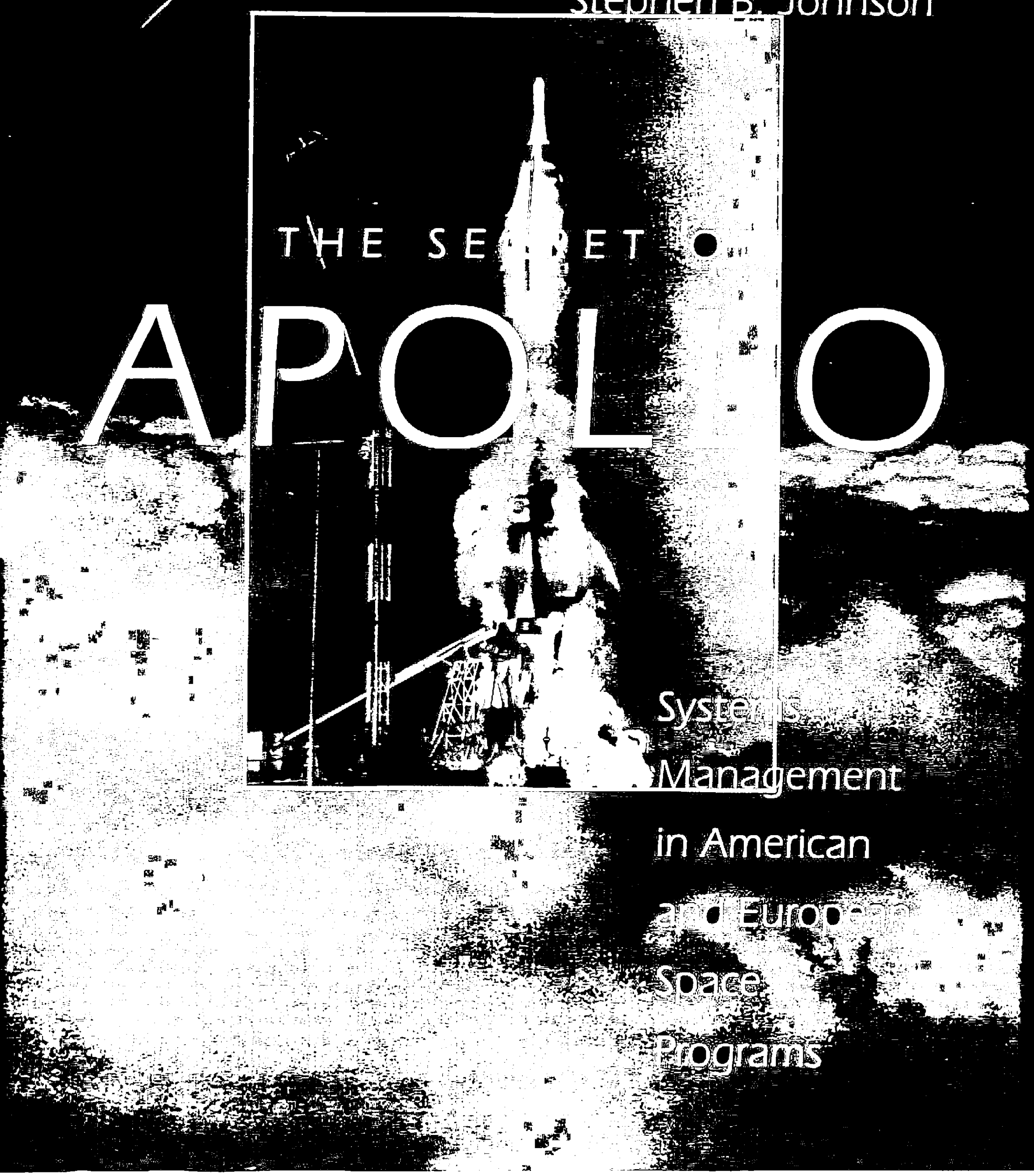
Stephen B. Johnson



THE SECRET OF APOLLO

Systems Management in American and European Space Programs

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THE SECRET OF APOLLO

Systems Management in American and European Space Programs

Stephen B. Johnson

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European frustration reached its peak in 1969, when NASA put men on the Moon while the European Space Vehicle Launcher Development Organisation (ELDO) endured yet another failure of its launcher. ELDO only haphazardly adopted American management methods, and the lack of authority meant that those that ELDO did adopt could not be consistently implemented. The failures of ELDO ultimately proved to be the spur for the Europeans to overcome their historic hostilities and create a highly successful integrated space organization, the European Space Agency. This new agency and its predecessor, the European Space Research Organisation, borrowed extensively from NASA and its contractors. NASA's management methods, when adapted to the European environment, became key ingredients in Europe's subsequent successful space program. The air force, the army's (and later NASA's) JPL, NASA's manned space programs, and the European integrated space programs all learned that spending more to ensure success was less expensive than failure.

The modern aerospace industry is paradoxical. It is both innovative, as its various air and space products attest, and bureaucratic, as evidenced by the hundreds of engineers assigned to each project and the overpriced components used. How can these two characteristics coexist? The answer lies in the nature of aerospace products, which must be extraordinarily dependable and robust, and in the processes that the industry uses to ensure extraordinary dependability. Spacecraft that fail as they approach Mars cannot be repaired. Hundreds can lose their lives if an aircraft crashes. The media's dramatization of aerospace failures is itself an indication that these failures are not the norm. In a hotly contested Cold War race for technical superiority, the extreme environment of space exacted its toll in numerous failures of extremely expensive systems. Those funding the race demanded results. In response, development organizations created what few expected and even fewer wanted—a bureaucracy for innovation. To begin to understand this apparent contradiction in terms, we must first understand the exacting nature of space technologies and the concerns of those who create them.

ONE

Social and Technical Issues of Spaceflight

> Europe's lag seems to concern *methods of organization* above all. The Americans know how to work in our countries better than we do ourselves. This is not a matter of "brain power" in the traditional sense of the term, but of organization, education, and training.
>
> —Jean-Jacques Servan-Schreiber, 1967

July 1969 marked two events in humanity's exploration of space. One became an international symbol of technological prowess; the other, a mere historical footnote, another dismal failure of a hapless organization.

"One small step for man, one giant leap for mankind." These words of American astronaut Neil Armstrong, spoken as he stepped onto the surface of the Moon in July 1969, represented the views not only of the National Aeronautics and Space Administration (NASA) but also of numerous Americans and space enthusiasts around the world. Many journalists, government heads, and industrial leaders believed that the Apollo program responsible for Armstrong's exotic walk had been a tremendous success. They marveled at NASA's ability to organize and direct hundreds of organizations and hundreds of thousands of individuals toward a single end. Even Congress was impressed, holding hearings to uncover the managerial secrets of NASA's success.[1]

Apollo was the centerpiece of NASA's efforts in the 1960s—the United States' most prestigious entry in the propaganda war with the Soviet Union. Purportedly, the massive program cost more than $19 billion through the first Moon landing and used 300,000 individuals working for 20,000 contractors and 200 universities in 80 countries.[2] It was a visual, technological, and publicity tour-de-force, capturing the world's attention with television broadcasts of the *Apollo 8* voyage to the Moon during Christmas 1968, the *Apollo 11* landing, and the dramatic near-disaster of *Apollo 13* in April 1970. Whatever else might be said about the program, it was an impressive technological feat.

This American achievement looked all the more impressive to European observers, who on July 3, 1969, witnessed the fourth consecutive failure of their own rocket, the grandiosely named *Europa I*. Whereas *Apollo*'s mandate included a presidential directive, national pride, and an all-out competition with the Soviet Union, *Europa I* began as a cast-off ballistic missile searching for a mission. When British leaders decided to use American missile technology in the late 1950s, their own obsolete rocket, *Blue Streak*, became expendable. The British decided to market it as the first stage of a European rocket, simultaneously salvaging their investment and signaling British willingness to cooperate with France, a gesture they hoped would lead to British acceptance into the Common Market. Complex negotiations ensued, as first Britain and France—and then West Germany, Italy, Belgium, and the Netherlands—warily decided to build a European rocket. All the countries hoped to gain access to their neighbors' technologies and markets, while protecting their own as much as possible.

The European Space Vehicle Launcher Development Organisation (ELDO) reflected these national ambitions. Without the ability to let contracts or to direct the technical efforts, ELDO's Secretariat tried with growing dismay to integrate the vehicle, while its member states minimized access to the data necessary for such integration. Not surprisingly, costs rose precipitously and schedules slipped. After successful tests of the relatively mature British stage, every flight that tried to integrate stages failed miserably. The contrast between European failure and American success in July 1969 could not have been more stark, with American astronauts returning to Earth to lead a round-the-world publicity tour, while European managers and engineers defended themselves from criticism as they analyzed yet another explosion. ELDO's record of failure continued for more than four years before frustrated European leaders dissolved the organization and started over.

Apollo was a grand symbol, arguably the largest development program ever undertaken. Many observers noted the massive size and "sheer competence" of the program and concluded that one of the major factors in Apollo's success was its management.[3] Learning the organizational secrets of Apollo and the American space program was a primary motivation for European government and industry involvement in space programs.[4]

French journalist Jean-Jacques Servan-Schreiber gave European fears of American domination a voice and a focus in his best-selling 1967 book, *The American Challenge*. Servan-Schreiber argued that the European problems were due to inadequacies in European educational methods and institutions as well as the inflexibility of European management and government. The availability of university education to the average American led to better management of technology development in commercial aircraft, space, and computers. Europeans needed to learn the dominant American model for managing and organizing aerospace projects: systems management.

European space organizations needed to create or learn new methods to successfully develop space technology. Wernher von Braun's rocket team in Nazi Germany confronted major technical problems in the 1930s and 1940s, requiring new kinds of organizational processes. In the 1950s, the army's Jet Propulsion Laboratory (JPL) and the air force—through its industrial contractors—developed progressively larger, more complex, and more powerful ballistic missiles. Both groups encountered obstacles that the application of more gadgetry could not overcome. Like von Braun's group, these groups found that changes in organization and management were crucial. NASA's manned program confronted similar issues in the 1960s, resulting in major organizational innovations borrowed from the air force. In each case, the unique technical problems of spaceflight posed difficulties requiring social solutions—changes in how people within organizations in design and manufacturing processes related to one another.

Technical Challenges in Missile and Space Projects

Missiles were developed from simple rocketry experimentation between World Wars I and II. Experimenters such as Robert Goddard and Frank Malina in the United States, von Braun in Germany, Robert Esnault-Pelterie in France, and Valentin Glushko in the Soviet Union found rocketry experimentation a dangerous business. All of them had their share of spectacular mishaps and explosions before achieving occasional success.[5]

The most obvious reason for the difficulty of rocketry was the extreme volatility of the fluid or solid propellants. Aside from the dangers of handling exotic and explosive materials such as liquid oxygen and hydrogen, alcohols, and kerosenes, the combustion of these materials had to be powerful and controlled. This meant that engineers had to channel the explosive power so that the heat and force neither burst nor melted the combustion chamber or nozzle. Rocket engineers learned to cool the walls of the combustion chamber and nozzle by maintaining a flow of the volatile liquids near the chamber and nozzle walls to carry off excess heat. They also enforced strict cleanliness in manufacturing, because impurities or particles could and did lodge in valves and pumps, with catastrophic results. Enforcement of rigid cleanliness standards and methods was one of many social solutions to the technical problems of rocketry.[6]

Engineers controlled the explosive force of the combustion through carefully designed liquid feed systems to smoothly deliver fuel. Instabilities in the fuel flow caused irregularities in the combustion, which often careened out of control, leading to explosions. Hydrodynamic instability could also ensue if the geometry of the combustion chamber or nozzle was inappropriate. Engineers learned through experimentation the proper sizes, shapes, and relationships of the nozzle throat, nozzle taper, and combustion chamber geometry. Because of the nonlinearity of hydrodynamic interactions, which implied that mathematical analyses were of little help, experimentation rather than theory determined the problems and solutions. For the *Saturn* rocket engines, von Braun's engineers went so far as to explode small bombs in the rocket exhaust to create hydrodynamic instabilities, to make sure that the engine design could recover from them.[7] For solid fuels, the shape of the solid determined the shape of the combustion chamber. Years of experimentation at JPL eventually led to a star configuration for solid fuels that provided steady fuel combustion and a clear path for exiting hot gases. Once engineers determined the proper engine geometry, rigid control of manufacturing became utterly critical. The smallest imperfection could and did lead to catastrophic failure. Again, social control in the form of inspections and testing was essential to ensuring manufacturing quality.

Rocket engines create severe structural vibrations. Aircraft designers recognized that propellers caused severe vibrations, but only at specific frequencies related to the propeller rotation rate. Jet engines posed similar problems, but at higher frequencies corresponding to the more rapid rotation of turbojet rotors. Rocket engines were much more problematic because their vibrations were large and occurred at a wide range of nearly random frequencies. The loss of fuel also changed a rocket's resonant frequencies, at which the structure bent most readily. This caused breakage of structural joints and the mechanical connections of electrical equipment, making it difficult to fly sensitive electrical equipment such as vacuum tubes, radio receivers, and guidance systems. Vibrations also occurred because of fuel sloshing in the emptying tanks and fuel lines. These "pogo" problems could be tested only in flight.

Vibration problems could not generally be solved through isolated technical fixes. Because vibration affected electrical equipment and mechanical connections throughout the entire vehicle, this problem often became one of the first so-called system issues—it transcended the realm of the structural engineer, the propulsion expert, or the electrical engineer alone. In the 1950s, vibration problems led to the development of the new discipline of reliability and to the enhancement of the older discipline of quality assurance, both of which crossed the traditional boundaries between engineering disciplines.[8]

Reliability and quality control required the creation or enhancement of social and technical methods. First, engineers placed stronger emphasis on the selection and testing of electronic components. Parts to be used in missiles had to pass more stringent tests than those used elsewhere, including vibration tests using the new vibration, or "shake," tables. Second, technicians assembled and fastened electronic and mechanical components to electronic boards and other components using rigorous soldering and fastening methods. This required specialized training and certification of manufacturing workers. Third, to ensure that manufacturing personnel followed these procedures, quality assurance personnel witnessed and documented all manufacturing actions. Military authorities gave quality assurance personnel independent reporting and communication channels to avoid possible pressures from contractors or government officials. Fourth, all components used in missiles and spacecraft had to be qualified for the space environment through a series of vibration, vacuum, and thermal tests. The quality of the materials used in flight components, and the processes used to create them, had to be tightly controlled as well. This entailed extensive documentation and verification of materials as well as of processes used by the component manufacturers. Organizations traced every part from manufacturing through flight.[9]

Only when engineers solved the vibration and environmental problems could they be certain the rocket's electronic equipment would send the signals necessary to determine how it was performing. Unlike aircraft, rockets were automated. Although automatic machinery had grown in importance since the eighteenth century, rockets took automation to another level. Pilots could fly aircraft because the dynamics of an aircraft moving through the air were slow enough that pilots could react sufficiently fast to correct deviations from the desired path and orientation of the aircraft. The same does not hold true for rockets. Combustion instabilities inside rocket engines occur in tens of milliseconds, and explosions within 100 to 500 milliseconds thereafter, leaving no time for pilot reaction. In addition, early rockets had far too little thrust to carry something as heavy as a human.

Because rockets and satellites were fully automated, and also because they went on a one-way trip, determining if a rocket worked correctly was (and is) problematic. Engineers developed sophisticated signaling equipment to send performance data to the ground. Assuming that this telemetry equipment survived the launch and vibration of the rocket, it sent sensor data to a ground receiving station that recorded it for later analysis. Collecting and processing these data was one of the first applications of analog and digital computing. Engineers used the data to determine if subsystems worked correctly, or more importantly, to determine what went wrong if they did not. The military's system for problem reporting depended upon pilots, but contractors and engineers would handle problem reporting for the new technologies—a significant social change. Whereas in the former system, the military tested and flew aircraft prototypes, for the new technologies contractors flew prototypes coming off an assembly line of missiles and the military merely witnessed the tests.[10]

Extensive use of radio signals caused more problems. Engineers used radio signals to send telemetry to ground stations and to send guidance and destruct signals from ground stations to rockets. They carefully designed the electronics and wiring so that electromagnetic waves from one wire did not interfere with other wires or radio signals. As engineers integrated numerous electronic packages, the interference of these signals occasionally caused failures. The analysis of "electromagnetic interference" became another systems specialty.[11]

Automation also included the advanced planning and programming of rocket operations known as sequencing. Rocket and satellite engineers developed automatic electrical or mechanical means to open and close propulsion valves as well as fire pyrotechnics to separate stages, release the vehicle from the ground equipment, and otherwise change rocket functions. These "sequencers" were usually specially designed mechanical or electromechanical devices, but they soon became candidates for the application of digital computers. A surprising number of rocket and satellite failures resulted from improper sequencing or sequencer failures. For example, rocket stage separation required precise synchronization of the electrical signals that fired the pyrotechnic charges with the signals that governed the fuel valves and pumps controlling propellant flow. Because engineers sometimes used engine turbopumps to generate electrical power, failure to synchronize the signals for separation and engine firing could lead to a loss of sequencer electrical power. This in turn could lead to a collision between the lower and upper stages, to an engine explosion or failure to ignite, or to no separation. The solution to sequencing problems involved close communication among a variety of design and operations groups to ensure that the intricate sequence of mechanical and electrical operations took place in the proper order.[12]

Because satellites traveled into space by riding on rockets, they shared some of the same problems as rockets, as well as having a few unique features. Satellites had to survive launch vehicle vibrations, so satellite designers applied strict selection and inspection of components, rigorous soldering methods, and extensive testing. Because of the great distances involved—particularly for planetary probes—satellites required very high performance radio equipment for telemetry and for commands sent from the ground.[13]

Thermal control posed unique problems for spacecraft, in part because of the temperature extremes in space, and in part because heat is difficult to dissipate in a vacuum. On Earth, designers explicitly or implicitly use air currents to cool hot components. Without air, spacecraft thermal design required conduction of heat through metals to large surfaces where the heat could radiate into space. Engineers soon designed large vacuum chambers to test thermal designs, which became another systems specialty.

Unlike the space thermal environment, which could be reproduced in a vacuum chamber, weightlessness could not be simulated by Earth-based equipment. The primary effect of zero gravity was to force strict standards of cleanliness in spacecraft manufacturing. On Earth, dust, fluids, and other contaminants eventually settle to the bottom of the spacecraft or into corners where air currents slow. In space, fluids and particles float freely and can damage electrical components. Early spacecraft did not usually have this problem because many of them were spin stabilized, meaning that engineers designed them to spin like a gyroscope to hold a fixed orientation. The spin caused particles to adhere to the outside wall of the interior of the spacecraft, just as they would on the ground where the spacecraft would have been spin tested.

Later spacecraft like JPL's *Ranger* series used three-axis stabilization whereby the spacecraft did not spin. These spacecraft, which used small rocket engines known as thrusters to hold a fixed orientation, were the first to encounter problems with floating debris. For example, the most likely cause of the *Ranger 3* failure was a floating metal particle that shorted out two adjacent wires. To protect against such events, engineers developed conformal coating to insulate exposed pins and connectors. Designers also separated electrically hot pins and wires so that floating particles could not connect them. Engineers also reduced the number of particles by developing clean rooms where technicians assembled and tested spacecraft.

Many problems occurred when engineers or technicians integrated components or subsystems, so engineers came to pay particular attention to these interconnections, which they called interfaces. Interfaces are the boundaries between components, whether mechanical, electrical, human, or "logical," as in the case of connections between software components. Problems between components at interfaces are often trivial, such as mismatched connectors or differing electrical impedance, resistance, or voltages. Mismatches between humans and machines are sometimes obvious, such as a door too high for a human to reach, or an emergency latch that takes too long to operate. Others are subtle, such as a display that has too many data or a console with distracting lights. Finally, operational sequences are interfaces of a sort. Machines can be (and often are) so complicated to operate that they are effectively unusable. Spacecraft, whether manned or unmanned, are complex machines that can be operated only by people with extensive training or by the engineers who built them. Greater complexity increases the potential for operator error. It is probably more accurate to classify operator errors as errors in design of the human-machine interface.[14]

Many technical failures can be attributed to interface problems. Simple problems are as likely to occur as complex ones. The first time the Germans and Italians connected their portions of the *Europa* rocket, the diameters of the connecting rings did not match. Between the British first stage and the French second stage, electrical sequencing at separation caused complex interactions between the electrical systems on each stage, leading ultimately to failure. Other interface problems were subtle. Such was the failure of *Ranger 6* as it neared the Moon, ultimately traced to flash combustion of propellant outside of the first stage of the launch vehicle, which shorted out some poorly encased electrical pins on a connector between the launch vehicle and the ground equipment. Because the electrical circuits connected the spacecraft to the offending stage, this interface design flaw led to a spacecraft failure three days later.[15]

Some farsighted managers and engineers recognized that interfaces represented the connection not simply between hardware but also between individuals and organizations. Differences in organizational cultures, national characteristics, and social groups became critical when these groups had to work together to produce an integrated product. As the number of organizations grew, so too did the problems of communication. Project managers and engineers struggled to develop better communication methods.

As might be expected, international projects had the most difficult problems with interfaces. The most severe example was ELDO's Europa I and Europa II projects. With different countries developing each of three stages, a test vehicle, and the ground and telemetry equipment, ELDO had to deal with seven national governments, military and civilian organizations, and national jealousies on all sides. Within one year after its official inception, both ELDO and the national governments realized that something had to be done about the "interface problem." An Industrial Integrating Group formed for the purpose could not overcome the inherent communication problems, and every one of ELDO's flights that involved multiple stages failed. All but one failed because of interface difficulties.[16]

By the early 1960s, systems engineers developed interface control documents to record and define interfaces between components. On the manned space projects, special committees with members from each contributing organization worked out interfaces between the spacecraft, the rocket stages, the launch complex, and mission operations. After the fledgling European Space Research Organisation began to work with American engineers and managers from Goddard Space Flight Center, the first letter from the American project manager to his European counterpart was a request to immediately begin work on the interface between the European spacecraft and the American launch vehicle.[17]

Systems management became the standard for missile and space systems because it addressed many of the major technical issues of rockets and spacecraft. The complexity of these systems meant that coordination and communication required greater emphasis in missile and space systems than they did in many other contemporary technologies. Proper communication helped to create better designs. However, these still had to be translated into technical artifacts, inspected and documented through rigid quality inspections and testing during manufacturing. Finally, the integrated system had to be tested on the ground and, if possible, in flight as well. The high cost and "nonreturn" of each missile and spacecraft meant that virtually every possible means of ground verification paid off, helping to avoid costly and difficult-to-analyze flight failures. All in all, the extremes of the space environment, automation, and the volatility of rocket fuels led to new social methods that emphasized considerable up-front planning, documentation, inspections, and testing. To be implemented properly, these social solutions had to satisfy the needs of the social groups that would have to implement them.

Systems Management and Its Promoters

Four social groups developed and spread systems management: military officers, scientists, engineers, and managers. All the groups promoted aspects of systems management that were congenial to their objectives and fought those that were not. For example, the military's conception of "concurrency" ran counter in a number of ways to the managerial idea of "phased planning," while the scientific conception of "systems analysis" differed from the engineering notion of "systems engineering." Academic working groups promoted by scientists and engineers conflicted with hierarchical structures found in the military and industry, and the working groups' informal methods frustrated attempts at hierarchical control through formal processes. The winners of these bureaucratic fights imposed new structures and processes that promoted their conceptions and power within and across organizations.

In the early 1950s, the prestige of scientists and the exigencies of the Cold War gave scientists and military officers the advantage in bureaucratic competition. Military leaders successfully harnessed scientific expertise through their lavish support of scientists, including the development of new laboratories and research institutions. Scientists in turn provided the military with technical and political support to develop new weapons.[18] The alliance of these two groups led to the dominance of the policy of concurrency in the 1950s.[19]

To the air force, concurrency meant conducting research and development in parallel with the manufacturing, testing, and production of a weapon. More generally, it referred to any parallel process or approach. Concurrency met the needs of military officers because of their tendency to emphasize external threats, which in turn required them to respond to those threats. Put differently, for military officers to acquire significant power in a civilian society, the society must believe in a credible threat that must be countered by military force. If the threat is credible, then military leaders must quickly develop countermeasures. If they do not, outsiders could conclude that a threat does not exist and could reduce the military's resources. For the armed forces, external threats, rapid technological development, and their own power and resources went hand in hand.

Scientists also liked concurrency, because they specialized in the rapid creation of novel "wonder weapons" such as radar and nuclear weapons. Even when scientists had little to do with major technological advances, as in the case of jet and rocket propulsion, society often deemed the engineers "rocket scientists." Scientists did little to discourage this misconception. They gained prestige from technical expertise and acquired power when others deemed technical expertise critical. Scientists predicted and fostered novelty because discovery of new natural laws and behaviors was their business. Novelty required scientific expertise, whereas "mundane" developments could be left to engineers.

SCI
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While the Cold War was tangibly hot in the late 1940s and 1950s, American leaders supported the search for wonder weapons to counter the Communist threat. Although very expensive, nuclear weapons were far less expensive than maintaining millions of troops in Europe, and they typified American preferences for technological solutions.[20] Military officers allied with scientists used this climate to rapidly drive technological development.

By 1959, however, Congress began to question the military's methods because these weapons cost far more than predicted and did not seem to work.[21] Embarrassing rocket explosions and air-defense system failures spurred critical scrutiny. Although Sputnik and the Cuban Missile Crisis dampened criticism somewhat, military officers had a difficult time explaining the apparent ineffectiveness of the new systems. Missiles that failed more than half the time were neither efficient military deterrents nor effective deterrents of congressional investigations. The military needed better cost control and technical reliability in its missile programs. Military officers and scientists were not particularly adept in these matters. However, managers and engineers were.

Engineers can be divided into two types: researchers and designers. Engineering researchers are similar to scientists, except that their quest involves technological novelty instead of "natural" novelty. They work in academia, government, and industrial laboratories and have norms involving the publication of papers, the development of new technologies and processes, and the diffusion of knowledge. By contrast, engineering designers spend most of their time designing, building, and testing artifacts. Depending upon the product, the success criteria involve cost, reliability, and performance. Design engineers have little time for publication and claim expertise through product success.

Even more than design engineers, managers pay explicit heed to cost considerations. They are experts in the effective use of human and material resources to accomplish organizational objectives. Managers measure their power from the size and funding of their organizations, so they have conflicting desires to use resources efficiently, which decreases organizational size, and to make their organizations grow so as to acquire more power. Ideally, managers efficiently achieve objectives, then gain more power by acquiring other organizations or tasks. Managers, like engineers, lose credibility if their end products fail.

As ballistic missiles and air-defense systems failed in the late 1950s, military officers and aerospace industry leaders had to heed congressional calls for greater reliability and more predictable cost. In consequence, managerial and engineering design considerations came to have relatively more weight in technology development than military and scientific considerations. Managers responded by applying extensive cost-accounting practices, while engineers performed more rigorous testing and analysis. The result was not a "low cost" design but a more reliable product whose cost was high but predictable. Engineers gained credibility through successful missile performance, and managers gained credibility through successful prediction of cost. Because of the high priority given to and the visibility of space programs, congressional leaders in the 1960s did not mind high costs, but they would not tolerate unpredictable costs or spectacular failures.

Systems management was the result of these conflicting interests and objectives. It was (and is) a mélange of techniques representing the interests of each contributing group. We can define systems management as *a set of organizational structures and processes to rapidly produce a novel but dependable technological artifact within a predictable budget.* In this definition, each group appears. Military officers demanded rapid progress. Scientists desired novelty. Engineers wanted a dependable product. Managers sought predictable costs. Only through successful collaboration could these goals be attained. To succeed in the Cold War missile and space race, systems management would also have to encompass techniques that could meet the extreme requirements of rocketry and space flight.

Conclusion

Social and technical concerns drove the development of systems management. The dangers of the Cold War fed American fears of Communist domination, leading to the American response to ensure technological superiority in the face of the quantitative superiority of Soviet and Chinese military forces. Military officers and scientists responded to the initial call by creating nuclear weapons and ballistic missiles as rapidly as possible.

Technical issues then reared their ugly heads, as the early missile systems exploded and failed frequently. Investigation of the technical issues led to the creation of stringent organizational methods such as system integration and testing, change control, quality inspections and documentation, and configuration management. Engineers led the development of these new technical coordination methods, while managers intervened to require cost and schedule information along with technical data with each engineering change.

The result of these changes was systems management, a mix of techniques that balanced the needs and issues of scientists, engineers, military officers, and industrial managers. While meeting these social needs, systems management also addressed the extreme environments, danger, and automation of missile and space flight technologies. By meeting these social and technical needs, systems management would become the standard for large-scale technical development in the aerospace industry and beyond.

TWO

Creating Concurrency

> We are in a technological race with the enemy. The time scale is incredibly compressed. The outcome may decide whether our form of government will survive. Therefore, it is important for us to explore whether it is possible to speed up our technology. Can we for example plan and actually *schedule* inventions? I believe this can be done in most instances, provided we are willing to pay the price and make no mistake about it, the price is high.
>
> —Colonel Norair M. Lulejian, 1962

The complex weapon systems of World War II and the Cold War involved enormous technical difficulties. Scale was not the problem, for large-scale systems such as the telephone network, electrical power systems, and skyscrapers had existed before. Rather, the difficulty lay in the heterogeneity of the components, their novelty, and their underlying complexity. Military personnel were unfamiliar with the new technologies of rocket engines, nuclear weapons, and guidance and control systems.

New technology provided opportunities for military officers with a technical bent. Allied with scientists and research engineers, these officers promoted the "air force of the future" over the traditional "air force of the present." Through wide-ranging research and fast-paced development, the air force would maintain a technological edge over its Communist adversaries. Separating research and development (R&D) from current operations, these officers created new methods to integrate technologies into novel "weapon systems." In so doing, they brought into being new organizations and niches for technical officers, scientists, and engineers.

Of the new technologies developed during World War II, ballistic missiles were among the most promising. The marriage of ballistic missiles with fusion warheads promised an invulnerable delivery system for the ultimate explosive. At the push of a button, an entire city could be obliterated within thirty minutes. While the bomber pilots who dominated the air force's leadership vacillated, technical officers and their scientific allies pressed ahead and past air force skeptics, winning top-priority status for intercontinental ballistic missiles (ICBMs). Led by Brig. Gen. Bernard Schriever, their success was the apex of scientific influence in the military and laid the foundation for a new way of organizing R&D. Combining scientific novelty with the military's need for rapid development, this new approach became known as concurrency.[1]

Concurrency replaced the air force's prior management methods for large-scale technology development. If the technology of ICBMs had been less complex, or if their development had occurred at a more relaxed pace, then the air force's existing management techniques might have sufficed. Facing the combined impact of technical difficulty and rapid tempo, however, the loosely organized technical divisions of the air force's development groups could not cope. Equally important, the scientists who advised the air force's leaders did not believe that traditional methods and organizations would succeed. Based on their recommendations, Schriever created a centralized, tightly planned management scheme to implement the air force's complex new weapon system as quickly as possible. To understand the changes that Schriever and his allies wrought, we must turn to the air force's methods prior to the development of ICBMs.

Aircraft before Systems

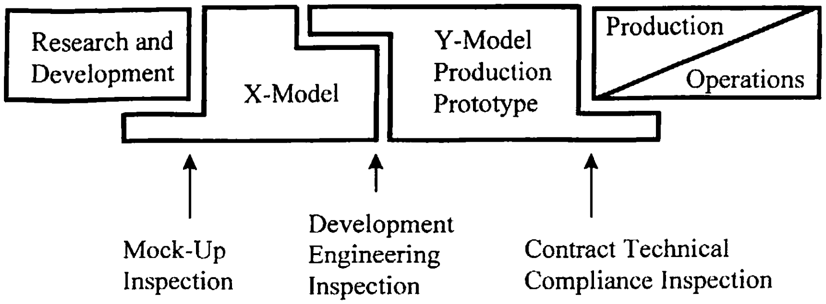
The air force's R&D methods trace back to the creation of aircraft in the first decade of the twentieth century. Because the army did not create an arsenal to develop aircraft, contractual relationships between the Army Air Corps and the aircraft industry governed military aircraft development. The Army Signal Corps ordered its first aircraft from the Wright brothers in 1908 using an incentive contract that awarded higher fees for a higher-speed aircraft.[2] Army evaluation and testing of aircraft began near the Wrights' plant in Dayton, Ohio. These facilities soon grew into the Air Corps's primary complex for aircraft development and testing.

While European powers rapidly developed aircraft for military purposes, the U.S. Army kept aircraft development a low priority. World War I broke American lethargy; in 1915, Congress created the National Advisory Committee for Aeronautics (NACA) to promote aircraft research, evaluation, and development for the military and the aircraft industry. Engineers at NACA's facility at Langley Field in Hampton, Virginia, concentrated on the testing and evaluation of aerodynamic structures and aircraft performance, using new wind-tunnel facilities to test fuselages, engine cowlings, propeller designs, and pilot-aircraft controllability. The United States mass-produced a few European designs during the war but rapidly dismantled most of its capability after the war's end.[3]

Between World War I and World War II, the Army Air Corps fostered aircraft development at a leisurely pace. Typically the engineering and procurement divisions at Wright Field in Dayton contracted with industry for aircraft, which officers, civilians, and operational commands then tested. Army Ordnance and the Army Signal Corps developed the armaments and electronic gear that Wright Field personnel then integrated into the aircraft. Wright Field procured the components, then modified them as necessary to integrate them into the aircraft. Funding constraints were more important than schedule considerations, leading to a rather deliberate development and testing program commonly described as the "fly before you buy" concept.[4]

After the Air Corps released design specifications, contractors designed, built, and delivered a prototype known as the X-model to the Air Corps. The Air Corps tested this model, making recommendations for changes. After completion of X-model testing, the contractor made the recommended design changes, then developed the Y-model production prototype. The Air Corps then ran another series of tests and made further design recommendations. After approval of the Y-model, the contractor released the production drawings and built the required number of aircraft.[5]

From the mid-1920s, Wright Field assigned a project engineer from its Engineering Division to monitor all aircraft design and development. By the late 1930s, Wright Field assigned a project officer to each aircraft in development, along with the project engineer and a small supporting staff. For example, in the Bombardment Branch before World War II, Col. Donald Putt and five other officers managed six aircraft projects with the assistance of a few secretaries and Wright Field engineers assigned to tasks as needed. Be-



"Fly before you buy" sequential development, typical of the Army Air Corps in the 1920s and 1930s. Adapted from Benjamin N. Bellis, L/Col USAF Office DCS/Systems, "The Requirements for Configuration Management During Concurrency," in AFSC Management Conference, Air Force Systems Command, Andrews Air Force Base, Washington, D.C., AFHRA Microfilm 26254, 5-24-2.

cause of the slow pace of development, the limited role of the government in testing and approving designs, and the fixed-price contracting method typical before the war, this small staff sufficed. Project officers focused on aircraft safety and on finding design weaknesses.[6]

As war loomed in 1940, Congress legalized negotiated cost-plus-fixed-fee (CPFF) production contracts. With a flood of funding and a goal of building 50,000 aircraft, the Air Corps immediately signed letters of intent to get design and production moving, with cost negotiations deferred until later. Under the prior competitive bidding process, procurement officers did not need to understand the financial details of a manufacturers' bid, because the manufacturer—not the government—lost money if it underbid. However, under CPFF arrangements, cost overruns were the government's problem. The Air Corps Procurement Branch grew rapidly to collect information and negotiate with contractors to assess the validity of cost charges and determine a fair profit.[7]

Unless Congress extended the authority to negotiate contracts after the war, the military's capability to control industry and influence scientists and their new technologies would dramatically decrease. Fortunately for the military, the Procurement Act of 1947 extended the military's wartime authority and tools, including the formerly controversial negotiated contract mechanism, into peacetime.

The importance of the 1947 act should not be underestimated, for it perpetuated government use of CPFF contracts. This had several significant ramifications. First, the CPFF contract reduced risk for industry. Where high risk was inherent, as it was in R&D, this drew profit-making corporations and universities into government-run activities. Second, to reduce government risk, CPFF contracts required a government bureaucracy sufficient to monitor contractors. Third, CPFF contracts turned attention from cost concerns to technical issues. This "performance first" attitude led to higher costs but also to a faster pace of technical innovation and occasionally to radical technological change. Last, the CPFF contract provided some military officers with the means to promote technological innovation along with their own careers.[8]

Negotiated contracts formed the basis for Cold War contractual relationships between government, industry, and academia. Government officials became both partners and controllers of the aircraft industry in a way unimagined before the war, with expanded procurement organizations that made the federal government a formidable negotiator. To fully exploit their extended authority to create new weapons, however, the Army Air Forces would also have to solidify its relationships with scientists and engineers.

Organizing to Communicate with Technologists

During World War II, scientists vastly increased the fighting capability of both Allied and Axis powers. The atomic bomb, radar, jet fighters, ballistic missiles, and operations research methods applied to fighter and bomber tactics all had significant impact on the war. Recognizing the contributions of scientists, Gen. H. H. "Hap" Arnold, commander of the Army Air Forces, advocated maintaining the partnership between military officers and scientists after the war's end. His plans led to the creation of several organizations that cemented the partnership between technically minded Army Air Forces officers and the community of scientific and technological researchers.

In 1944, Arnold met briefly with eminent aerodynamicist Theodore von Kármán of the California Institute of Technology and asked him to assemble a group of scientists to evaluate German capabilities and study the Army Air Forces' postwar future. Among the group's recommendations were the establishment of a high-level staff position for R&D, a permanent board of scientists to advise the Army Air Forces, and better means to educate Army Air Forces officers in science and technology.[9] The Army Air Forces acted first to maintain the services of von Kármán and his scientific friends. Supported by General Arnold, the Army Air Forces established the Scientific Advisory Board (SAB) in June 1946 as a semipermanent adviser to the staff.[10]

Arnold recognized that establishing an external board of scientists would do little to change the Army Air Forces unless he also created internal positions to act as bridges and advocates for scientific ideas. He established the position of scientific liaison in the air staff and elevated his protégé Col. Bernard Schriever into the position in 1946. Schriever had known Arnold since 1933, when as a reserve officer Schriever was a bomber pilot and maintenance officer under Arnold. Schriever's mother became a close friend of Arnold's wife, leading to a lifelong friendship with the Arnold family. Arnold encouraged Schriever to take a full commission, which Schriever did prior to World War II. Schriever served with distinction in the Pacific, and his work in logistics brought him into contact with procurement officers at Wright Field. After the war, Arnold moved him to the Pentagon. As scientific liaison, Schriever helped create the air force's R&D infrastructure, including test facilities at Cape Canaveral, Florida, and in the Mojave Desert north of Los Angeles as well as research centers in Tennessee and near Boston. He worked closely with the SAB, an association that would have far-reaching consequences.[11]

Despite the creation of a research office in Air Materiel Command (AMC),[12] an increasing number of military officers believed that AMC did not pursue R&D with sufficient vigor. The controversy revolved around the conflict between technologically oriented officers who promoted the "air force of the future" and the traditional pilots who focused on the "air force of the present." Advocates of the future air force had powerful allies in General Arnold and in Lt. General Donald Putt, a longtime aircraft procurement officer from Wright Field. Putt had been a student of von Kármán at Caltech and in the late 1940s was director of R&D in the air force headquarters staff.[13]

Putt and an energetic group of colonels under him discussed how to improve air force R&D, which in their opinion languished in AMC. As budgets shrank after the war, AMC gave high priority to maintaining operational forces, leading to R&D budget cuts. This concerned members of the SAB as well as Putt's allies. Putt and his colonels plotted how the SAB could aid their cause.[14]

Capitalizing on an upcoming meeting of the SAB in the spring of 1949, Putt asked the chief of the Air Staff, Gen. Hoyt Vandenberg, to speak to the board. Vandenberg agreed, but only if Putt would write his speech. This was the opportunity that Putt and his protégés sought. Putt asked one of his allies, SAB military secretary Col. Ted Walkowicz, to write the speech. Walkowicz included "a request of the Board to study the Air Force organization to see what could be done to increase the effectiveness of Air Force Research and Development." Putt "rather doubted that Vandenberg would make that request." Fortunately for Putt, Vandenberg at the last minute backed out and had his deputy, Gen. Muir Fairchild, appear before the board. Fairchild, an advocate of R&D, read the speech all the way through, including the request. Putt had already warned SAB Chairman von Kármán what was coming, so von Kármán quickly accepted the request.[15]

Putt and his colonels knew that this was only the first step in the upcoming fight. They also had to ensure that the report would be read. Putt's group carefully picked the SAB committee to include members that had credibility in the air force. They selected as chairman Louis Ridenour, well known for his work on radar at the Massachusetts Institute of Technology's Radiation Laboratory. More important was the inclusion of James Doolittle, the famed air force bomber pilot and pioneer aviator who was also Vandenberg's close friend. Putt persuaded Doolittle to go on a duck hunting trip with Vandenberg after Ridenour and von Kármán presented the study results to the Air Staff. Putt later commented that "this worked perfectly," gaining the chief's ear and favor. Putt's group also coordinated a separate air force review to assess the results of the scientific committee. After hand-picking its members as well and ensuring coordination with Ridenour's group, Putt noted that "strangely enough, they both came out with the same recommendations."[16]

The Ridenour Report charted the air force's course over the next few years. It recommended the creation of a new command for R&D, a new graduate study program in the air force to educate officers in technical matters, and improved career paths for technical officers. The report also recommended the creation of a new general staff position for R&D separated from logistics and production, and a centralized accounting system to better track R&D expenditures. After a few months of internal debate, General Fairchild approved the creation of Air Research and Development Command (ARDC), separating the R&D functions from AMC. Along with ARDC, Fairchild approved creation of a new Air Staff position, the deputy chief of staff, development (DCS/D).[17]

With the official establishment of ARDC and the DCS/D on January 23, 1950, the air force completed the development of its first organizations to cement ties between technically minded military officers and scientific and technological researchers. These new organizations, which also included the RAND Corporation,[18] the Research and Development Board (RDB),[19] and the SAB, would in theory make the fruits of scientific and technological research available to the air force. The RDB and SAB coordinated air force efforts with the help of the scientists and engineers, similar to how the wartime Office of Scientific Research and Development had operated, but RAND was a new kind of organization, a "think tank." ARDC and the DCS/D would attempt to centralize and control the air force's R&D efforts. They would soon find that for large projects, they would have to centralize authority around the project, instead of the technical groups of AMC or ARDC.

The Rise of the Weapon System Concept

The air force had to develop two kinds of technologies. The majority of the projects were concerned with component development. On account of their great cost and complexity, however, large-scale weapons such as bombers, fighters, and missiles took up the bulk of the air force's R&D resources. To manage these so-called weapon systems, air force officers found that their loosely organized prewar methods did not suffice. For the new systems, the air force looked to new models of centralized project management.

Two World War II aircraft projects fit the bill. The complex B-29 and P-61 projects both used committees to coordinate the development of the airframe, electronics, and armament during development, instead of after airframe manufacture and testing.[20] For the complex and pressurized *B-29*, engineers designed armament and communications together from the start, because the aircraft's computer-controlled fire-control systems were integrally connected to the airframe. For the *B-29* and the *P-61*, officers considered the entire aircraft a system that included manufacturing and training as well as hardware.[21]

Another influential World War II program was the Manhattan Project to build the atomic bomb. Gen. Leslie Groves of the Army Corps of Engineers managed the project, gathering physicists, chemists, and engineers at Los Alamos, New Mexico, to design the bomb. Groves administered the project with a staff of three and made major decisions with a small committee consisting of himself, Vannevar Bush, James Conant, and representatives of each of the services. Army officers directed day-to-day operations at each of the project's field sites, most of which had traditional hierarchical organizations, albeit cloaked in secrecy. Because of technical and scientific uncertainties, the project developed two bomb designs and three methods to create the fissile material.[22]

The organization at Los Alamos differed from the organization at other project sites. Director Robert Oppenheimer wrested a degree of freedom of speech for the scientists and ensured that they remained civilians. Oppenheimer, to respect the traditional independence of scientists and maintain open communication, initially adopted the loose department structure of universities. This changed in the spring of 1944, when tests showed that the plutonium gun assembly bomb would not work. The tests led to an acceleration of work on the more complex implosion design. As R&D teams grew, the project needed and obtained strong managers like Robert Bacher and George Kistiakowsky, who transformed the project's organization from an academic model to divisions organized around the end-product—a project organization.[23]

Americans also learned from the organization of the German V-2 project, headed by Wernher von Braun. Reporting to General Arnold on German scientific capabilities at the end of World War II, von Kármán stated that one of the major factors in the success of the German V-2 project was its organization:

> Leadership in the development of these new weapons of the future can be assured only by uniting experts in aerodynamics, structural design, electronics, servomechanisms, gyros, control devices, propulsion, and warhead under one leadership, and providing them with facilities for laboratory and model shop production in their specialties and with facilities for field tests. Such a center must be adequately supported by the highest ranking military and civilian leadership and must be adequately financed, including the support of related

> work on special aspects of various problems at other laboratories and the support of special industrial developments. It seems to us that this is the lesson to be learned from the activities of the German Peenemünde group.[24]

In the Ridenour Report of 1949, the SAB remembered the lessons of the Manhattan and V-2 projects for organizing large new technologies. They noted that new systems were far more complex than their prewar counterparts, making it necessary for some engineers to concentrate on the entire system instead of its components only. Project officers also needed greater authority to better lead a task force of "systems and components specialists organized on a semi-permanent basis." Because the air force had few qualified technical officers, the committee recommended that the air force draw upon the "very important reservoir of talent available for systems planning in the engineering design staffs of the industries of the country."[25]

Despite the recommendations of the Ridenour Report, AMC officers at Wright Field continued to organize projects on functional lines mirroring academic disciplines and to coordinate projects through small project offices. As late as 1950, typical project offices had fewer than ten members, and engineering expertise, parceled out from Wright Field's functional divisions, were, as one historian put it, "only casually responsible" to the project office.[26] At the time, AMC's Col. Marvin Demler stated: "Due to the complexity of the mechanisms which we develop, and our organization by hardware specialties, a very high degree of cooperation and coordination is required between organizations at all levels. In fact, an experienced officer or civilian engineer coming to Wright Field for the first time simply cannot be effective for perhaps six months to one year while he learns 'the ropes' of coordination with other offices. The communication between individuals necessary for the solution of our problems of coordination defy formal organizational lines."[27]

For large projects, this informal structure was not to continue for much longer. When the Korean War broke out in late 1950, the air force found itself with numerous unusable aircraft. In January 1951, Vice Chief of Staff Nathan Twining instructed DCS/D Gen. Gordon Saville to investigate the air force's organization to determine whether it contributed to the poor aircraft readiness. Saville ordered the formation of a study group, led by Colonel Schriever, to investigate the problem. The group returned to the comments of

the Ridenour Report regarding the lack of technical capability in the air force and the problems caused by separating airframe development from component development.[28]

Schriever's group completed its study in April 1951 and released an influential paper called "Combat Ready Aircraft." It pinpointed two major problems with current aircraft: requirements based on short-term factors, leading to continuous modifications, and insufficient coordination and direction of all elements of the "complete weapon."[29] The latter concern probably arose from the Ridenour Report and the examples of the *B-29*, the *V-2*, and the Manhattan Project.

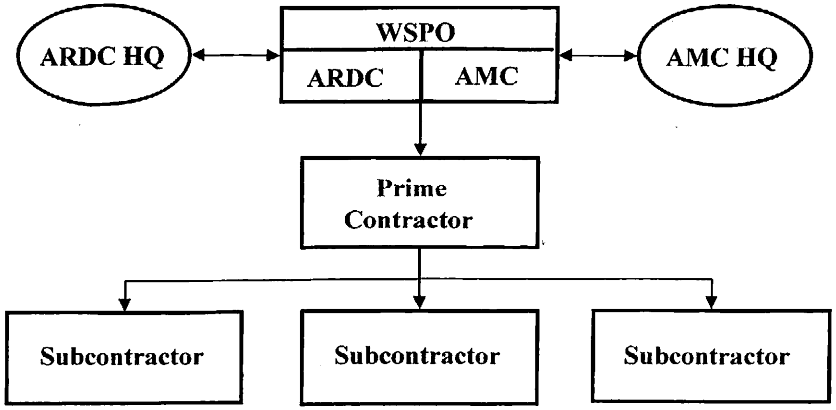
To solve these problems, the group recommended that the air force create an organization and process with responsibility and authority over the complete weapon by adding "planning, budgeting, programming, and control" to the functions of the responsible air force organizations. The organizations would have complete control over the entire projects, enforced through full budget authority.[30] Examples of this kind of organization already existed in the air force's guided missile programs. These weapons differed substantially from piloted aircraft, and the separate procurement of airframe, engines, and armament (payload) made little sense.[31] The study group suggested that the air force let prime contracts to a single contractor to integrate the entire weapon and that the air force organize on a project basis.

Changes to the procurement cycle had to be addressed as well. The group noted that in World War II, decisions to produce aircraft occurred haphazardly and that aircraft rolled off the assembly line directly to combat units at the same time as they were delivered to testing. Because production continued rapidly and little testing occurred, invariably the operational units found numerous problems, leading to the grounding of aircraft for modifications. Believing the current emergency did not allow for the fly-before-you-buy sequential approach and that the delivery of the production aircraft to combat units was dangerous and wasteful, the group selected a solution that was a compromise. It recommended eliminating the X- and Y-model aircraft but slowing the initial production line until test organizations found and eliminated design bugs. Only then should production be accelerated, it said. The air force would select contractors based on the best proposal instead of through a "fly-off" of aircraft prototypes. These ideas, along with projectcentered organization and simultaneous planning of all components throughout the weapon's life cycle, defined the weapon system concept.[32]

Brigadier General Putt, now commander of Wright Air Development Center, immediately campaigned for the weapon system concept among the component developers at Wright Field. He had a difficult sell because the new organization had moved power from the functional organizations to the project offices. The project office was to act on a systems basis, making compromises between cost, performance, quality, and quantity. Putt admonished the component engineers: "Somebody has to be captain of the team, and decide what has to be compromised and why. And that responsibility we have placed on the project offices." He also stated in no uncertain terms who had the authority, telling the component engineers that they needed to be "sure that all the facts" had "been placed before" the project office. "At that time," he told the engineers, "your responsibility ceases."[33]

Without a large number of technical officers, the air force handed substantial authority to industry. Under the weapon system concept, the air force "purchased *management* of *new* weapon system development and production." However, contractors had to "accept the Air Force as the monitor of his [the contractor's] plans and progress, with the cautionary power of a partner and the final veto power of the customer." The air force stated that it could not "escape its own responsibility for system management simply by assigning larger blocks of design and engineering responsibility to industry." Although the new process gave industry a larger role, air force officers would not remain passive.[34]

Adoption of the weapon system concept throughout the air force did not go smoothly, because of continuing disagreements between the DCS/D and ARDC on one hand, and the deputy chief of staff, materiel (DCS/M), and AMC on the other. The key question that divided the fledgling ARDC and its parent, AMC, was when "development" ended and "production" began. If production started early in a weapon's life cycle, then AMC maintained greater control, whereas if development ended relatively late in the cycle, then ARDC acquired more power. Not surprisingly, AMC leaned toward a definition of production that encompassed earlier phases of the life cycle, while ARDC opted for late-ending development. Because development continued as long as changes to the weapon occurred, and because production began the moment the first prototype was built, no objective definition tipped the scales one way or another. Under such circumstances, the air force's official arbitrator between ARDC and AMC, James Doolittle, had to intervene.



Weapon System Project Office implementation of the "system concept."

In April 1951, Doolittle reported that because development continued through a system's entire life cycle, the ARDC definition should hold. In consequence, ARDC should control production engineering.[35] The new agreement led to the issuance of Air Force Regulation (AFR) 20-10, "Weapon System Project Offices," in October 1951. The regulation specified that every major project should have a Weapon System Project Office (WSPO), with officers from ARDC and AMC in charge.

A marvel of diplomacy, the document stated that during the early portions of development, the ARDC representative would be the "team captain," and in the later portions, after a decision to produce the article in quantity, the AMC representative would be the "team captain." In practice, the line between the two was fuzzy, leaving the two officers to work it out for themselves based on circumstances or personalities. The team captain coordinated the activities for the entire project but did not have authority over the other officer. If the two could not agree, they would both have to take the problem to higher authorities, potentially all the way up to the DCS/D and DCS/M at air force headquarters.[36]

The resulting ambiguities continued to cause organizational headaches, leading once again to intervention by Doolittle. This time Doolittle did not feel comfortable forcing a solution, so he recommended another Air Staff study to investigate the problem. His only proviso was that the group protect the importance of R&D. The Air Staff gave the DCS/M, Lt. General Orval Cook, responsibility for solving the interface problems. In cooperation with DCS/D Laurence Craigie, Cook appointed a task group, the "Cook-Craigie Group," to work on the issue. Group members decided that ARDC should keep responsibility for weapon systems until the Air Staff stated in writing that the weapon should be purchased.[37] The new process, known as the Cook-Craigie Procedures of March 1954 and formalized by modification of AFR 20-10 in August of that year, momentarily ended the bickering between the development and materiel groups. Their unity would be tested severely with the development of the air force's most radical new weapon, ballistic missiles.

ICBMs and Formation of the Inglewood Complex

Missiles, particularly ballistic missiles,[38] disrupted the air force's culture, operations, and organization in several important ways. First, and most obviously, missiles had no pilots, relegating humans to only pushing a button. Second, maintenance and long-term operations of missiles amounted to storage and occasional refurbishment, as opposed to the ongoing repairs typical for aircraft. Third, because missiles were used just once, missile testing required the creation of a missile production line. Unlike aircraft, where a few prototypes could be built and tested with dozens or hundreds of flights each, every missile test required a new missile. This implied that the fly-before-you-buy concept, where aircraft could be tested before instigation of full-scale production, no longer applied. For missiles, testing required a production line. Finally, missiles involved a variety of challenging new technical issues, as described in the previous chapter. Simply put, many of the air force's existing organizational and technical processes did not work for missiles.

Ballistic missile programs languished at a low priority during and after World War II, as the air force concentrated its efforts first on manned bombers, and then on jet fighters for the Korean War.[39] The rapidly escalating Cold War provided the impetus to transform the loosely organized missile projects. Successful testing of the Soviet atomic bomb in 1949 spurred the United States to develop a fusion weapon. In March 1953, Assistant for Development Planning Bernard Schriever learned of the success of American thermonuclear tests from the SAB. Recognizing the implications of this news, within days Schriever met renowned mathematician John von Neumann at his Princeton office. Von Neumann predicted that scientists would soon develop nuclear warheads of small enough size and large enough explosive power to be placed on ICBMs. Because of their speed and in-flight invulnerability, ICBMs were the preferred method for nuclear weapons delivery, if the air force could make them work. Realizing that he needed official backing, Schriever talked with James Doolittle, who approached Chief of Staff Vandenberg to have the SAB investigate the question.[40]

The Nuclear Weapons Panel of the SAB, headed by von Neumann, reported to the air force staff in October 1953. In the meantime, Trevor Gardner, assistant to the secretary of the air force, volunteered to head a Department of Defense (DOD) Study Group on Guided Missiles. Gardner learned of Convair's progress on its *Atlas* ICBM and met with Dr. Simon Ramo, an old friend and head of Hughes Aircraft Company's successful air-to-air missile project, the Falcon. Based on the results of his study group, Gardner and Air Force Secretary Talbott formed the Strategic Missiles Evaluation Committee, or Teapot Committee, to recommend a course of action for strategic ballistic missiles.[41]

Von Neumann headed the group, and Gardner selected Ramo's newly created Ramo-Wooldridge Corporation (R-W) to do the paperwork and manage the day-to-day operations of the study. Ramo had partnered with fellow Hughes manager Dean Wooldridge to form R-W.[42] In February 1954 the Teapot Committee recommended that ICBMs be developed "to the maximum extent that technology would allow." It also recommended the creation of an organization that hearkened back to the Manhattan Project and Radiation Laboratory of World War II: "The nature of the task for this new agency requires that over-all technical direction be in the hands of an unusually competent group of scientists and engineers capable of making systems analyses, supervising the research phases, and completely controlling the experimental and hardware phases of the program — the present ones as well as the subsequent ones that will have to be initiated."[43]

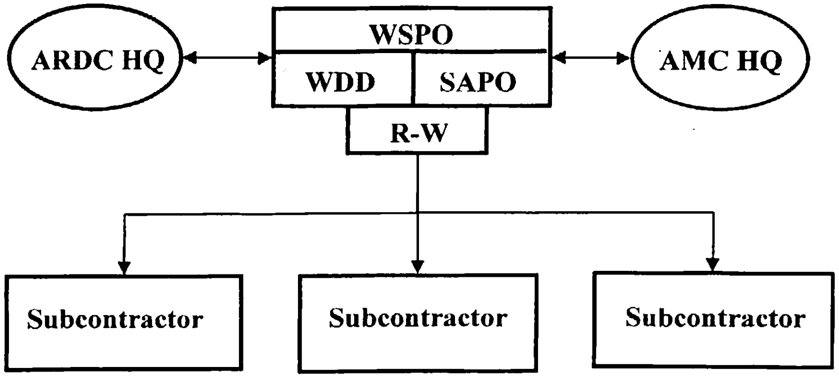
On May 14, 1954, the air force made Convair's *Atlas* its highest R&D priority. Because Convair and the majority of the aircraft industry hailed from

Southern California, the air force established its new ICBM development organization, the Western Development Division (WDD), in a vacant church building in Inglewood, near Los Angeles airport. Air force leaders placed newly promoted Maj. General Bernard Schriever in command on August 2, 1954. Because the Teapot Committee had recommended creation of a "Manhattan-like" project organization, one of Schriever's first tasks was to see if this made sense and determine who would oversee the technical aspects of the project.[44]

Schriever rejected the Manhattan Project organization because ICBMs were significantly more complicated than the atomic bomb.[45] Because neither he nor the scientists believed that the air force had the technical expertise to manage the program, Schriever could hire Convair as prime contractor, or he could hire R-W as the system integrator, with Convair and other contractors as associate contractors. The air force used the prime contractor procedure on most programs, but this assumed that the prime contractor had the wherewithal to design and build the product. Schriever was already unhappy with Convair because he believed Convair kept "in-house" elements such as guidance and electronics in which it had little experience, to the program's detriment.[46]

Scientists with whom he had worked for nearly a decade also deeply influenced Schriever. Von Neumann and his fellow scientists believed the Soviet threat required a response like the Manhattan Project a decade earlier, bringing together the nation's best scientists to marry ballistic missiles to thermonuclear warheads. Schriever later explained:

> Complex requirements of the ICBM and the predominant role of systems engineering in insuring that the requirements were met, demanded an across-the-board competence in the physical sciences not to be found in existing organizations. Scientists rated the aircraft industry relatively weak in this phase of engineering, which was closely tied to recent advances in physics. The aircraft industry, moreover, was heavily committed on major projects, as shown by existing backlogs. Its ability to hire the necessary scientific and engineering talent at existing pay-scales was doubted, and with the profit motive dominant, scientists would not be particularly attracted to the low-level positions accorded to such personnel in industry.[47]



Organization of the Inglewood complex: the Western Development Division, the Special Aircraft Projects Office, and Ramo-Wooldridge.

Many years later Schriever described his admiration of the scientists: "I became really a disciple of the scientists who were working with us in the Pentagon, the RAND Corporation also, so that I felt very strongly that the scientists had a broader view and had more capabilities. We needed engineers, that's for sure, but engineers were trained more in a, let's say a narrow track having to do with materials than with vision."[48]

To capitalize on the vision and expertise of physical scientists and mathematicians such as von Neumann and von Kármán, Schriever created an organizational scheme whereby the leading scientists could guide the ICBM program. Following the von Neumann committee recommendations, Schriever selected R-W for systems engineering and integration.[49] Free of civil service regulations, R-W could hire the requisite scientific and technical talent. The air force could more easily direct R-W than Convair, because R-W had few contracts and no production capability. The aircraft industry disputed this unusual arrangement, fearing that it established a precedent for "strong system management control" by the air force and also that it might create a powerful new competitor with inside information about air force contracts and contractor capabilities. On both counts, the aircraft industry was correct.[50]

Selecting the best and brightest technical officers from ARDC, Schriever's talented staff quickly took charge of ICBM development. Because AMC retained procurement authority, it set up a field office known as the Special Aircraft Projects Office (SAPO) alongside Schriever's ARDC staff in Inglewood. By September 1954, air force headquarters approved Schriever's selection of R-W, confirming the triumvirate of the WDD, the SAPO, and R-W. Schriever's next battle would be to establish the authority and credibility of his team in the face of skepticism at air force headquarters and the outright hostility of the aircraft industry.[51]

Establishing the WDD's Authority

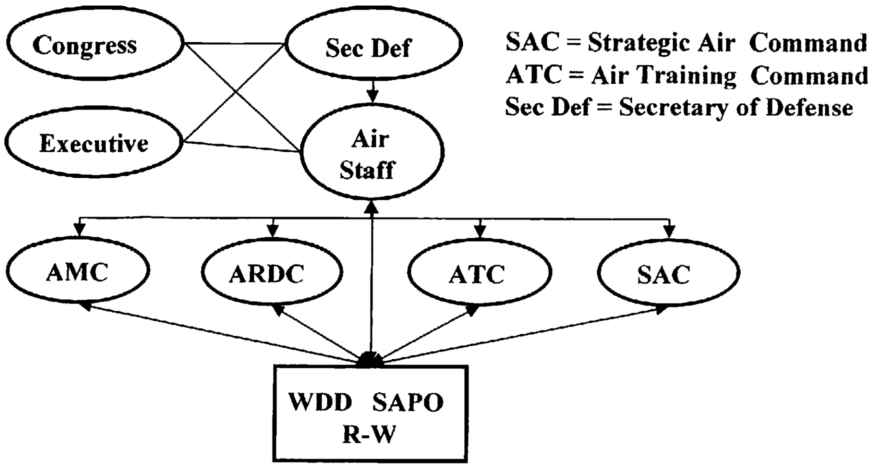
With Schriever's organizational foundations set, the immediate task was to push ICBM development rapidly forward and create a detailed plan within a year. Headquarters control and oversight would come through the budget process, so Schriever knew that until he had his plans worked out, he had to keep the budget profile low. He reallocated budgets from several air force organizations and was careful not to ask for too much at the start. Over the long haul, Schriever knew that the massive budget that he needed would require congressional appropriations and that he would have to vigorously defend his plan and its costs. To put off this day of reckoning, in October 1954 he requested a relatively small budget, realizing that there would have to be a major readjustment in the spring. "This support can be obtained by carefully planned and formalized action at the highest levels in the administration," he recognized. In this breathing space, he developed his technical plans, costs, justifications, and political strategy.[52]

Selection of Atlas contractors was the next task of Schriever's team. With the design still in flux, this would have to be done based on company capabilities instead of design competitions. Bypassing standard procurement regulations, Schriever ordered R-W to let subcontracts to potential suppliers to involve them in and educate them on the program. This allowed R-W to assess contractors as well as speed development and procurement. Schriever could not ignore all of the air force's procurement procedures. He had his team create performance specifications and perform "prebidding activities" to prepare for a competitive bidder's conference. Because of the in-depth knowledge R-W had gained through its subcontracts, Schriever had R-W contribute to the Source Selection Boards, providing inputs as requested by the air force. This was a serious (and possibly illegal) departure from standard procurement policy, which required that only government officials control contractor selection.[53]

Schriever directed R-W and his air force team to reassess the *Atlas* design and to determine Convair's role. Convair, which had been developing *Atlas* since January 1946, understandably believed that it deserved the prime contract to build, integrate, and test the vehicle. It vigorously campaigned against Schriever and the upstart R-W. Convair's leaders sparred with Schriever's organization for the next few months before they resigned themselves to R-W's presence. To appease the air force's scientific advisers, and to gain electronics capability, Convair executives hired highly educated scientists and engineers. For his part, Schriever placed restrictions on R-W to maintain some semblance of support from the aircraft industry. In a memo dated February 24, 1955, the air force prohibited R-W from engaging in hardware production on any ICBM program in which it acted as the air force's adviser and systems engineer.[54]

R-W had three tasks: to establish and operate the facilities for the Inglewood complex, to assess contractor capabilities, and to investigate the *Atlas* design. R-W made its first important contribution in the design task. The required mass and performance of the missile depended upon the size of the warhead and the reentry vehicle, for small changes in their mass led to large changes in the required launch vehicle mass. Working with the Atomic Energy Commission and other scientists, R-W scientists and engineers found that a new blunt cone design decreased the nose cone's weight by half, from about 7,000 to 3,500 pounds. This in turn decreased required launch vehicle weight from 460,000 to 240,000 pounds and reduced the number of engines from five to three. This dramatic improvement discredited Convair's claim to expertise and convinced Schriever, his team, and his superior officers that the selection of R-W had been correct.[55]

The most significant technical issue facing Schriever's group in the fall and winter of 1954 was the uncertainty of the design. Group members simply could not predict which parts of the design would work and which might not. R-W had been investigating a two-stage vehicle, and the initial results looked promising. In March 1955, Schriever convinced Lt. General Thomas Power,



Pre-Gillette organization of ballistic missile development.

the ARDC commander, that a two-stage vehicle should be developed as a backup to *Atlas*. By May 1955, the WDD was working on *Atlas*, the two-stage *Titan*, and a tactical ballistic missile (ultimately known as *Thor*) as well.[56]

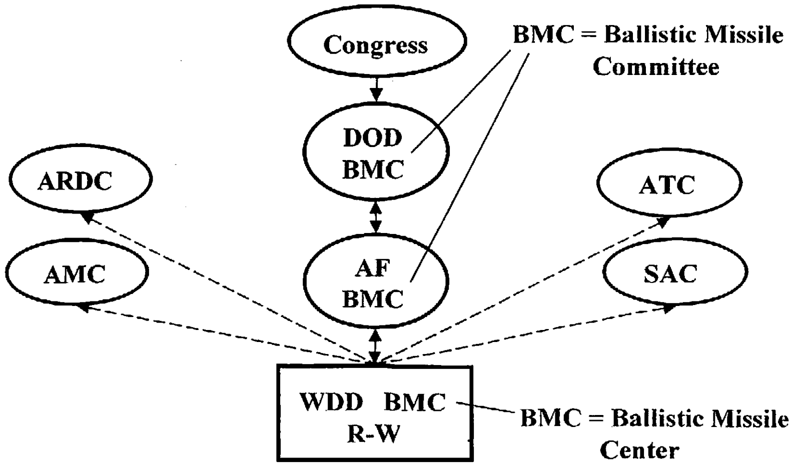
In the meantime, Schriever considered how best to fund the program. One possibility was to allocate the funds to a number of different budgets, then pull them back together in Schriever's group. This approach would hide the true budget amounts from effective oversight. However, the budgets required were too large to hide in this manner. With programmatic invisibility unlikely, Schriever's deputy, William Sheppard, argued that the best approach was to have a "separately justified and separately managed lump sum."[57]

Schriever had already discussed this approach with Gardner, and the two of them plotted a political strategy. Many of Schriever's budget actions required coordination with and justification to various organizations. Frustrated with the delays inherent in this coordination, Gardner and Schriever decided that they had to increase Schriever's authority and funding and decrease the number of organizations that could oversee and delay ICBM development. Both Schriever and Gardner recognized that they needed political support, so they vigorously sought it in Congress and within the Eisenhower administration. Gardner and Schriever briefed President Dwight D. Eisenhower in July 1955, eventually convincing him and Vice President Richard M. Nixon—with John

von Neumann's timely support—to make ICBMs the nation's top defense priority.[58]

With the president's endorsement in hand by September, Schriever presented to Gardner the entire air force approval process, which required 38 air force and DOD approvals or concurrences for the development of ICBM testing facilities. Appalled, Gardner had him show it to Secretary of the Air Force Donald Quarles, who asked them to recommend changes to reduce the paperwork and delays. Gardner and Schriever formed a study group, loading it, as Schriever put it later, "pretty much with people who knew and who would come up with the right answers." Hyde Gillette, the deputy for budget and program management in the Office of the Secretary of Defense, chaired the group, which was to recommend management changes to speed ballistic missile development.[59]

Despite objections from AMC, which did not want to lose any more authority, the Gillette Committee agreed with Schriever that the multiple approvals and reporting lines caused months of delay. In consequence, the "Gillette Procedures," approved by Secretary of Defense Charles Wilson on



Ballistic missile organization—Gillette Procedures. *Solid lines with arrows* show the direct chain of authority. The air force's commands have no authority over ballistic missile development, and the Air Staff has input only through the Department of Defense Ballistic Missile Committee.

November 8, 1955, funneled all ballistic missile decisions through a single Ballistic Missile Committee in the Office of the Secretary of Defense. Although evading ARDC and AMC for approvals and decisions, Schriever's organization needed to provide them information. Schriever stated: "We had to give them information because they provide a lot of support, you see, so it wasn't the fact that we were trying to bypass them. We just didn't want to have a lot of peons at the various staff levels so they could get their fingers on it."[60] The Ballistic Missile Committee reviewed an annual ICBM development plan, and the Office of the Secretary of Defense would present, approve, and fund the ICBM program separately from the air force's regular procedures. In the development plan would be information on programming (linking plans to budgets), facilities, testing, personnel, aircraft allocation, financial plans, and current status. By 1958, AMC managers had trimmed industrial facility lead time from 251 to 43 days, showing the effectiveness of the new process.[61]

The Gillette Procedures relegated AMC, ARDC, and the operational commands to aiding the ICBM program, without the authority to change or delay it. From a parochial air force viewpoint, the only good thing about the program was that the completed missiles would eventually become part of the Strategic Air Command. Many in the air force did not take ballistic missiles seriously enough to fight for control over them. Col. Ray Soper, one of Schriever's trusted subordinates, noted that "the Ops [operational commands] attitude, at the Pentagon, was to let the 'longhairs' develop the system—they really didn't take a very serious view of the ballistic missile, for it was thought to be more a psychological weapon than anything else."[62]

With the adoption of the Gillette Procedures, Schriever garnered authority directly from the president, with a single approval of a single document each year required for ICBM development. Schriever's organization drew upon the best personnel and air force services, without having them interfere with his authority or decision processes. These new procedures represented the first full application of project management in the air force, where the project manager had both technical and budget authority for the project. Prior to this time, each project drew funds from several budgets and thus required separate justifications for each. The Gillette Procedures made the air force's financial and accounting system consistent with the authority of the project manager, although Gardner was unable to separate the ICBM budgets from the rest of the air force.[63] With these procedures in hand, Convair and the contractors under control, and the air force's regular bureaucracy shunted out of the way, Schriever drove the ICBM program at full speed, with little heed to cost, using the strategy of concurrency.

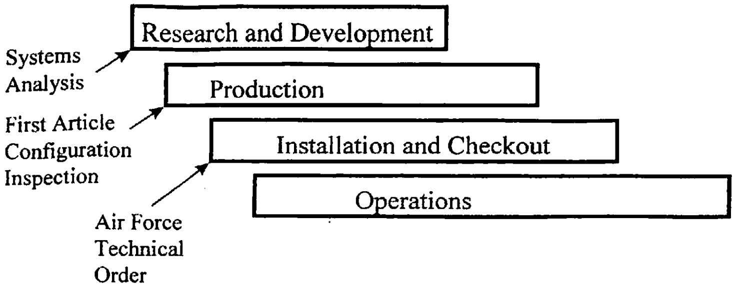
Concurrency

Rapid development of ICBMs required parallel development of all system elements, regardless of their technological maturity. Schriever called this *concurrency*, a handy word that meant that managers telescoped several typically serial activities into parallel ones. In serial development, research led to initial design, which led to prototype creation, testing, and manufacturing. Once the new weapon was manufactured, the operational units developed maintenance and training methods to use it. Under concurrency, these elements overlapped. Schriever did not invent the process but rather coined the term as a way of explaining the process to outsiders.[64]

Schriever's version of concurrency combined concepts learned over the previous decade. Parallel development had been practiced during World War II on the Manhattan and B-29 projects. Management structured around the product instead of by discipline had also been used on these projects. The combination of ARDC and AMC officers into a project-based office was a method applied since 1952, and Schriever's use of R-W to perform systems analyses like the *Atlas*'s nose cone design had also been foreshadowed by the RAND Corporation's development of systems analysis after World War II. Schriever claimed that concurrency was a new process. But was it?

One difference was that in the 1950s parallel development, once a wartime expedient, became a peacetime activity. With Congress exercising detailed oversight typical of peacetime, Schriever had to explain his processes in more detail than his wartime predecessors had. As Secretary of the Air Force James Douglas later told Congress, "I am entirely ready to express the view that . . . you have to subordinate the expenditure . . . to the urgency of looking to the end result." Or as Gardner succinctly stated, "We have to buy time with money." The term "concurrency" helped explain and justify their actions to higher authorities.[65]

A second major difference was in the nature of the technologies to be inte-



Concurrency. Adapted from Benjamin N. Bellis, L/Col USAF Office DCS/Systems, "The Requirements for Configuration Management During Concurrency," in AFSC Management Conference, Air Force Systems Command, Andrews Air Force Base, Washington, D.C., AFHRA Microfilm 26254, 5-24-3.

grated into ICBMs. In pre–World War II bombers, for example, engineers simply mounted machine guns at open side windows. However, with the *B-29* bomber, and for postwar aircraft, operators maneuvered machine guns with servomechanisms within a pressurized bubble, itself part of the airframe. Similarly, missiles had to be built with all elements planned and coordinated with each other from the start. Postwar weapons were far more complex than their prewar counterparts and more complex than the nuclear weapons of the Manhattan Project. Concurrency in the Cold War required far more detailed planning than previous concurrent approaches.

One application of concurrency was in selection of contractors for Atlas, and then for Titan and Thor. R-W performed the technical evaluations and gave input to ad hoc teams of WDD and SAPO personnel. The AMC-ARDC committees selected which companies they would ask to bid, evaluated the bids, and selected a second contractor for some subsystems. Selecting a concurrent contractor increased chances of technical success, stimulated better contractor performance by threatening a competitive contract if the first contractor performed poorly, and kept contractors working while the air force made decisions. To speed development, the SAPO issued letter contracts, deferring contract negotiations until later. In January 1955, the SAPO formalized the ad hoc committees, which became the AMC-ARDC Source Selection Board.[66]

To maximize flexibility and speed, Schriever initially organized the WDD with disciplinary divisions modeled on academia. Only in 1956 did the proliferation of projects lead him to create WSPOs for each project, consisting of AMC and ARDC representatives, as required by the weapon system concept. Until that time, most work occurred through ad hoc teams led by officers to whom Schriever had assigned the responsibility and authority for the task at hand. For example, when the WDD began to develop design criteria for facilities in March 1955, Schriever named Col. Charles Terhune, his technical deputy, "team captain" for the task. He also requested that R-W personnel assist. Terhune then led an ad hoc group to accomplish the task, and that group dissolved upon task completion.[67]

The fluid nature of the ad hoc groups and committees may well have maximized speed, but they also played havoc with standard procedures of the rest of the air force, which after all had to support ICBM development. Schriever initiated a series of coordination meetings with AMC, Strategic Air Command, air force headquarters, and other commands in December 1954. After the December meeting, the AMC Council decided it needed quarterly reports from the WDD to keep abreast of events. Over the next six months, AMC planning groups bickered with WDD personnel over reporting and support, as AMC needed information for personnel and logistics planning. AMC tried to plan tasks from Wright Field, whereas the WDD (and soon the SAPO) accomplished planning rapidly on-site, with little documentation or formality. AMC accused the WDD of refusing to provide the necessary data, whereas the WDD accused AMC officers of a lack of interest.

Disturbed because Schriever's crew had neither WSPOs nor Weapon System Phasing Groups (normally used to coordinate logistics), AMC had some reason to complain. As stated by the assistant for development programming, Brig. Gen. Ben Funk, "The normal organizational mechanisms and procedures for collecting and disseminating weapon system planning during the weapon system development phase did not exist," leading to gaps in the flow of information necessary for coordination. By the summer of 1955, SAPO personnel at the WDD made concerted efforts to pass information to AMC headquarters and to bring AMC planning information into the WDD.[68]

Schriever's need for speed led to extensive use of letter contracts through 1954 and 1955. Procurement officials in the SAPO and technical officers in the WDD realized that they needed to track expenditures relative to technical progress, but the rapid pace of the program and the lack of documentation quickly led to a financial and contractual morass. Complicated by the WDD's lack of personnel and the new process of working with R-W to issue technical directives, contractual problems became a major headache for the SAPO and AMC and another source of friction between Schriever and AMC leaders.[69]

The SAPO had authority to negotiate and administer contracts but initially lacked the personnel to administer them over the long term. Instead, SAPO personnel reassigned administration to the field offices of other commands "through special written agreements."[70] This complicated arrangement led to trouble. Part of the problem was the difficulty of integrating R-W into the management of the program. R-W had authority to issue contractually binding "technical directives" to the contractors, but instead of using these, R-W personnel sometimes "used the technical directive as a last resort, preferring persuasion first through either periodic meetings with contractor personnel or person-to-person visits between R-W and contractor personnel." This meant that many design changes occurred with no legal or contractual documentation. Because officers in the SAPO did not have enough personnel to monitor all meetings between R-W and the contractors and were not initially included in the "technical directive coordination cycle," matters soon got out of hand.[71]

This problem emerged during contract negotiations, as SAPO procurement officers and the contractors unearthed numerous mismatches between the official record of technical directives and the actual contractor tasks and designs. As differences emerged, costs spiraled upward, leaving huge cost overruns that could not be covered by any existing or planned funding. A committee appointed to investigate the problem concluded in June 1956 that "almost everyone concerned had been more interested in getting his work done fast than in observing regulations." It took the committee somewhat more than six months to establish revised procedures acceptable to all parties.[72]

The initial application of concurrency in Schriever's triad of the WDD, the SAPO, and R-W sped ICBM development but also spread confusion, disrupted communications with other organizations, and created a mountain of contractual, financial, and, as we shall see, technical problems. Flexible committees flicked in and out of existence, while supporting organizations outside of Schriever's group struggled to acquire the information they needed to assist. The strategy of parallel development, separated from the air force's normal routine, produced quick results, but the mounting confusion begged for a stronger management scheme than ad hoc committees.

Conclusion

World War II and the Cold War enabled the military to consolidate and extend its relationships with both academia and industry. When in 1947 the Procurement Act gave the DOD the permanent authority to negotiate contracts, military officers enlisted the support of academia and industry. Air force officers such as Hap Arnold, Donald Putt, and Bernard Schriever used scientists to create a technologically competent and powerful air force. Two models for relationships between the air force and the scientists evolved. First, RAND, the SAB, and the RDB continued the voluntary association of scientists with the military, as had occurred in World War II. However, the DCS/D and ARDC represented new air force efforts to gain control over the scientists through a standard air force hierarchy. Both models would continue into the future. Through these organizations and their personnel, air force officers hoped to develop the air force of the future.

When ICBMs became a possibility in late 1953, Schriever capitalized on his scientific connections, urging John von Neumann to head the Teapot Committee, which recommended that ICBMs be developed with the utmost speed and urgency. While Schriever and Assistant Secretary of the Air Force Trevor Gardner maneuvered behind the scenes to promote ICBMs, the Teapot Committee recommended the creation of a scientific organization on the Los Alamos model to recruit scientists to run the ICBM program. Unsure of the industry's capability to develop the *Atlas* ICBM, Schriever and Gardner hired R-W to serve as the technical direction contractor, an adviser to air force officers, and a technical watchdog over the contractors.

Feeling bogged down in "Wright Field procedures," external approvals, and funding difficulties, Schriever and Gardner appealed to President Eisenhower to break the logjam. The president complied, and so Schriever, armed with a presidential directive, hand-picked a committee to develop procedures that gave him the authority to acquire the services he needed from the air force without having to answer to the air force. The Gillette Procedures carved out a space in which Schriever, his officers, and scientific allies could craft their own development methods, largely separated from the air force's standard processes.

Under "concurrency," Schriever's complex of the WDD, the SAPO, and R-W created and adopted a number of methods to speed ICBM development. With funding a nonissue, these organizations and their contractors tossed aside standard regulations and developed alternate technical systems such as the *Titan* ICBM to ensure success. The air force's regular methods, based on academic-style disciplinary groups, no longer sufficed. Schriever broke away from dependence on Wright Field's technical groups and committees, but in the first years of ICBM development, he merely substituted his own officers and contractors, unencumbered by paperwork. The WDD, the SAPO, and R-W recreated an ICBM-oriented Wright Field on the West Coast, albeit without the years of history and bureaucracy.

The proof of their efforts would come when ICBM testing began in the late 1950s. As long as the Cold War remained hot and his scientific friends delivered technical success, Schriever could sustain concurrency. Unfortunately, tests would show that these new wonder weapons had major problems. Under these circumstances, politicians and managers would rein in the rapidly moving ICBM programs, replacing Schriever's all-out concurrency with a new, centralized bureaucracy that incorporated some of the key lessons of ICBM development.

THREE

From Concurrency to Systems Management

> We have found that concurrency is as unforgiving to inept management principles as a high performance aircraft is to pilot error. In fact, it requires *MORE* formality, not *LESS.*
>
> —Lieutenant Colonel Benjamin Bellis, 1962

By 1955, Bernard Schriever's Western Development Division (WDD), in conjunction with the Special Aircraft Projects Office (SAPO) and Ramo-Wooldridge Corporation (R-W), had implemented concurrency to rapidly move intercontinental ballistic missiles (ICBMs) from development into testing. As tests unfolded in 1956 and 1957, Schriever's officers and contractors found, much to their consternation, that *Atlas* failed at an alarmingly high rate. In the rush to push ICBMs into service, Schriever had created an organization that was remarkably informal and flexible but whose disregard of regular procedures also cut out many essential functions of the air force's bureaucracy. Many of these techniques had been put into place to ensure that there was communication among technical, financial, legal, and operational personnel. Focusing explicitly on the technical issues, Schriever's officers and contractors let other concerns fall to the wayside. Problems with financing and scheduling were compounded by technical problems endemic to radical new technologies.

To fend off criticism, Schriever's organization had to improve the reliability of the complex weapons and better predict and control costs. This required more formal engineering and management practices. Engineers made missiles more dependable through exhaustive testing, component tracking, and