfigurable. Whereas the safety requirements for human operators drive up costs, unmanned vehicles can provide

42 Michael A. Dornheim, "X-31 Flight Tests to Explore Combat Agility to 70 Deg. AOA, " *Aviation Week & Space Technology*, vol. 134, No. 10, Mar. 11, 1991, p. 38 The $200 million figure includes the design and construction of two prototypes and initial flight testing.

43 Karen W. Tyson et al., *Acquiring Major Systems*, op. cit., footnote 15, p. VIII-2.

useful information at no risk to human life. (See box 3-E.) In the case of advanced-development prototypes, costs can be reduced by building subscale models when the effects of scale are understood. During the development of the Avro Vulcan strategic bomber, for example, the British saved money by building two full-scale prototypes to evaluate flight characteristics, and four subscale prototypes to test other aspects of the aircraft such as power-control systems and electronics.[44] Another approach is to prototype only the critical components of a weapon system. In prototyping an aircraft carrier, it might be sufficient to build a control tower on a barge to test the command-and-control, threat-assessment, and other systems.

Finally, the United States might consider engaging in more collaborative prototyping programs with the NATO allies, the industrialized countries of the Pacific Rim, and possibly Russia. The advantage of international collaboration is that it permits sharing of development costs and enables U.S. firms to gain access to foreign technologies. Collaboration is likely to become a more attractive option as defense budgets are reduced and U.S. forces engage in multinational military operations, such as the Gulf War, reinforcing the need for interoperability. A drawback is that collaboration can increase U.S. dependence on offshore sources; it also inevitably entails compromises on program objectives, specifications, schedules, and worksharing. Further, transfers of U.S. technology might enable some foreign firms to become more formidable competitors in the future. Collaborative programs must therefore provide for a two-way flow of important technologies, so that the U.S. industry gains at least as much as it gives.

Although West European firms have engaged in joint development programs since the mid-1950s, this approach is relatively new for the United States. A recent example is the X-31 technology demonstrator, jointly developed by Rockwell International and the German firm Messerschmitt-Bolkow-Blohm (MBB). Launched in 1986, this program was funded under the 1985 Num-Quayle Amendment. According to a Memorandum of Understanding between the U.S. and German governments, the X-31 program is managed jointly by DARPA as overall program manager and the German Ministry of Defense as deputy program manager. The development and production work has been divided between the two firms in proportion to each country's financial contribution to the program (about 72 percent American and 28 percent German), and a joint working group resolves all interface problems.

Box 3-E—Remotely Piloted Research Vehicles

To explore the limits of fighter maneuverability achievable with current structural and propulsion technologies, NASA and the Air Force contracted Rockwell International to develop a remotely piloted research vehicle called Highly Maneuverable Aircraft Technology (HiMAT'). The HiMAT contained a TV control system, telemetry~, and a suite of research instruments. Because of its modular design and construction, the basic components of the aircraft could be altered to evaluate design changes, such as new relationships among control surfaces, modified airfoils, and various types of thrust-vectoring engine nozzles.[1] Other advantages of the HiMAT vehicle were its reduced size, which made it inexpensive to build and operate, and the fact that it could withstand accelerations that would kill human pilots. The chief drawback of the system was the need to develop a parallel command-and-control structure on the groumd to operate it.

DARPA has developed a related concept known as Advanced Configuration Remotely Operated Basic Agility Technologies (ACROBAT), a family of subscale demonstrator aircraft that would be flown remotely from a computer terminal on the ground whose configuration could be easily

1 Christopher Chant, *Aircraft Prototypes* (Seacaucus, NJ: Chartwell Books, 1990), p. 118.

2 Interview with Lt. CO1. Michael S. Francis, Advanced Systems Technology Office, DARPA, Sept. 1991.

The collaboration has worked well because Rockwell and MBB have complementary technological strengths. Whereas MBB developed the basic enhanced-maneuverability concept, Rockwell offered its system-integration skills. Both firms benefitted from sharing resources, people, and ideas. Based on their positive experience with the X-31, MBB and Rockwell plan to collaborate on other projects In addition, the U.S. and German governments are (considering a 5-year joint research program aimed at making fighter

44 Chant, *Aircraft Prototypes*, op. cit., footnote 9, p. 32.

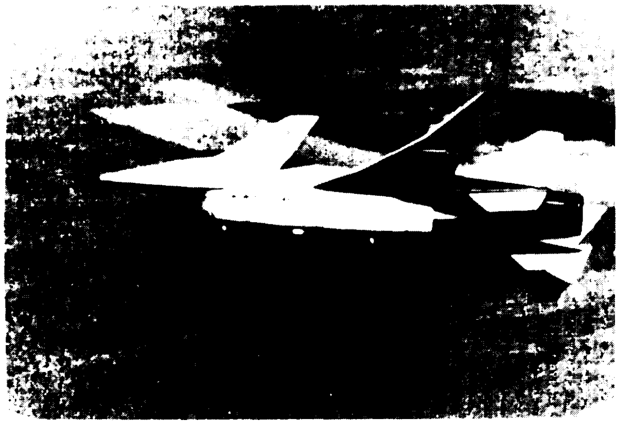


Photo credit: DoD

Remotely operated experimental aircraft called Hi MAT was designed to test new technologies for future fighters. Less expensive than a manned aircraft, it can do high-G maneuvers without risking pilots' lives.

aircraft more maneuverable, building on the results of the X-31 demonstrator.[45]

Rethinking the Acquisition Process

Throughout the cold war, the defense industry was oriented toward the need to counter a large and immediate Soviet threat. But the waning of that threat has given the United States the opportunity to shift its emphasis from short-term military capabilities to long-term military potential. In the new security environment, developing multiple prototypes makes more sense than committing scarce resources to the production of current-generation weapons, of which there is already an abundance. A prototyping-plus strategy would provide an opportunity to continue technological innovation, maintain the defense technology base, and prepare for the future. It would also keep design teams together and, through the judicious use of concurrent engineering and limited production, help to maintain manufacturing skills.

To hedge against uncertainties in both technology and the security environment, the number of prototyping programs should be large relative to the number of systems that enter quantity production. Even though most prototyping programs would not lead to a design that is produced in quantity, they would still yield useful information and technologies that could be recycled into the next generation of systems or transferred to other programs. Since prototyping is a form of experimentation, it would not be redundant to build multiple prototypes with dissimilar designs in response to a given military requirement.

Shifting to a prototyping-plus strategy **would entail a fundamental "cultural" change in both the defense industry and the government weapons-acquisition community.** First, it would require a restructuring of the weapons-acquisition process away from the linear pipeline process culminating in production. The current model would be replaced with a new paradigm in which prototypes are developed to acquire new technical knowledge and to enhance the Nation's long-term readiness against a spectrum of possible threats. Selected prototypes would be manufactured in limited numbers on soft tooling for operational testing; when a military requirement arose, prototypes could be moved into quantity production.

Although greater use of concurrent engineering would reduce development time and total procurement costs, the DoD must give defense contractors incentives **to develop more manufacturable systems. One** approach would be for the DoD to award prototyping contracts based on the performance, manufacturability, and maintainability of proposed designs. The winning firm might also receive the added bonus of a contract for limited production of the prototype, without second-source competition, At the same time, it will be necessary to discipline the development process with cost and schedule targets; otherwise, designers will never stop tinkering, and no one at the user or procurement level will abandon the quest for the ideal solution. A streamlined approach to development, known as quick-reaction prototyping, was used successfully during the Gulf War. (See box 3-F.)

A prototyping-plus strategy would also require restructuring the defense industry to reduce capacity and create **more flexible manufacturing practices, such as multiproduct assembly lines.** To this end, the DoD would need to support the development of innovative manufacturing processes and novel materials, such as the radar-absorbing composites used in stealth aircraft. This investment would be critical because the very nature of most defense production—uncertainty over orders, the

45 Barbara Opall, "U. S., Germans Plan Research on Fighter Jets, ' *Defense News,* vol. 7, No. 4, Jan. 27, 1992, p, 4.

Box 3-F-Quick-Reaction Prototyping

During the Persian Gulf War, personnel from Texas Instruments, Lockheed Missiles and Space, and Eglin Air Force Base took only 37 days to develop the GBU-28 penetrator bomb, which was then used to destroy an Iraqi command bunker that had survived direct hits from 2,000-pound bombs. Development of the new weapon required great speed and secrecy, use of existing industrial capacity and parts, and cooperation among private firms, Army arsenals, and an Air Force base.

Development of the GBU-28 began on January 21, 1991, in the midst of the air campaign against Iraq. The Air Force gave industry and its own designated project staff a free hand to get the job done as quickly as possible, with a minimum of red tape. As a first step, Eglin personnel requested the use of old 8-inch howitzer barrels stored at Letterkenny Arsenal in Pennsylvania. The gun barrels were shipped to Watervliet Arsenal in New York where they were machined into the bodies of the new bombs. Lockheed then developed the warhead, while Texas Instruments developed the guidance units. Designers at Texas Instruments took only 4 days to craft a quarter-scale aluminum model of the bomb for wind-tunnel testing of the body and tail-fin configuration.

Meanwhile, otherTI engineers used computer simulation to develop guidance software for - delivering the bomb with pinpoint accuracy. The TI team compressed the software development and testing-normally an 18-month to 2-year process-into less than 2 weeks. After field-testing at ranges in Nevada and New Mexico, two GBU-28 s-each more than 18 feet long and weighing 4,700 pounds-were flown to Saudi Arabia. They were then fitted to the undercarriages of a pair of F-ills and used successfully on February 27, 1991 to destroy the Iraqi command bunker at Al Taji Air Base north of Baghdad.[1]

[1] Gregg Jones, "Genesis of a Bomb: 'f'I's Role Critical in Quick Development of Weapon, " *Dallas Morning News*, June 30, 1991.

small size of production runs, excess capacity and the consequent difficulty in recovering the investment in tooling-makes defense firms reluctant to invest their own money to develop new manufacturing technologies.

Finally, a prototyping-plus strategy would require new approaches to program management. Specific changes might include new systems for monitoring costs, schedule, and performance; improved liaison with system users; new arrangements for managing subcontracts; and enhanced logistics planning to maintain the currency of prototypes. Other options for managing prototyping programs follow:

1. *Use performance criteria rather than specifications.* **Giving** prototype designers greater flexibility would enable them to trade off performance against cost. Cost discipline could be maintained through competition between prototype designs, government auditing, and positive fee or profit incentives for completing prototype development on time and under budget. In this way, contractors would have the freedom to be creative without having to give ur) proprietary information to ''level the playing field. '
2. *Reconsider the role of (competition.* It would not make sense for every new prototype to undergo the 2-4 year source-selection process now used for most full-cycle procurement programs. Thus, competition may have to be achieved in more flexible ways.

POLICY IMPLICATIONS

Congress must decide whether it wishes to invest in maintaining innovatation, preserving the defense technology base, and hedging against future technological breakthroughs by potential adversaries. If so, then a prototyping-plus strategy should be part of the answer. Since private industry' will be unable and unwilling to invest its own money in prototype development without the immediate prospect of a lucrative production contract, the DoD will have to bear the full cost of **prototyping. Thus, for a prototyping-plus strategy to be viable, it would require a long-term funding commitment from Congress. Even so, the** total cost would be considerably less than the alternative of maintaining a warm production base **for most military items, which is simply not feasible in the current budgetary or strategic environment.**

There are several options for carrying out prototyping programs, including competition among private fins; sole-source development in public or private ' 'arsenals; and the use of specialized engineering firms (' 'design houses' '). industry officials contend that prototyping in public arsenals would not be effective because the government does not have a good track record as a systems integrator and would not face the same cost discipline as firms competing in the marketplace. The aerospace and armored vehicle industries also oppose the use of specialized design houses, although the Navy makes extensive use of them. Since design houses are less capable of concurrent engineering, they would result in higher downstream production and life-cycle costs. Moreover, without manufacturing experience, the transition from prototyping to production would be very difficult.

Alternatively, the DoD could award prototyping contrasts to full-service firms that do both R&D and manufacturing. Such firms might build prototypes on flexible production lines. (See ch. 4.) Another option would be to consolidate development and manufacturing in several Skunk Works-like organizations, which would build competing prototypes during the concept-definition phase. Advocates of this approach argue that it would promote fresh technological approaches and force efficiencies through competition.

Other questions about a prototyping-plus strategy remain to be answered. How can prototyping contracts be made sufficiently interesting and profitable to motivate companies, scientists, and engineers to focus on state-of-the-art developments unique to military systems? With reduced defense budgets, how many prototyping-plus programs could be financed at any one time? How much would companies learn about manufacturing by using soft tooling? And should government laboratories assume the role of developing enabling technologies in those areas where the specialized nature of the application limits private-sector incentives? These unanswered questions suggest that while prototyping-plus is a promising approach, it will need more refinement before it is ready for implementation.

Finally, while a prototyping-plus strategy would preserve essential design and manufacturing capabilities and foster technological innovation, it could not by itself maintain the defense manufacturing base over time. Firms might rely on prototyping to preserve their core competencies, but they could only survive financially by: eliminating excess capacity; drawing on other businesses, such as supporting and upgrading fielded weapon systems; and diversifying into civilian markets. prototyping-plus must therefore be seen in the context of a broad restructuring of the DTIB,