The B-52 Stratofortress: A Case Study

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Chapter 1. Introduction

On March 15, 1952, the first B-52 Stratofortress rolled out of Boeing Plant 2 in Seattle, WA. The massive aircraft weighed more than 200 tons and stood an impressive two stories high. The B-52 was certainly an incredible sight in 1952, not only for the Boeing engineers who had designed the colossus, but also for the main customer, the United States Air Force (USAF). Through what seemed like uncountable requirements changes and design versions over six years, the stakeholders (Boeing, Pratt & Whitney and the USAF) saw their efforts come to fruition. The B-52, the second-generation long-range bomber that was to be the cornerstone of the fledgling USAF, had finally been built.

Today, there are 76 B-52s still in service with the United States Air Force, out of 744 built. These aircraft have been versatile enough to be used as both a long-range nuclear munitions carrier during the Cold War and as a carpet-bombing, "Bomb Truck" in conflicts ranging from the Vietnam War to Operation Enduring Freedom. Within these conflicts, they have proven their unsurpassable and irreplaceable worth to the USAF through their extremely effective military service. For example, of the bombs dropped by coalition forces in the Persian Gulf War, one-third came from the B-52 Stratofortress, which, at the time, was nearly 40 years old!

What are the secrets behind the success of this aircraft? How could a bomber created in a hotel room in Dayton, Ohio over 50 years ago still play an integral role in United States Air Force operations? What impact has the success of the B-52 had on subsequent bombers and commercial aircraft? This document attempts to answer these questions by presenting a detailed case study of the B-52 Stratofortress aircraft system.

The objective of this case study is to gain a greater understanding not only of the specifications of the B-52 aircraft in detail, but also key design drivers, decisions and features of the B-52 in general. This document takes into consideration the design of the various technical subsystems that comprise the Stratofortress as well as the social, political and market concerns throughout the B-52's extensive lifetime. The aircraft systems engineering approach is a holistic view of aircraft development, and it is in this vein that the development, lifecycle and future of the B-52 Stratofortress are examined.

The B-52 Stratofortress case study begins with a high-level description of the aircraft's primary mission and market as well as an overview of the aircraft itself. Chapter 3 provides the history of its development, a detailed timeline of its long lifetime and a description of the political and market context in which it was developed and built. In Chapter 4 a summary of the aircraft's value proposition including key stakeholders and their expectations is described. Chapter 5 reviews the high-level requirements of the B-52 and how those requirements flowed down into design decisions. A detailed vehicle description of the aircraft is then provided in Chapter 6, which includes performance metrics, discussions of each subsystem and their interactions. In Chapter 7 a description of the aircraft's lifecycle, including procurement cost, prototyping, manufacturing, verification and validation, disposal and derivatives is provided. Chapter 8 describes the sales, accidents and anomalies, maintenance and operating cost, which comprise the aircraft's overall operating experience. Chapter 9 discusses the future of the B-52, including its projected lifetime, how the B-52 fits in with other bombers in the U.S. Air Force, and the case to re-engine the B-52 with commercial turbofan engines. Chapter 10 presents the conclusion of this case study including the success and legacy of the B-52 Stratofortress as well as the value delivered to the key stakeholders described in Chapter 4.

Chapter 2. High-Level System Overview

This chapter provides a description of the primary mission and market of the B-52 Stratofortress as well as an overview of the aircraft itself. A brief summary of the original design is provided and includes information concerning the aircraft's structure, landing gear, propulsion, flight deck, flight control system and power and electrical systems. These subsystems are expounded upon in Chapter 6.

The market for the B-52 developed over the years between its proposal, dating back to 1941, and production, which was completed in 1952. The need for a large bomber to carry out special missions (i.e. carrying nuclear weapons) increased as the Cold War escalated. By 1951, the Strategic Air Command and USAF Headquarters were requesting an aircraft that could function both as a reconnaissance plane and as a nuclear or conventional weapons bomber. This aircraft would be a second-generation bomber to replace the B-36. With a sound design and newer technology, the B-52 was faster than previous bombers with a large capacity for future growth. A total of 744 B-52 bombers were produced between 1952 and 1962.

The technical performance of the B-52 met the Air Force's requirements for its desired long-range bomber. The aircraft had a range of more than 7,000 miles at a cruising speed of 520 mph with a 10,000 lb. bomb payload. It was designed to cruise at 45,000 ft with a gross takeoff weight of 420,000 lbs.[12]

An overall three-view of the B-52A and the B-52B (the first editions of the B-52) is shown in Figure 1. With a wingspan of 185 ft, an overall length of nearly 158 ft and standing 48 ft tall, the B-52 is an impressive aircraft. Even today, the shear size of the aircraft is striking. The B-52 was not the largest bomber the government had built by 1951, but with its swept wings and eight jet engines, the B-52 was the most capable bomber in terms of range and payload capacity.

The wings of the B-52 represented the triumph and pride of the Boeing aerodynamicists. The B-52 wing was only the second bomber built with swept wings. Its 185 ft wingspan and sweep of 35° was an aggressive design at the time. The 4,000 ft of wing area and aspect ratio of 8.55 gave the B-52 exceptional aerodynamic efficiency and extended range.[12]

The fuselage of the B-52 served a variety of purposes. Occupying the majority of the fuselage was the weapons bay, which was 28 ft long, 6 ft wide, about half the total fuselage height and was capable of carrying any weapon in the US arsenal. In addition to the enormous weapons bay, much of the fuselage of the B-52 was dedicated to storing fuel for long-range missions. Approximately 9,000 gallons of fuel could be housed in the fuselage, with another 9,300 gallons stored in each wings.[12]

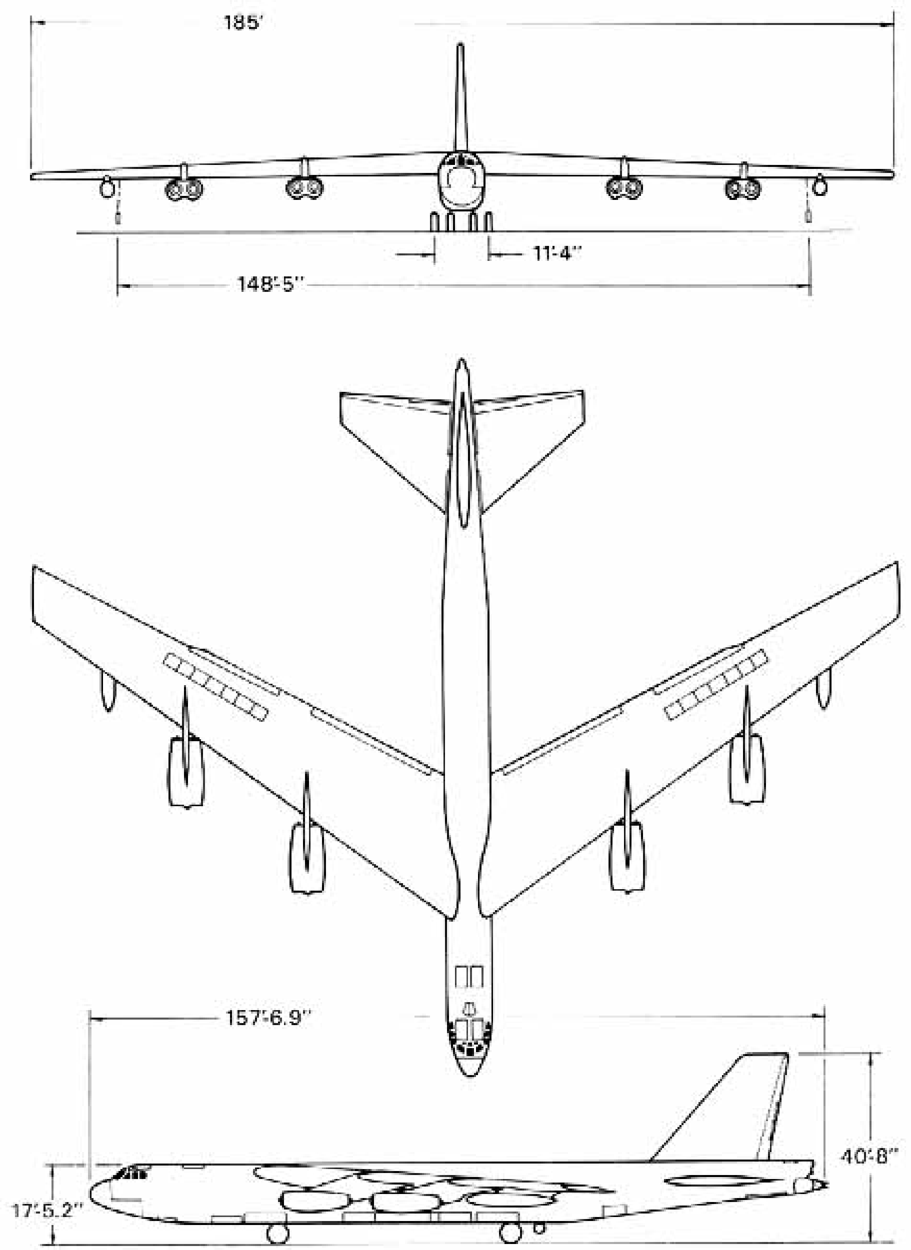


Figure 1. B-52H Three View [4]

The landing gear consisted of four sets of twin wheeled units, two fore and two aft. Each unit could be independently raised or lowered and steered. In other words, each unit could be rotated up to 20° from the long axis of the fuselage allowing the B-52 to point into a crosswind on landing or take-off while the wheels would be still in line with the runway.

The eight jet engines of the B-52 were contained in four nacelles and attached by pylons to the under-side of the wings. The original B-52A engines were J57 variants built by Pratt & Whitney, a trusted Air Force client for turboprop aircraft. Each engine provided about 10,000 lbs of thrust and a total of about 80,000 lbs for all eight engines. The pylons that held the engines were carefully placed on the wings to limit aerodynamic drag and structural loads.

Although a massive bomber, the B-52 was fairly maneuverable for its size. The ailerons on the wings enabled the B-52 to execute standard roll maneuvers during flight. For added control authority, the wings were also equipped with spoilers that enabled the aircraft to perform a 40° banked turn if necessary.

The vertical stabilizer stood over 48 feet (five stories) tall with a full-span rudder. At such a height, the vertical tail had to fold sideways so that it could fit in hangars with lower ceilings. The horizontal tail was of the fully variable type with a range of motion from 9° up to 4° down. Both stabilizers were also trimmable, a first for an aircraft of the B-52's size. The trimmable stabilizer allowed for easier rotation on take-off and landing while flaring the aircraft.[10]

The B-52 cockpit accommodated five crewmembers. A pilot and co-pilot sat in a forward cockpit with a navigator and radar operator sitting in the lower deck. A tail gunner operated a 0.50 caliber tail gun at the extreme aft of the fuselage.

Chapter 3. Program Overview

This chapter presents the historical and technical context in which the B-52 Stratofortress program emerged. From the early beginnings of jet-powered bombers and the B-47 through the 51-year career of the B-52, the story is told from a historical perspective, which provides the context for the remainder of this detailed case study. Insights into the development of the Stratofortress from Bob Withington (one of the original drafters of the B-52 proposal) are also included to provide a first-hand account of the emergence of the most successful bomber ever constructed.

3.1. Historical and Technical Program Context

The story of the B-52 begins with the development of the B-47, the first of a new generation of aircraft. It signaled the end of the piston-engine era, and heralded a new age of jet engines and swept wings. The B-47 set precedence for all bombers that followed it.

In April of 1944, the United States Army Air Corps called for a jet bomber with a top speed of 500 mph. Toward the end of WWII, the Germans and the British were both developing their own jet bombers and fighters, and the Army Air Corps wanted to keep pace. Five designs were proposed by the leading aero-engineering companies of the day. North American proposed the XB-45, which was a straight-winged jet aircraft. Convair proposed the XB-46, another straight winged aircraft, but they were already amidst heavy production of the B-36. Martin proposed the XB-48. Northrup put forward the XB-35, which was a revolutionary flying wing concept with excellent performance. And finally, Boeing proposed the XB-47.

Figure 2. Boeing XB-47 [4]

Each plane was flight tested in 1947 and Boeing's XB-47 won by a large margin for various reasons. First, and foremost, the XB-47 had swept wings. The XB-47 was originally a straight-winged aircraft. The design team was frustrated by a lift-to-drag ratio that fell off drastically at Mach 0.6 due to the compressibility effects of flying faster with jet engines. The only feasible solution at the time was to switch back to turbo-prop engines to reduce the cruise speed.

However, an American engineer by the name of Robert T. Jones had come up with a theory for alleviating the L/D ratio problems by sweeping the wings back. The theory was not originally applied to the XB-47 because, at first, no one believed him. However, at the end of WWII, interviews with German Luftwaffe engineers validated Jones' theory. Therefore, Boeing adopted the swept wing for the XB-47.

In addition to swept wings, the XB-47 also utilized engine pylons, allowing more fuel to be stored inside the wings. This contrasted with previous aircraft designs that had engines embedded in the wings, thereby precluding fuel storage. This had the double effect of making the wings lighter and engine maintenance easier. Finally, the XB-47 had a bicycle landing gear, a relatively new technology at the time. These factors all contributed to the USAF adopting the XB-47 as their new medium range bomber and the first operational B-47 Stratojet was delivered October 23, 1951, ushering in the new era of jet bombers.

Although the B-47 was a technical marvel and a pleasure to fly by the pilots of the time, there were many problems with it. Due to scheduling constraints, the Boeing aerodynamicists did not have adequate time to design the wing [11]. The B-47 wing was simply rectangular and swept back to 35 degrees. Not enough consideration was given to the airfoil cross-section or taper ratio. The wings were also too thin and could not carry any fuel. Since jet engines were a new technology at the time, the engines on the B-47 had a high specific fuel consumption. In addition, the Air Force did not continue to evidence a great deal of interest in the B-47 because it fell midway between medium and heavy bombers. The B-47 continued its service to the USAF through 1965, but its true contribution was that it set the stage for the development of the B-52, for which the story begins in 1941.

In August of 1941, President Franklin Delano Roosevelt and British Prime Minister Winston Churchill met in Placentia Bay, Newfoundland in the first of nine conferences that defined the aims of the allies in WWII. The Atlantic Charter was the result of this first meeting and outlined the need for the United States to create a bomber with a sizable bomb load that would be able to operate against Germany from the US in the event that Great Britain was invaded and had to operate from its Empire outposts [4]. The requirements included the following:

- A 10,000 lb bomb load (Grand Slam configuration bomb) and a range of 10,000 miles (5,000 mile radius).
- A 72,000 lb bomb load (general purpose, conventional, high-explosive bombs) over shorter distances.
- A 35,000 ft operating altitude of 250 to 300 mph flight speed.
- Be able to operate from 5,000 ft runways.
- A minimum crew of five, an undetermined number of 20-millimeter cannon operators for offensive and defensive armament and a six-man relief crew.
- Armor protection for the crew, fuel, engines and other vital components consistent with weight and performance.
- Reliability, ease of maintenance, reduction in fire hazards, good visibility, quick-change features and simplicity in design.

At that time, Boeing was too caught up with the production of the B-29 and therefore did not put in a bid. Consolidated Vultee proposed the B-36. Douglas dropped out of the competition, because they believed that the technology of the day had not matured to the point where creating an aircraft to fulfill these requirements was possible. Finally, Northrup put forward the XB-35, a revolutionary flying wing with excellent performance.

Figure 3. Northrop XB-35 [4]

Due to political maneuvering, Consolidated's B-36 was chosen and first flew on August 8, 1946, after both Japan and Germany had been defeated and the Cold War had not yet spawned another need for the bomber.[4]

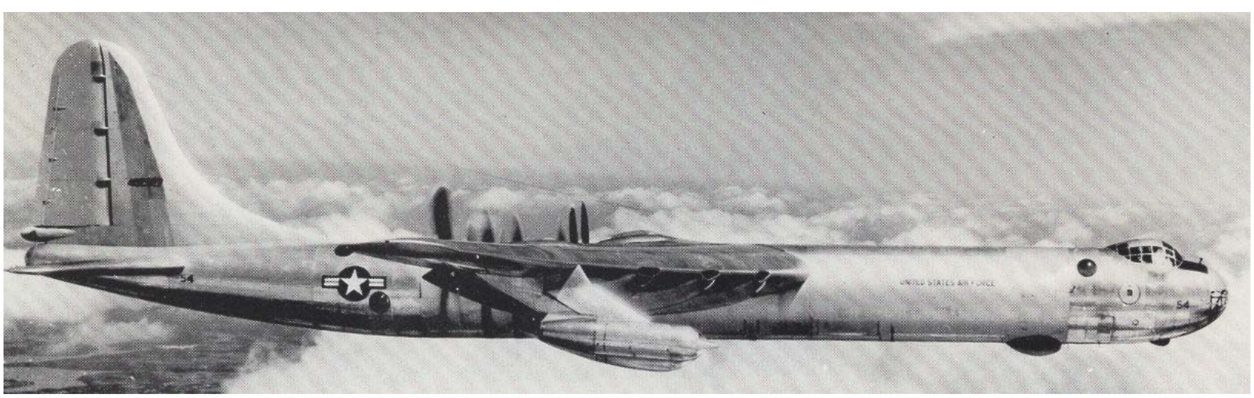


Figure 4. Consolidated Vultee B-36 [4]

Shortly after the end of WWII, the USAF sought to create a "second generation" successor to the B-36. The requirements were similar to the original set except for the following changes:

- A speed of 450 mph at 35,000 ft altitude.
- Be able to operate from 7,500 ft runway with a 50 ft take-off obstacle.

In February 1946, the Air Force gave out invitations to bid on the military characteristics outlined above. Boeing, Glenn L. Martin Company, and Consolidated submitted cost quotations and preliminary design data close to the requirements. Although the B-47 met most of the requirements, it was not considered because both Boeing and the USAF agreed that it was simply not big enough to accomplish all that might eventually be required of it. On May 29, 1946 the bid from Boeing, Model 462, was accepted. The Boeing Model 462 had six turbo-prop engines and came very close to meeting the requirements set for the by the USAF.

On November 27, 1946, the Deputy Chief of the Strategic Air Command (SAC) for Research and Development, Major General Curtis E. LeMay, and Strategic Air Command offices proposed the following additional requirements:

- An operating radius of 5,000 miles and a reserve of 2,000 miles with one "Fat Man" Mk III bomb.
- Atomic bomb mission only with a maximum payload between 20,000 and 30,000 lbs.

In response, Boeing created Model 464-17, which had a tapered straight wing powered by four turboprop (T-35) engines. The SAC eventually accepted the Model 464-17, but expressed concern about fuel protection. Boeing made several aerodynamic improvements that increased the cruising speed of Model 464-17, leading to Model 464-29.

After numerous additional changes to the requirements from 1947 – 48, the SAC cancelled their original acceptance of the Boeing proposal and issued the final set of requirements for the "second generation" bomber in early 1948. In this iteration, the SAC required that the aircraft fulfill the following specifications:

- A range of 8,000 miles (4,000 mile combat radius).
- A cruising speed of 550 mph and 550+ mph over a defended area.
- A tactical operating altitude of 40,000 ft or 45,000 ft if desired.
- Droppable landing gear.
- Full purging and self-sealing tanks for fuel.
- Be able to refuel in air.

In 1948, the current iteration of the Boeing proposal was Model 464-35, which still used turboprop engines. In October of 1948 in Dayton, Ohio, the Chief of Bomber Development, Colonel Henry E. "Pete" Warden told the Boeing team to "Get rid of the props" [1]. The team, which included Edward C. Wells, George S. Schairer, H. W. "Bob" Withington, Vaughn Blumenthal, Art Carlsen and Maynard Pennell, spent the weekend in the Boeing Suite at the Van Cleve hotel, getting rid of the props for fear that Boeing would lose the bid completely.

Bob Withington, see Figure 5, had been, for some time, developing an aircraft called the B-55, which used jets and swept wings. The team members decided to apply the B-55 design to Model 464-35 and compile a database of performance data based on the B-55 model. By Sunday they had a 33-page document (Document 10,000) with data and had finished a balsa-wood model of Boeing Model 464-49-0. The secretary typed up their report and it was presented to Warden and the USAF on Monday morning. The proposal was accepted and funding for the aircraft was delivered within a few months. Model 464-49-0 became the XB-52. Table 18 in Appendix A lists the various requirements for the long-range, heavy bomber from 1941 through 1948.

Figure 5. Holden White "Bob" Withington [4]

The two prototype aircraft, the XB-52 and the YB-52, were swiftly put together in a classified area of Boeing's Plant 2 in Seattle. The two planes were essentially identical except that only the YB was instrumented for flutter tests. The XB-52 would have been the first Stratofortress to fly, except the trailing edge of the wing blew out in a full pressure test of the pneumatic system. Thus, the YB-52 (tail number 49-231) had the honor of the maiden voyage of the B-52 series on March 15, 1952. The first flight was publicly announced for Tuesday, April 15, 1952. The XB-52 made its first flight on October 2, 1952. A picture of the YB-52 can be seen in Figure 6.

Figure 6. Boeing YB-52 [22]

Since its initial production, the B-52 has gone through a series of modifications from models A to H. A brief history of the various B-52 models is described below. A more detailed description of the B-52 derivatives is provided in Chapter 8.5.

The general layout of the two B-52 prototypes, the XB-52 and the YB-52, was similar to that of the B-47. Boeing engineers retained the 35-degree swept wing, pylon-mounted engines, braking parachute, bubble canopy and bicycle-type landing gear. The main difference was the use of four separate and steerable landing-gear units. The use of a completely moveable horizontal tail, instead of conventional elevators, for pitch control was another innovation. This system was the standard for jet fighters of the period, but had not been used before on jet bombers.

The B-52B, the first production Stratofortress, had increased gross weight and larger jet engines compared to the B-52A, which was primarily used as flight-test aircraft. The B-52B entered service with the U.S. Air Force's Strategic Air Command on June 29, 1955 with the 93rd Bomb Wing at Castle Air Force Base, California. With photographic reconnaissance or electronic capsules installed in their bomb bays, 27 of the 50 B-52Bs built were designated RB-52Bs.

Next came 35 B-52Cs, which featured further improvements but also resulted in a higher gross weight of 450,000 pounds. The B-52C had an extended “un-refueled” range, because of an increased total fuel capacity of 41,700 gallons. The B-52D made its first flight in 1956 and was essentially the B-52C without the alternative reconnaissance capsule feature. A total of 170 B-52Ds were built: 101 in Seattle and 69 in Wichita.

One hundred B-52Es and 89 B-52Fs followed the D models. The Es and Fs were exclusively long-range, heavy bombers. Equipped with the Boeing-developed flying boom system for in-flight refueling, they had a virtually unlimited range. The B-52E first flew in 1957, with improved bombing, navigation and electronic systems. It was the least expensive of the series, costing slightly more than $6 million per airplane. The B-52F, the last model before the bomber went through a major redesign, used 13,750 pound-thrust Pratt & Whitney J57-43W turbojet engines.

Seattle production of the B-52 ended in 1958, when the last of 44 B-52Fs rolled off the assembly line. However, another 45 B-52Fs were produced in Wichita, where the substantially improved G and H models also were built. While B-52Cs and Es were phased out during the early 1970s and the Fs in the late 1970s, B-52Ds remained in service until 1983.

The B-52G and B-52H looked very similar to earlier Stratofortress models, but they were technically very different and capable of fulfilling a variety of new mission objectives. The B-52G made its first flight in 1958 and was the first variant to introduce major innovations to the original design. It had a redesigned wing and a shorter vertical fin. Its internal fuel capacity was increased to 46,000 gallons by using built-in wing tanks rather than the flexible bladders of earlier versions. This gave the B-52Gs a range almost 2,000 miles greater than the first B-52s.

The gunner left his rear compartment and was moved forward to be with the rest of the crew, since the tail guns on the B-52G were fired by remote control using a TV link. Although equipped as a standard bomber, the B-52G could carry two North American Aviation AGM-28

Hound Dog supersonic air-to-surface missiles on pylons under each wing. The Hound Dog, capable of streaking several hundred miles to the target on its own inertial guidance system, changed the B-52 into a missile-launch platform. A total of 193 G models were built, and they remained in service until 1994.

The B-52H first flew in 1961 and incorporated all of the B-52G's improvements. The H model was developed specifically to carry four Douglas AGM-87A Skybolt missiles. However, after cancellation of the Skybolt program, the B-52H reverted to carrying AGM-28 Hound Dogs. A major advancement for the B-52H was the switch to Pratt & Whitney TF33 turbofan engines. With more than 17,000pounds of thrust, the turbofans were much more powerful than the turbojets. Other improvements included more refined electronic defensive and offensive systems, and the ability to fly at extremely low altitudes.

A total of 744 B-52s were built by Boeing between 1952 and 1962. Only the B-52H remains in service today.

3.2. Boeing Competitors

Boeing, Consolidated Vultee, and Glenn L. Martin all submitted proposals in response to the requirements posted in January of 1946. Boeing won the initial bid in June of 1946 with Model 462, powered by six turboprop engines. The service designation XB-52 was assigned, and Boeing was given more funding and a request to increase the speed of the plane.

Other possibilities were considered twice after the initial contract was given, first in January, 1948 and again in January, 1950. Alternatives to the Boeing design included new proposals from Douglas Republic, the Fairchild Aircraft Corporation, the Northrop B-35 flying wing, the swept-wing Convair YB-60 and two new designs based on the B-47. The two designs that posed the biggest threat were the enhanced models of the B-47 and the YB-60. The Convair YB-60 was a swept wing version of the B-36, powered by J57 engines. There were not considerable improvements in the airfoil or the structure, and it could not compete with the B-52 technically. Enhanced models of the B-47 could have competed with the B-52 in terms of range, but were also faced with some technical and political issues. Two new maneuvers were tested on these adapted B-47s, because they were needed to deal with the increasing threats from Ground-to-Air missiles. These maneuvers caused significant stress on the airframe, leading to structural problems. Politically, General LeMay knew the B-52 design was the way of the future and did not want to endanger this project with competition from the older B-47. Upon reviewing plans for the new B-47 models, he actually went so far as to tell the Boeing engineers to let the B-47 die [4].

3.3. Project Design Organization

For more than 30 years Boeing relied upon a consistent division of its engineers to conceive and design its aircraft. The project organization grew out of Boeing experience during World War II and persisted into the 1980s. The engineers were given authority, autonomy and funding to assume complete responsibility for the design of Boeing aircraft. The engineers were young, highly motivated and highly dedicated to their work. They would meet directly with the president of the company who supported them generously with funds and allowed them to manage themselves. This contrasts with the Boeing today which relies heavily on systems engineering, management and Integrated Product Teams. The upper Boeing management had a great deal of trust in their engineers. Bob Withington described the organizational structure as he remembered it.

All of the engineers reported to the Chief of Engineering. At the time of B-52 design, Ed Wells was at the helm of Boeing engineering. The engineers were divided into two categories. The first was the *technical staff* and the second was the *project engineers*. The technical staff, headed by George Schairer, was more theoretical and conceptual than the project engineers and utilized the laboratories which included the wind tunnel, structural and mechanical testing, etc. The project engineers were experienced at the routine aircraft design steps, relating the design to the factory and procurement. Each aircraft project at Boeing consisted of a set of technical staff and project engineers. Similarly, new aircraft were assigned to a small group of engineers consisting mostly of technical staff, but some project engineers as well. The technical staff employed the design methods and laboratories at their disposal to arrive at the original aircraft configuration. The aerodynamics was primarily the biggest technical hurdle to overcome with new aircraft, so aerodynamic performance considerations and aerodynamicists usually trumped the considerations of other engineers.[17]

The use of laboratories, especially the wind tunnel, must be especially emphasized. Bob Withington was hired from MIT specifically for the design and implementation of the Boeing in-house wind tunnel. In the early 1940s, most corporations only used wind tunnels for testing or fixing or design flaws. They relied upon the wind tunnels located at MIT, CalTech, the University of Washington and Cornell University. George Schairer realized that the wind tunnel could serve as a design tool as well. Thus, Boeing set out to construct their own wind tunnel and, upon the advice of leading aerodynamicists of the time, pushed the wind tunnel speed capabilities up to the transonic regime. At the time though, all aircraft were propeller driven aircraft flying at only 300mph. However, once the jet engine became a more mature technology, the capabilities of the transonic speed test section of the Boeing wind tunnel enabled them to pioneer the swept wing of the transport aircraft. No other company had a wind tunnel for design at the time, so no other company could experiment with swept wing aircraft and pylon mounted jet engines. Thus, much of the Boeing success and development of the B-52 should be attributed to their keen aerodynamicists and wind tunnel testing facilities.

3.4. Program Timeline

The following timeline provides the major milestones in the development of the B-52 and its 51-year service [2].

3.4.1. The Forties

February 13, 1946: The U.S Army Air Corps issues basic requirements for a new long-range, heavy bomber.

June 28, 1946: Boeing awarded engineering study and preliminary design contract for turboprop-powered B-52 bomber.

October 25, 1948: Boeing presents the Air Force with a proposal for B-52s powered by eight jets engines.

January 26, 1949: The Air Force informs Boeing that work can proceed on two experimental, jet-powered B-52s under the original contract.

3.4.2. The Fifties

April 15, 1952: YB-52 prototype makes first flight in Seattle.

September 28, 1953: Boeing's Wichita plant announced as second source for B-52 production.

August 5, 1954: B-52A first flight.

January 25, 1955: B-52B first flight.

June 29, 1955: First B-52B for the Air Force's Strategic Air Command is delivered to 93rd Bomb Wing at Castle Air Force Base, Calif.

March 9, 1956: B-52C first flight.

May 14, 1956: First Wichita-built B-52, a D model, makes first flight.

September 28, 1956: First Seattle-built B-52D makes first flight.

December 6, 1956: B-52 wins National Aeronautic Association's Collier Trophy for 1955.

January 18, 1957: Three B-52Bs fly around the world in 45 hours and 19 minutes, averaging 530 mph over the 24,325-mile course. This cuts the previous record in half.

October 3, 1957: B-52E makes first flight in Seattle.

October 17, 1957: B-52E makes first flight in Wichita.

May 6, 1958: B-52F makes first flight in Seattle.

May 14, 1958: B-52F makes first flight in Wichita.

October 27, 1958: B-52G makes first flight in Wichita.

February 25, 1959: Last Seattle-built B-52, an F model, is delivered.

April 23, 1959: First test flight of North American Aviation's AGM-28A Hound Dog supersonic air-to-surface missiles from B-52.

September 17, 1959: NASA's X-15 research rocket plane makes its first powered flight, carried aloft and released from an NB-52A.

3.4.3. The Sixties

February 1960: The McDonnell Aircraft GAM-72 Quail decoy missile goes into service on B-52Gs at Eglin Air Force Base, Fla.

March 16, 1961: B-52H makes first flight in Wichita.

May 9, 1961: First B-52H is delivered to 379th Bomb Wing at Wurtsmith Air Force Base, Michigan.

October 26, 1962: Last B-52 (B-52H, tail number 61-040) is delivered by the Wichita plant to the 4136th Strategic Wing at Minot Air Force Base, North Dakota.

June 18, 1965: Strategic Air Command B-52s strike targets in Vietnam for the first time.

3.4.4. The Seventies

September 15, 1972: Boeing AGM-69A Short-Range Attack Missiles, or SRAMs, become operational on B-52s with the 42nd Bomb Wing at Loring Air Force Base, Maine.

December 18, 1972: Staff Sgt. Samuel Turner becomes first B-52 gunner to shoot down an enemy aircraft when he hits a North Vietnamese MiG-21 during Operation Linebacker II.

June 24, 1973: First B-52H with Electro-Optical Viewing System, or EVS, to enhance vision when flying at low level at night is delivered.

August 15, 1973: Strategic Air Command B-52s fly final mission in Southeast Asia.

February 21, 1974: First B-52H equipped with Phase VI Electronic Counter Measures, or ECM, to upgrade defensive avionics system is delivered.

December 7, 1979: First B-52G arrives in Wichita to receive computer-controlled Offensive Avionics Systems, or OAS, upgrade.

3.4.5. The Eighties

January 11, 1981: First Boeing AGM-86B Air Launched Cruise Missiles, or ALCM, are delivered for carriage on B-52G under-wing pylons.

June 10, 1982: Strategic Air Command's first all-female KC-135 Stratotanker crew refuels a B-52 during a five-hour training mission.

June 30, 1985: McDonnell Douglas AGM-84D Harpoon anti-ship missiles are added to 30 B-52Gs.

June 30, 1987: The AGM-129A Advanced Cruise Missile, or ACM, is added to B-52 arsenal.

January 1988: Boeing AGM-86C Conventional Air Launched Cruise Missiles, or CALCM, declared operational on B-52Gs.

3.4.6. The Nineties

January 16, 1991: Operation Desert Storm: Air operations begin when seven B-52Gs take off from Barksdale Air Force Base, La., and head for the combat zone. After hitting targets in Iraq, the B-52s return to Barksdale, thus flying the longest air combat mission in history up to that time. The mission also sees first combat use of CALCM.

September 1991: Strategic Air Command's B-52 ground nuclear alert status is ended.

October 1, 1991: B-52 gunner position eliminated.

September 30, 1992: The Boeing Common Strategic Rotary Launcher Integration, or CSRLI, modification is completed for B-52H fleet. The launcher is fitted inside the bomb bay and can carry up to eight AGM-86 cruise missiles.

February 15, 1994: Boeing Wichita receives initial development contract to integrate precision-guided munitions (Wind-Corrected Munitions Dispenser and Joint Direct Attack Munition) on B-52Hs.

May 16, 1994: Due to retirement of the B-52G, the "Rapid Eight" modification program begins to provide the B-52H with guided-missile capability.

August 24, 1994: Start of Conventional Enhancement Modification, or CEM, program. This gives the B-52H fleet capability for delivery of a new generation of precision-guided conventional weapons. Included in the upgrade is the addition of a Global Positioning System.

March 8, 1995: B-52H successfully launches AGM-142A Have Nap electro/optical guided missile.

July 25, 1995: The first live shot of Harpoon missile from B-52H using the Harpoon Aircraft Command Launch Control Set, or HACLCS.

September 3, 1996: Operation Desert Strike was the B-52 mission flown in support of the larger U.S. effort called Operation Southern Watch.

September 1998: Joint Direct Attack Munition, or JDAM, is declared operational for use on B-52H. JDAM uses Global Positioning System for precise hits on aim points.

March 24, 1999: Operation Allied Force: B-52Hs open NATO's air campaign in the Balkans by launching CALCM cruise missiles at military targets throughout Yugoslavia. Later the bombers transition to delivering general-purpose weapons on Serbian army positions and staging areas.

June 1999: Wind-Corrected Munitions Dispenser, or WCMD, declared operational for use on B-52H. WCMD uses a tail kit attached to a cluster bomb unit to adjust the bomb's flight path for wind changes.

December 23, 1999: The B-52H Avionics Midlife Improvement, or AMI, program is initiated to modernize offensive avionics processors and navigation systems on the Stratofortress.

3.4.7. The 21st Century

April 1, 2000: Situational Awareness Defensive Improvements, or SADI, program is initiated to upgrade defense systems for the B-52H fleet.

October 7, 2001: Operation Enduring Freedom: B-52H bombers take part in initial air attacks. The B-52H arsenal included JDAM and WCMD precision-strike weapons, AGM-142 Have Nap guided missiles, GBU-28 laser guided bombs and MK-82 general-purpose bombs. The B-52s were the first to use the WCMD in combat. They also participated in psychological warfare operations using their M129 leaflet dispensers.

November 2001: AGM-86D CALCM Penetrator is declared operational on the B-52H. The penetrating warhead allows the missile to destroy buried or reinforced targets from standoff ranges of hundreds of miles.

January 31, 2002: B-52 nominated for National Aeronautic Association's 2001 Collier Trophy.

April 15, 2002: 50th anniversary of B-52 first flight.

3.5. Political Issues

World political events helped shape the development of the B-52. The requirements for a second-generation long-range bomber were first set in January of 1946, just five months after atomic bombs were dropped on Hiroshima and Nagasaki and the end of WWII. The European mainland and the Japanese empire lay decimated while the US and the Soviet Union stood strong as the clear global superpowers.

In the first couple of years after the end of the war, relations between the US and USSR were in flux. The Cold War had not yet coalesced into any recognizable form and the two countries explored the nature of their future relationship. As the State Department sought to work with the USSR, it did not take long for the DoS to become frustrated with the USSR's intransigence and immutability in the face of external pressures. There was no economic or political leverage that the US could muster over the Soviet Union. It was in this context that George F. Kennan wrote a primer on American-Soviet relations that gained widespread acceptance and vaulted him to the head of the "Policy Planning Staff," a think tank for US foreign policy established by Secretary of State, George C. Marshall.

Kennan shaped and defined American national security policy up until the Korean War. He coined the term, *containment* and, as the Head of the Policy Planning Staff, set out the long term goals and methods for achieving containment as the goal of American foreign policy. Kennan sought security for the United States and its way of life in the post-WWII climate by restoring the balance of power between Europe, Asia and the US. This approach aligned well with the Marshall Plan outlined by the Secretary of State, which devoted large amounts of US capital to countries that were destroyed by the war and to resist Communist influences.

Kennan fully recognized the importance of armed strength in restoring and maintaining a balance of power. Kennan wrote that the mere existence of armed forces "is probably the most important single instrumentality in the conduct of US foreign policy" [3]. Military might gave credence to political positions, served as a deterrent against attack, instilled confidence in allies and would prove essential in the event of war.

This was the philosophical and environmental context in which the B-52 was envisioned. A bomber that could launch from within the bastion of the US borders, fly directly to Moscow to deliver nuclear munitions and return without stopping would be politically invaluable. It would move the center of battle away from the war-torn European mainland, thereby instilling confidence in American allies in Europe. A long-range bomber would also dramatically increase the sphere of influence the military could exert as well as serve as a pillar of deterrence against Soviet attack. Events such as the Berlin Blockade by the Soviet Union in 1948 only served to reinforce and invigorate the demand for a strategic, nuclear bomber. Neither the State Department nor the Strategic Air Command planned directly to use the B-52 against the USSR, but its existence and capabilities would aid the US in its overall goal of containment and restoration. By the time the B-52 entered development, the Korean War was in full swing and the Cold War had evolved into a recognizable element in world order.

Internal politics also played a large role in the development of the B-52. A new branch of the Armed Forces was formed in 1947 when the Army Air Force split with the Army to become the United States Air Force. As its own service, the Air Force needed to establish a place for itself in the US Armed Forces. In the years after the Air Force was formed, Air Force leaders had three main goals. First, they wanted to reduce their dependency on the Army and Navy and show they could be an independent organization within the Armed Forces. Second, they wanted to justify their strategic bombardment doctrine, which is based on the idea that strategic bombing against an enemy's economic and technical infrastructure would prevent the enemy from being able to wage war and thus, could prevent an armed invasion. Finally, the Air Force was now competing with the Army and Navy for more budget considerations and an increased role in national security missions.

After WWII, the State Department was concerned about relying on overseas bases to provide support for bombing missions into the Soviet Union. They worried overseas bases might not be available in the event of a war between the United States and the Soviet Union. The State Department's mentality fit in well with Air Force efforts to reduce their dependency on the Army and Navy to hold overseas bases for them. The Air Force wished to reduce their need for overseas bases with fleets of intercontinental bombers that could reach Soviet targets from US soil. The development of the B-52 enabled the State Department and the Air Force to achieve their goals of reduced dependence on overseas bases as well as allowing the Air Force to justify their strategic bombardment doctrine and gain a larger role in national security operations [5].

The operational requirements of the B-52 project were set to meet the political and technical needs of the fledgling Air Force, rather than simply to take advantage of new technology that was becoming available (i.e. swept wings and turbojet engines). Throughout the development of the B-52, the operational requirements changed several times to insure the performance of the aircraft would meet the political needs of the Air Force [5].

Chapter 4. Aircraft Value Proposition

The number of stakeholders in any large aircraft development project is quite large. From the contractors to the customer, suppliers and political actors, a single aircraft can have a resonant influence on many individuals, corporations and/or agencies. Although the B-52 was developed fifty years ago, it still boasts a significant number of stakeholders. Four of these stakeholders stand out as the most prominent: the US Air Force, the Boeing Corporation, Pratt & Whitney and the US State Department. This chapter describes these key stakeholders in the B-52 Stratofortress project. Their expectations for the B-52 and what the stakeholders hoped to gain in participating in the project are also described.

4.1. Key Stakeholders

The US Air Force actually had a few different stakeholders in its ranks that had contrasting interests. Between the pilots and mechanics working with the aircraft, the generals involved in strategy planning, and the Air Staff in Washington, D.C., the USAF had great interest in the success of the B-52 program. The Boeing Corporation was awarded the contract to build the B-52 and worked closely with the USAF and Pratt & Whitney in its development. It invested many corporate resources into the design and fabrication of the B-52. Pratt & Whitney, as the engine supplier, also had a large investment and stake in the success of the B-52. It continued a long history of cooperation with Boeing and the USAF. The US State Department and its foreign policy interests originally provided the prime impetus for the B-52 program. Therefore, the government and the citizens the State Department represented had a great investment in the success of the B-52 program.

4.2. Value Expectations

As discussed in Section 3.1 and detailed extensively in Appendix A, the SAC requirements and Boeing B-52 proposals underwent many iterations. What started as a straight wing, turboprop aircraft ended as a swept wing, turbojet aircraft. The repeated revisions to the requirements and Boeing proposals can be thought of as iterating on the *value identification* and *value proposal* of the aircraft. The SAC saw value in a long range, heavy nuclear bomber. However, the B-52 had to meet certain performance specifications in terms of range and payload in order to realize the SAC's value expectations for the aircraft. In turn, Boeing and Pratt & Whitney saw much more value in pursuing swept wing and turbojet technology than in adhering to traditional designs. When the technology became available, the B-52 value expectations for Boeing and Pratt & Whitney grew tremendously. Thus, the final Value Proposition was arrived at dynamically, through the interactions of three of the primary stakeholders (the DoS did not play a role in the iteration of requirements and proposals).

4.2.1. United States Air Force

The value expectation of the fledgling USAF in the B-52 project stemmed from being the customer and the end-user of the aircraft, as well as attempting to establish its credibility as a major service of the US Defense Department.

As a consumer, the Air Force desired a quality product. The USAF expected a product that was aerodynamically efficient, cheap to operate and reliable. The B-52 Stratofortress offered advanced technological concepts such as wing sweep and jet engines, which the Air Force had interest in seeing come to fruition.

The expectations of the Air Force as the end-user differed only slightly from its expectations as a consumer. For the crew, the B-52 needed to provide them with the capability of completing their mission and returning safely to ground. The mechanics wanted a product that was reliable and easy to work with. There were others in the Air Force, such as the acquisition officers and support staff that also had various expectations of the B-52, which are outside the scope of this case study.

The need for a long-range bomber was augmented by current events of the time. After the Berlin Blockade and the escalation of tension between the US and the Soviet Union, the USAF Strategic Air Command felt an urgency to have a long-range bomber in its array of counter-measures. It needed a bomber that did not rely on the use of intermediate bases offered by other non-ally countries, based on the US military experience during the Pacific battles in WWII. Thus, for the generals around the planning table, the B-52 also served their interests.

The USAF also relied upon the B-52 to help establish its identity. The Department of Defense was reorganized after WWII and the Air Force became its own service, separate from the Army and Navy. As a new service, the Air Force needed to define itself and its niche in the greater realm of US Armed Forces. Moreover, the Air Force was competing with the Navy for funds and responsibility to be the service endowed with the mission of delivering a nuclear bomb to the Soviet Union if needed. Therefore, the USAF expected the B-52 to help define and assert its role amongst the other services, as well as demonstrate that it was capable of fulfilling the vital role of bombing the USSR.

4.2.2. The Boeing Corporation

One of the major stakeholders for the B-52 was the Boeing Corporation. It won the bid to manufacture the B-52, competing against two other manufactures – the Glenn L. Martin Company and Consolidated Vultee. All three submitted quotations and preliminary design data based on specifications received from the USAF in November 1946.

One of the main economic incentives for Boeing to win the contract was that the new bomber project would become the cornerstone of the next generation of long-range bombers to be employed by the USAF. In addition, the company would be able to further develop the technology of swept wings (acquired from the Germans after WWII) together with the USAF, helping the Boeing Corporation to maintain is status as the forerunner of innovation in the aviation industry.

Boeing's first proposed design, the Model 462, fell short of the range requirement. However, it still won the competition. It faced many redesigns to suit the changing requirements of the Air Force. Further attempts at improving the existing model lead to 464-35, which the Air Force approved as Boeing's Phase II proposal in July 1948.

Boeing also initiated in-house feasibility studies on the development of an all jet bomber, through the B-47 and B-55, as opposed to their current proposal, which was powered by turboprops. These studies were funded entirely by the Boeing Corporation in its bid to win the USAF contract. They eventually led Boeing to propose the final eight engine jet design of the B-52. With all of the resources it spent, Boeing expected a significant return on investment through the success of the B-52 Stratofortress.

4.2.3. Pratt & Whitney

Although the initial Boeing designs called for turboprops for the new B-52 bomber project, it was later suggested that turbojets should be used. This would give the model a longer range of operation and would be closer to Air Force expectations for its "second generation" bomber program. Initially, the incorporation of turbojets was rejected, because both the aircraft companies and the US Air Force believed that turbojets were still in their infancy and provided inadequate power for a heavy bomber. However, as a result of studies performed by Boeing, Pratt & Whitney was tasked with manufacturing the eight jet engines to be used on the B-52. This jet engine technology became a primary operational requirement for later bombers.

Pratt and Whitney benefited from its research and development of the jet engines for the B-52. It had not been a pioneer in jet engine development, because the US government wanted Pratt & Whitney to concentrate on producing their series of air-cooled piston engines during the war. Thus, its learning experience in the B-52 program enabled the company to remain competitive in the future of jet aviation.

In addition to the technical expertise gained in developing jet engines, Pratt & Whitney also sought a continuing partnership with the Boeing Corporation and the US Air Force. The aviation industry had changed dramatically after WWII; aligning with a major aircraft manufacturer and the Air Force was a strategic move for Pratt & Whitney. The B-52 project offered a solidification of these partnerships that would lead to many future contracts for Pratt & Whitney.

4.2.4. United States State Department

The end of WWII and the emergence of the Soviet Union as a major military power prompted the US to reformulate its military doctrine. At that time, the US national security strategy was centered on its containment policy and a nuclear deterrent against Soviet aggression. The US wanted a strong bomber fleet to counter the threat from Moscow and the ability to deliver a nuclear weapon if needed.

The capabilities of the B-52 offered significant leverage to accomplish foreign policy goals. With a long-range bomber and a nuclear payload, the DoS could divert the focus of military activity away from Western Europe and instill confidence in its allies such as England, France, Spain and West Germany. This was an essential step as Western Europe was decimated by the perdition of WWII. Moreover, the ability to launch a nuclear strike from within the borders of the US drastically expanded the military's sphere of influence and was therefore a deterrent against Soviet attacks upon US interests abroad.

4.3. Value Proposition

After the critical weekend in Dayton, where the B-52 with swept wings and turbojets was born, all of the parties agreed to push ahead with the project. The US Air Force agreed to buy the aircraft from Boeing equipped with Pratt & Whitney J57 engines. Boeing, in turn, committed to deliver the aircraft capable of flying 8,000 miles without refueling with a 10,000 lb bomb load at a cruise speed of 520 mph at 45,000 ft [12]. Pratt & Whitney was under pressure from Boeing to deliver a power plant for the B-52 efficient enough to meet the range requirements. After observing the capabilities of the XB-52 in 1951, the Air Force agreed to production of the first B-52As, with an initial contract order of 13 aircraft to be delivered by April, 1953 [10]. When the B-52 was actually ordered into production by the Air Force in 1951, the country was ensconced in the Korean War and the Cold War had begun. The State Department knew full well the political leverage and tactical advantage the B-52 would offer.

By 1962, Boeing had delivered 744 B-52 aircraft to the USAF and production was halted. Nevertheless, the B-52s remain in service today, more than 50 years after their initial production run. The enduring success of the B-52 program is indicative of the value delivered to its stakeholders.

Boeing and Pratt & Whitney benefited greatly from the B-52 program, both financially and competitively. Both companies continue to be dominant players in the aerospace defense industry where many others have folded or merged, perhaps due to the prominence of successful programs such as the B-52.

The USAF has obviously appreciated the reliability and effectiveness of the B-52. While the B-52B saw some high accident rates in the first couple years of service, its problems were remedied in later derivatives. The Strategic Air Command had the capability to deliver heavy bombs from a great distance. Although they never exercised this capability against the USSR, the B-52 was used heavily in Vietnam, the Persian Gulf War and recent conflicts as well. The SAC continues to find value in the B-52 as the most reliable and cost efficient, "Bomb Truck" in recent conflicts. It is also possible that the B-52, occupying such a key nuclear and combat niche, along with the demonstration of importance of air superiority in Korea, propelled the USAF into a position of credibility amongst rival services. Not until the later development of the Titan intercontinental ballistic missile could the US launch a nuclear attack from within the protective confines of its borders towards the USSR.

Unfortunately, the value delivered to the State Department is more difficult to gauge. There is no specific Soviet action that can be pinpointed as a response to the B-52 and the DoS goals of containment and deterrence are difficult to measure. Nuclear war was certainly deterred, but it would be difficult to argue that Communist expansion was "contained." If anything, the B-52 only served to escalate the Cold War. However, foreign policy and global events are driven by so many factors, the B-52 program was only a small piece of the puzzle.

Chapter 5. Requirements

Requirements are at the heart of all engineering endeavors. This chapter outlines the high-level requirements that laid the foundation for the B-52 Stratofortress. It also examines how these high-level requirements manifested themselves in the actual aircraft; in other words, it considers how the flow-down of the requirements drove the design of the B-52 and in turn impacted the formation of the most successful bomber to date.

5.1. High-Level Requirements

As mentioned in Section 3.1, Franklin Roosevelt and Winston Churchill first drafted the preliminary concept and requirements for the B-52 in 1941. The details and specifications of the requirements changed somewhat during the 1940s, but throughout the many iterations the underlying need for the B-52 remained immutable; the Air Force wanted a long-range, heavy bomber capable of delivering a nuclear bomb to the USSR. This mission guideline translated into the functional requirements that drove the design of the B-52; specifically, the range and payload stipulations determined design decisions more so than any other requirement.

The original Atlantic Charter, drafted in 1941 by Roosevelt and Churchill, called for an aircraft with a range of 10,000 miles with a 10,000lb payload. The payload requirement reflected the intent to have the B-52 be able to deliver a nuclear bomb. By 1948, the range requirement had been reduced to 8,000 miles, but the payload demands remained steadfast. The first B-52s delivered to the Air Force had a range of over 7,000 miles and could carry any munition in the US arsenal. Later modifications to the B-52 improved its range performance to well over 8,000 miles.

There were several secondary requirements aside from the range and payload requirement for the B-52. The Air Force wanted a bomber that had a tactical operating altitude of 45,000 ft and a cruise speed of 550 mph to ensure its safety from ground launched anti-aircraft missiles, while also having limited capability to defend itself, refuel in mid-air and be able to take-off from a 7,500 ft runway. These requirements also factored into the design decisions in the development of the B-52.

5.2. Requirements Flow Down

Range and payload performance were the key drivers of design decisions for the B-52. The flow-down of requirements is illustrated in Figure 7. Almost all of the features of the B-52 can be traced back to the range and payload goals. The Breguet Range equation expresses how range is comprised of aerodynamic efficiency (lift-to-drag ratio), cruise velocity, thrust specific fuel consumption (TSFC) and high fuel-to-weight ratio. Each of these elements contributed to B-52 design decisions.

The necessity for aerodynamic efficiency and high cruise velocity steered the Boeing engineers to swept wings and turbojets, the two most innovative design decisions associated with the B-52. For good L/D performance, the Boeing engineers employed current technologies at the time by using a high aspect ratio wing and varying airfoil cross-sections. However, they were unsatisfied with the drag rise associated with transonic flight at flight Mach numbers around 0.8. If the B-52 was going to meet the range and cruise speed requirements, the wings of the B-52 had to be swept back. Boeing's experience with the B-47 gave the designers the tools necessary to sweep back the wing enough to delay the transonic drag rise to higher Mach numbers, without encountering control difficulties.

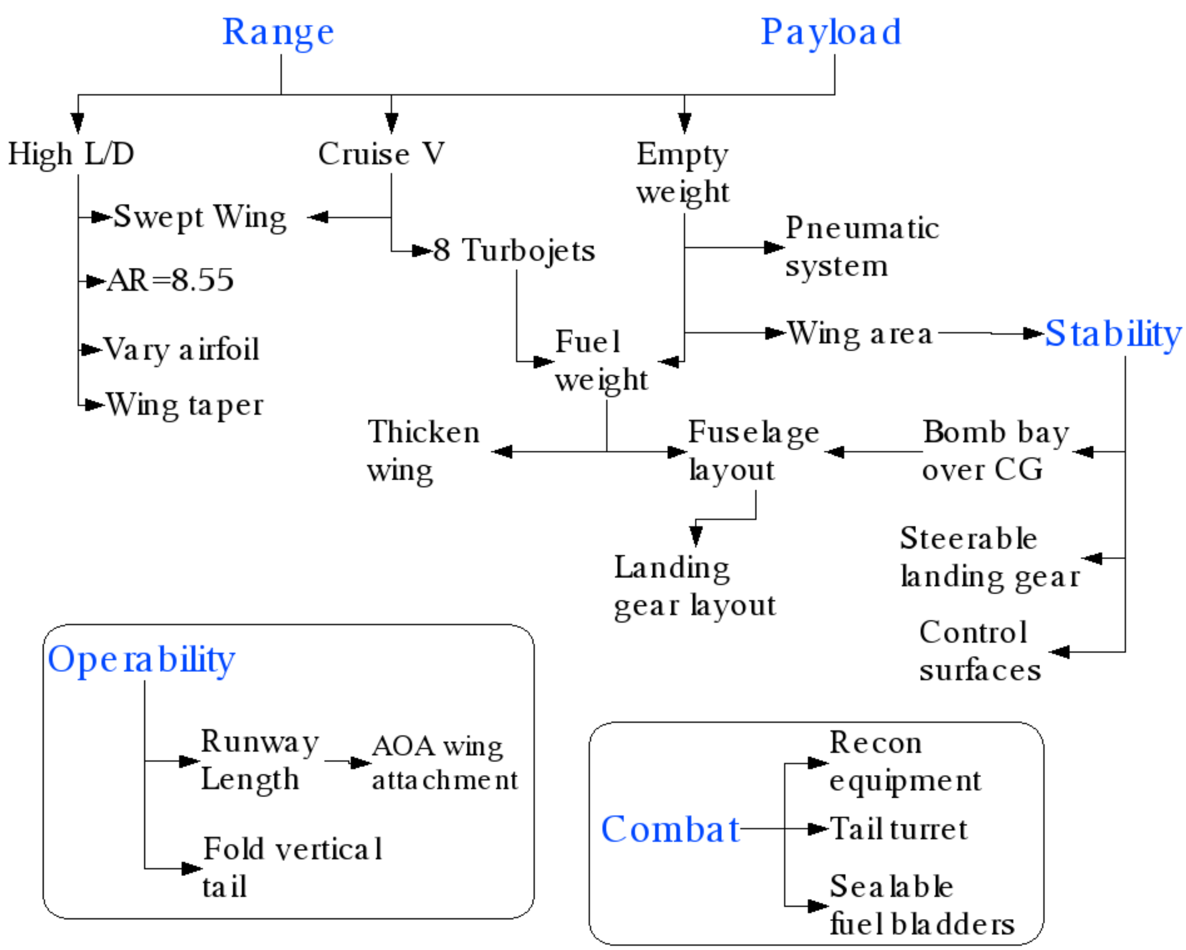


Figure 7. Requirements Flow-down Diagram

Similar to the swept wings, the cruise velocity and range requirements demanded that the Boeing engineers opt for a turbojet-powered aircraft. As the B-52 developed through its preliminary design iterations, the turboprops envisioned for the aircraft became increasingly more complicated, with counter-rotating shafts and a 20-foot diameter propeller. Despite their size and complexity, these engines had difficulty meeting the range requirement, especially when coupled with the altitude and cruising speed requests of the Air Force. Throughout the early development of the B-52, jet engine technology had not matured enough to provide the necessary efficiency to fulfill the Air Force requirements. However, by the late 1940s the technology had matured enough to warrant discarding the turboprops in favor of turbojets. In order to meet takeoff and climb performance demands, eight engines were required. This approach contrasts with aircraft design today when takeoff and climb performance specifications can be met by increasing the jet engine performance. The Boeing engineers were at the limit of jet engine performance. To obtain more thrust, they could only opt for more, not bigger, engines.

After the design decisions of swept wings and turbojet engines were made, the rest of the key decisions flowed naturally, as seen in Figure 7. The fuel consumption of the engines and the desired range set the amount of fuel the aircraft needed to carry. In order to accommodate the fuel, the wings were thickened and much of the fuselage was devoted to fuel storage. To reduce structural weight, a pneumatic system to drive the electric alternators and hydraulic actuators on the control surfaces and bomb bay doors was used. Although the engineers had many years of experience with hydraulic systems and pneumatic systems were difficult to maintain, the pneumatic system offered an attractive weight savings [11].

The structural weight of the aircraft sized the surface area of the wings to supply the necessary lift. This in turn sized the control surfaces for controllability. The size and weight of the B-52 were so big, that the Boeing engineers opted for a steerable landing gear to assist in crosswind landings. Essentially, the B-52 could land with a sideslip angle up to 20 degrees. Also for stability considerations, the bomb bay was placed directly over the center of gravity to avoid imbalances when a 10,000 lb payload was suddenly dropped from the aircraft. The placement of the bomb bay and the amount of fuel carried in the fuselage dictated the layout of the entire fuselage. This layout also precluded the use of the commonplace tricycle type landing gear. Instead, there were four landing gear units, two fore and two aft of the bomb bay [11].

In addition to range and performance, there were some operability considerations that drove some design decisions on the B-52 as well. To fit into some maintenance hangars, the vertical tail was hinged so that it could fold down. Also, to takeoff from shorter runways, the wings were attached to the fuselage at an angle of attack of 6 degrees. This reduced the amount of rotation about the aft gear necessary for takeoff.

The B-52 was ultimately a military and combat aircraft, so there design features that went beyond technical performance. There was a tail turret and gunner at the far aft of the fuselage for limited defense capability. Similarly, the fuel bladders were sealable in case they were punctured by gunfire. Finally, to placate the multi-faceted requirements of the Strategic Air Command (SAC), the bomb bay could house a pressurized capsule of reconnaissance equipment instead of munitions.

5.3. Lessons of the B-52 Requirements Process

The requirements for the entire aircraft flowed down from the range and payload specifications set by the SAC. As mentioned previously, these specifications, as well as the Boeing proposals, changed repeatedly in the 1940s. Given the subsequent success of the B-52 in the 50 years after the requirements were set, lessons might be extracted from the clearly iterative requirements process.

The feature of the requirements process that ensured the future success of the B-52 was the cooperation of Boeing and the USAF, the manufacturer and its customer. Many systems engineering experts advocate that the involvement of the customer as early as possible in the design process is an essential element to program success.[28] Usually, creeping requirements is a sign of an unhealthy engineering program. However, the B-52 requirements were not creeping. The range and payload specifications did not fluctuate during the detailed design process. Rather, Boeing and the USAF negotiated together appropriate requirements well ahead of the design process. Although the conceptual design of the B-52 predated the evolution of systems engineering, its development program is a clear example of building a successful and lucid set of requirements.

Both Boeing and the SAC played off one another to converge on a set of requirements for which both parties were content. The SAC initially issued requirements that pushed the envelope of turboprop capabilities. With each proposal by Boeing, the SAC pushed the specifications further until both parties agreed that the adoption of the emerging swept wing and jet engine technologies was the right path for the B-52. Once those technologies were espoused, the requirements iterated until the range and payload specifications were set at aggressive, yet realistic goals. The requirements process was iterative, but it was also a negotiation. The SAC provided its vision of a second generation bomber. Boeing and Pratt & Whitney brought the technology readiness and engineering talent to the table. Between them, they were able to hash out a set of requirements and design proposals that locked-in the success of the B-52 well into the future.

The importance of Boeing being able to negotiate with Col. Pete Warden, himself an MIT graduate, instead of Washington bureaucrats also cannot be underestimated. The customer was able to understand and appreciate the engineering tradeoffs involved in the design process. The iterative requirements process might have been useless and frustrating if the customer had no grasp of the design process and the limits of the new technologies involved with the B-52. This is a caveat to the lesson of involving the customer early in the requirements and conceptual design process. The customer representative must have an understanding of the engineering fundamentals that drives the design of their product.

Chapter 6. Detailed Vehicle Description

A thorough understanding of the B-52 program history, the key stakeholders in the B-52's value proposition and the high-level requirements that drove the design of the Stratofortress provides the context within which a detailed description of the aircraft can be discussed. From its configuration and performance characteristics created over a weekend in a hotel room in Dayton, Ohio to the final procurement costs of the aircraft, this chapter describes in detail the various design aspects of the B-52 Stratofortress.

6.1. Configuration

The configuration of the B-52 might seem commonplace today, but it set the standard for all future transport aircraft. This indicated that the B-52 represented a "dominant design" which was the result of a number of factors including technological integration, appropriate timing of development, and good infrastructure. The swept wings and pylon-mounted jet engines underneath the wings were both novel at the time. The legacy of success of the B-52 is a testament to the merits of its configuration. Every major transport aircraft has essentially modeled itself after the B-52. Table 1 provides an overview of the specifications of the B-52B, the first production model of the B-52 used extensively by the Air Force.

Table 1. B-52B Specification Data Overview [6]

B-52B	
Power Plants	Eight Pratt & Whitney J57-P-1WA turbojet engines, each rated at 10,000 lbs of thrust dry and 11,000 lbs of thrust with water injection
Dimensions	Length 156 feet 6.9 inches; span 185 feet; height 48 feet 3.6 inches; wing area 4000 square feet
Weights	Empty 164,081 lbs; combat 272,000 lbs; maximum take-off 420,000lbs
Defensive Armament	Two 20mm M24A1 cannons, with 400 rounds each or four 0.50 caliber M-3 machine guns, with 600 rounds each
Offensive Payload	43,000 lbs
Performance	Maximum speed at optimum altitude 546 kts at 19,800ft; service ceiling at combat weight 47,300ft; combat radius 3110 nautical miles; take-off ground run 8200ft

6.2. Performance

The performance information for the B-52A is quite limited, because only two were built and production progressed almost immediately to the B-52B. The performance data available for the B-52A includes a maximum level speed of approximately 449 mph and a range of greater than 10,000 miles. Table 2 contains more detailed performance information for the B-52B. The preliminary design data for the B-52 from the 1948 proposal provides more detailed estimates of performance. This data is represented in Figure 8–Figure 16.[12].

Table 2. B-52B Performance Specifications [6]

Maximum Speed	630 mph at 19,800 ft 598 mph at 35,000 ft 571 mph at 45,750 ft
Cruising Speed	523 mph
Service Ceiling	47,300 ft at combat weight
Combat Radius	3,590 miles with 10,000 lb bomb load
Ferry Range	7,343 miles
T/O Ground Run	8,200 ft 10,500 ft over a 50 ft obstacle

Figure 8 – Figure 11 depict the various mission profiles for the B-52 Stratofortress. The refueled mission can fly a further combat radius, but must take an extra half hour to refuel before the bomb is dropped. This idea is echoed in the range versus landing weight graph, which illustrates how longer-range missions will exhibit a smaller landing weight, because of the additional fuel burn. This preliminary design data helped the engineers decide on a feasible landing weight that would maximize range, approximately 155,000 pounds. In the same respect, the gross weight of the B-52 increases as the range increases, as seen in Figure 12. As the range increases, so does the fuel consumption. Therefore, the aircraft must carry more fuel, which increases the weight of the aircraft. Figure 13 highlights the performance available to the B-52 in terms of altitude and flight speed for different aircraft weights.

It is interesting to note that the B-52 was one of the first US aircraft in which the aerodynamicists modeled the effects of drag on the aircraft flying at transonic Mach numbers. The drag rise characteristics chart in Figure 14 was one of the first to illustrate this concept. As the aircraft approaches the speed of sound, the drag coefficient increases suddenly and significantly. These characteristics of drag are also echoed in Figure 15, which is a drag polar of the same data.

The final performance graph, Figure 16, depict the take-off length of the B-52 as a function of the aircraft's gross weight.

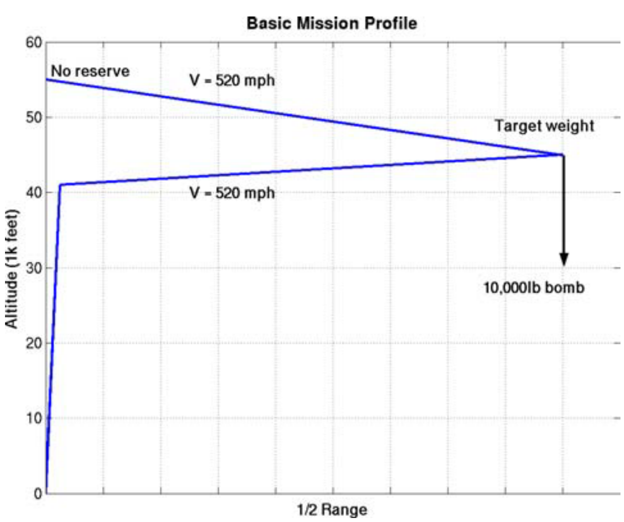


Figure 8. Basic Mission Profile [12]

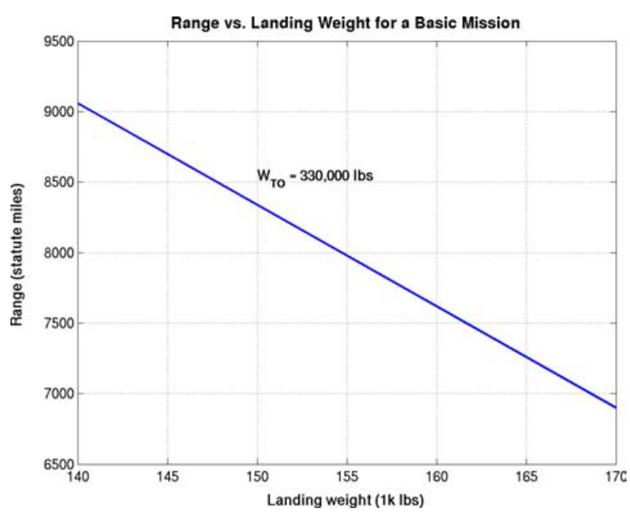


Figure 9. Range vs. Landing Weight, Basic Mission [12]

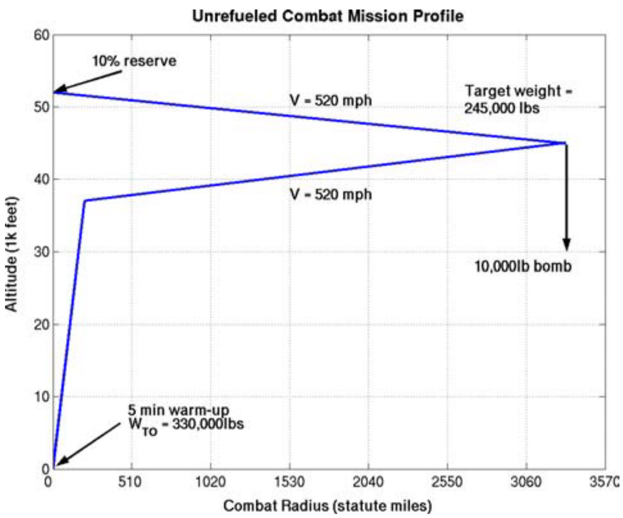


Figure 10. Unrefueled Combat Mission [12]

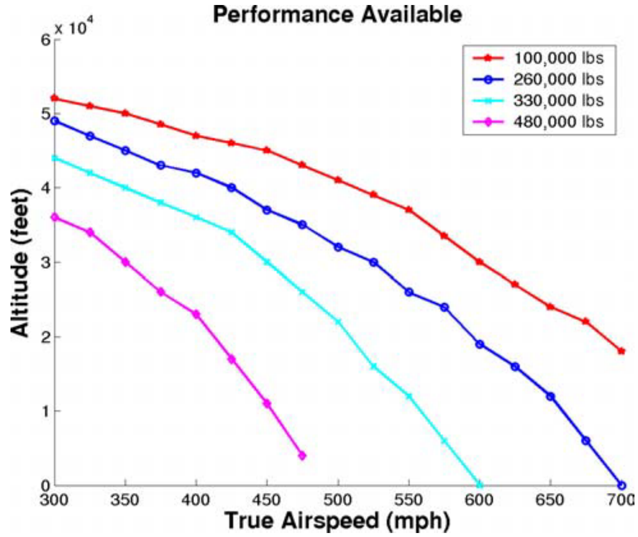


Figure 13. Available Performance [12]

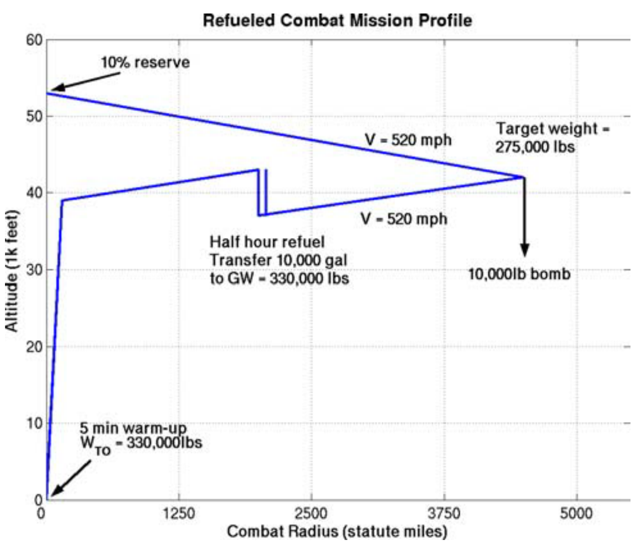


Figure 11. Refueled Combat Mission [12]

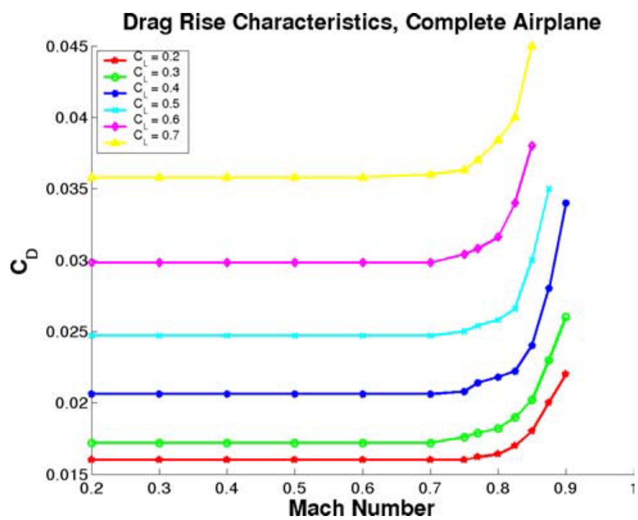


Figure 14. Drag Rise Characteristics [12]

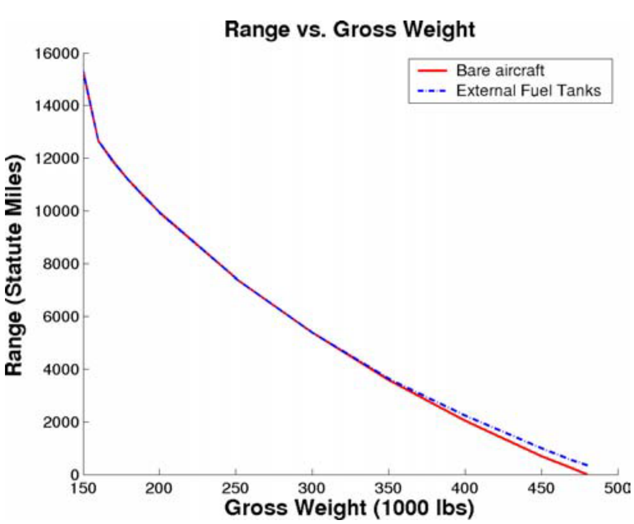


Figure 12. Range vs. Gross Takeoff Weight [12]

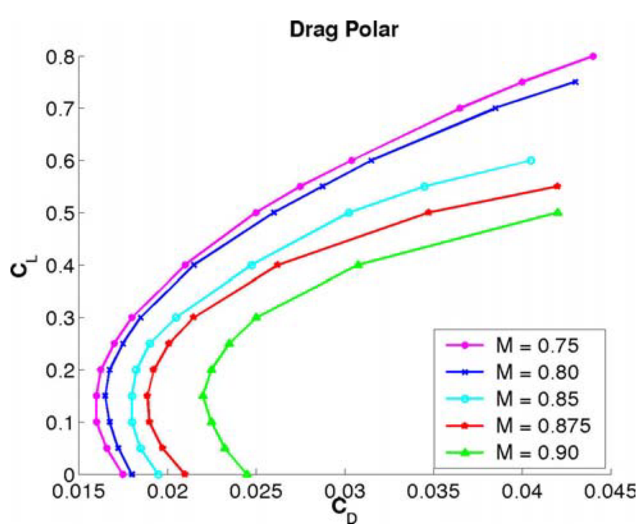


Figure 15. Drag Polar [12]

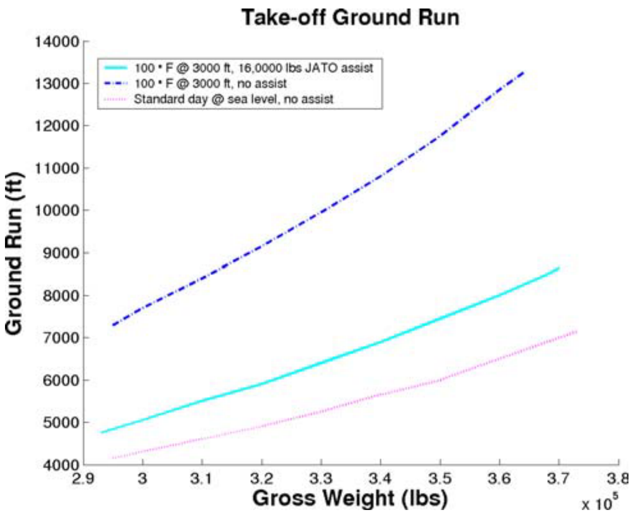


Figure 16. Take-Off Ground Roll [12]

6.3. Major Subsystems

Over 5000 subcontractor firms made contributions at some stage of the program for the first production model of the B-52 [6]. The contribution of subcontractors peaked at just below 57% of the weight during the course of the B-52D production run. Despite the many different locations of origin, it seemed that there were no major difficulties encountered in the assembly process. Table 3 lists the major subcontractors and their responsibilities.

Table 3. Major Subcontractors and their Responsibilities [6]

Subcontractor	Responsibility
Goodyear	Fuselage fuel cells and side panel assemblies, fuel decks and panels, wing stub structure, wing fuel cells
Firestone	Wing fuel cells (with Goodyear)
Aeronca	Bomb bay doors and panels, wheel well doors, rudder, elevators, ailerons and spoilers
Fairchild	Outer wing sections, top panel assemblies, fin and outrigger units, rear fuselage sections
Temco	Rear fuselage sections (with Fairchild)
Cessna	Horizontal tail surfaces
Rohr	Aft fuselage and gunners compartment, flap tracks, auxiliary fuel tanks and engine pylon struts and Nacelles
A O Smith	Landing gear bulkheads and main landing gear units
Twin-Coach	Flaps
Zenith Plastics	Wing tips

6.3.1. Structure

The choice of structural material was made primarily on the basis of weight. The material used was to be the lightest material that satisfactorily met the requirement of each application considered. In applications where aluminum alloys could be used, 75ST (Al 7075) or 24ST (Al 2024) alloys were the standard materials for extrusions and sheet, and 14ST (Al 2014) and 75ST for forging blocks. Magnesium alloy sheet, extrusion, forgings, and castings were used for primary structures if a weight saving resulted. In applications where steel was required, the alloys used were AISI 4130, 4135, 4140, certain corrosion-resistant steel alloys and plain carbon steels. Figure 17 shows the primary structural members of the B-52.

Because of its high strength-to-weight ratio, magnesium was primarily chosen for secondary structures such as wing leading and trailing edges. However, the choice of bonded magnesium trailing edge structures was quickly shown to be unsatisfactory for the sonic fatigue environment of the water assist take-off of the early model turbojet engines. While no fleet-wide modifications were required, the magnesium structures were gradually replaced with aluminum.

Major structural modifications were required to satisfy the long-term structural life objective of the B-52 fleet over the years in service. Structural modifications have included changes in section properties with corresponding reduction in basic stress levels, and material substitutions to increase strength and fatigue properties. Advances in airplane design and material development have also allowed for more suitable material selections.

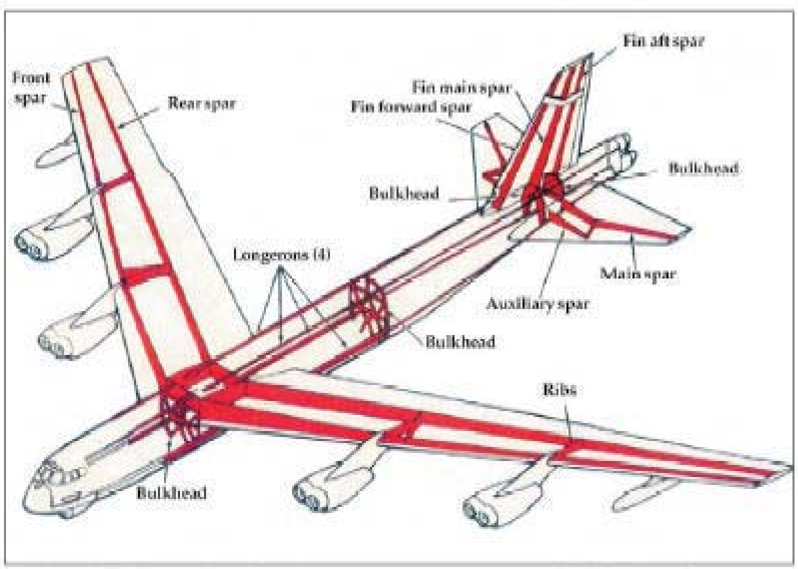


Figure 17. Primary Structural Members of the B-52 [38]

6.3.1.1 Wings

Due to scheduling constraints, the Boeing aerodynamicists did not have adequate time to design the B-47 wing [11]. This wing was simply rectangular and swept back to 35 degrees. Not enough consideration was given to the airfoil cross-section or taper ratio. The wings were also too thin and could not carry any fuel

Boeing engineers applied lessons learned from work with swept wings on the B-47 to improve the wing design for the B-52. The wings on the B-52 had a 185-ft. wingspan with a 35 degree sweep angle and incorporated variable airfoil cross-sections, a tapered airfoil from root to tip, and increased root wing thickness over the B-47. The wing structure had a thickness ratio of 16.2% on the centerline of the fuselage. This dropped to 10.3% at 25% of the span, 9.4% at 57% of the span and 8.0% at the tip. The airfoil was modified from a NACA 64 series at the root to a 66 series at the tip. The much thicker wing root section meant two immediate advantages. First, it allowed for a much lighter construction and thus a reduction in overall weight. Second, fuel could be stored in the wing, which allowed for span loading that led to a structural weight reduction. Because the wing was so thin, the maximum wing tip up to wing tip down deflection was 32 ft. The 4,000 square ft wing area and aspect ratio of 8.55 of the B-52B enhanced the lift capabilities of the aircraft and thus contributed to its long-range performance. The wings are set at an angle of incidence of six degrees, necessary because the bicycle landing gear configuration did not allow the B-52 to rotate on takeoff. The top, bottom and font views of the B-52 wing are shown in Figure 17, Figure 19 and Figure 20 respectively.

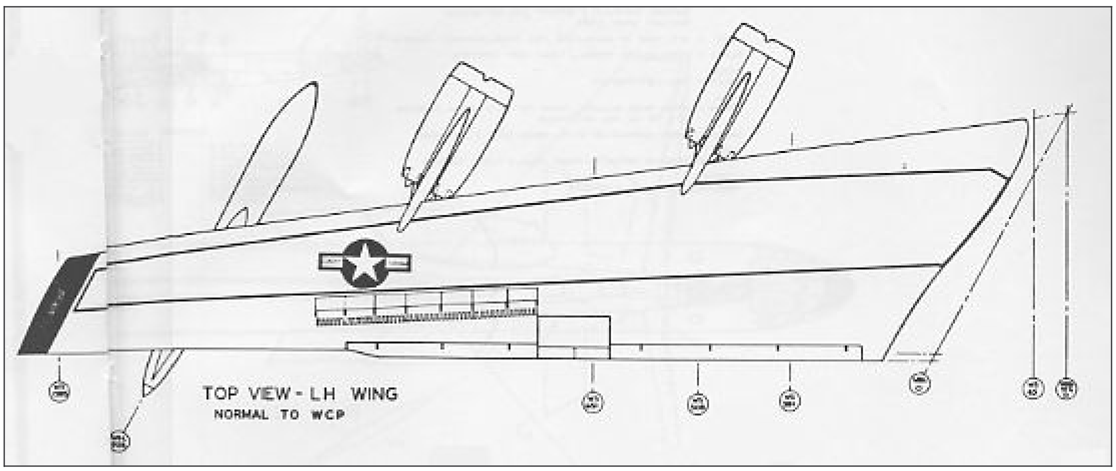


Figure 18. Top View of Wing [4]

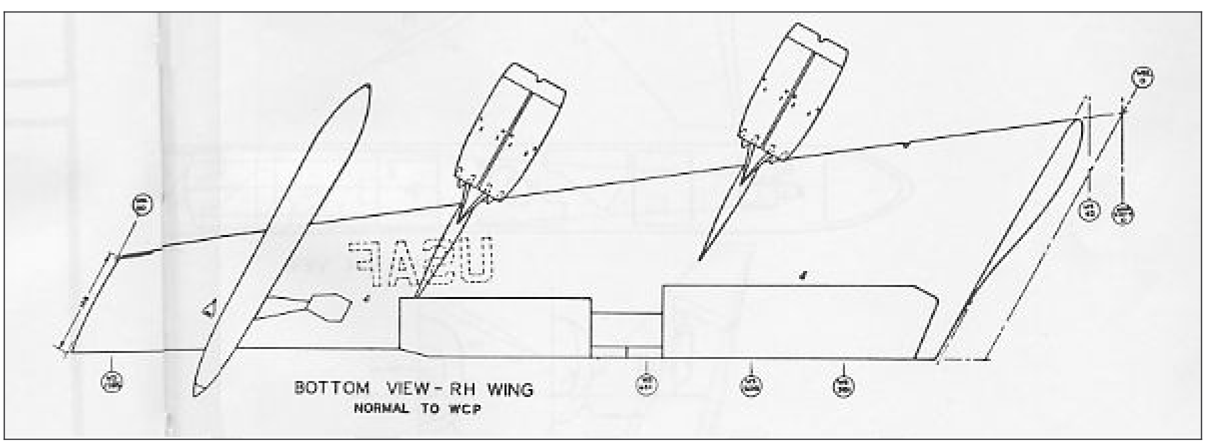


Figure 19. Bottom View of Wing [4]

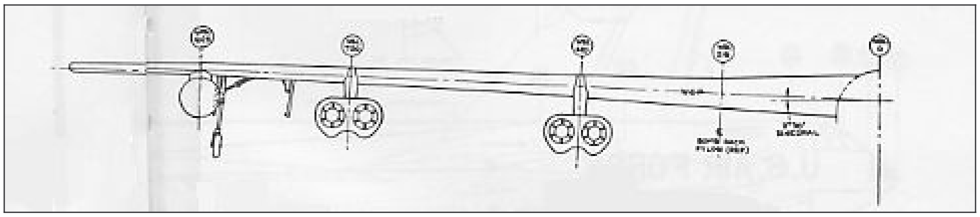


Figure 20. Front View of Wing [4]

In the B-52G there was a significant change in the wing design. The redesigned wing was based upon integral tank construction in which the wing was one huge fuel tank and served to increase range because of increased fuel capacity. However this resulted in a need for stronger materials. Al 7178 was selected for the construction of the new wing. The stronger alloy contributed to the longer range but the higher design stresses would result in a reduction in life. Analysis from an accident in 1961 led to the conclusion that the alloy was not appropriate for the fatigue environment of the new low-level missions of the B-52. It was decided to replace the wing upper surfaces with Al 7075 alloy and lower surfaces with Al 2024 lower skin and 7075 lower skin stiffeners. Cyclic tests showed that the redesigned wing easily achieved the design goal of 12,000 hours. The inside of the wing structure, with aluminum ribs, is shown in Figure 21.

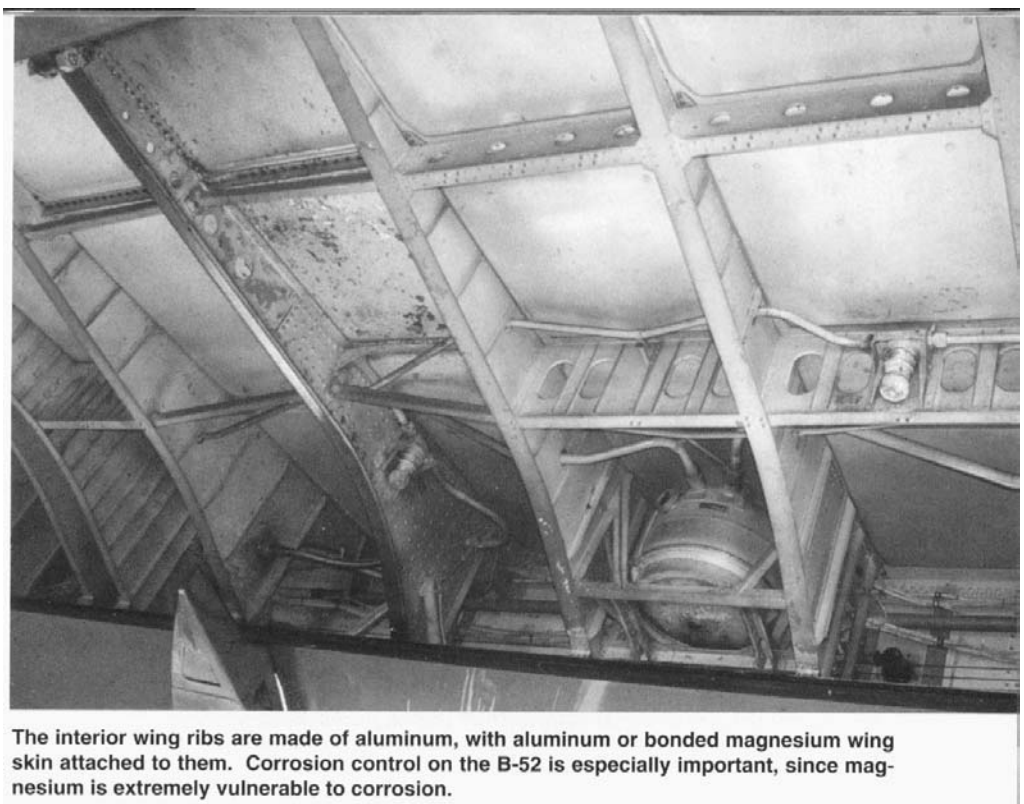


Figure 21. B-52 Internal Wing Structure [29]

6.3.2. Propulsion System

The engines of the B-52B/RB-52B were initially the Pratt and Whitney J57-P-1W, -1WA or -1WB turbojets rated at 10,000 lbs of thrust dry and 11,000 lbs of thrust with water injection.

About half of the B-52B/RB-52Bs were delivered with these engines. The thrust specific fuel consumption (TSFC) of these engines is 0.8 lb/lb/hr. There were problems encountered with the water injection and efforts were made to correct them. All these efforts were expected to lead to the J57-P-29W engine with titanium compressor blades. However, in the end, steel blades were used in the J57-P-29W and J57-P-29WA engines and installed in the bulk of the remaining B-52B/RB-52Bs because of problems with manufacturing the titanium blades. The J57-P-29W engine was rated at 10,500 lbs thrust dry and 11,000 lbs thrust wet. The J57-P-29WA engine had twice the water flow rate as the J-57-P-29W, and had 12,100 lbs thrust wet rating. The problems with the titanium blades were finally overcome in the summer of 1956, which led to the J57-P-19W version, which was installed in the final five aircraft delivered. [39]

The J57 production engine was the world's first jet engine to develop 10,000 lbs. thrust. This engine evolved from the T45 turboprop engine designed for the XB-52 program. Because the advances in the B-52 design dictated larger power requirements, the turboprop concept was discarded and the J57 turbojet was developed. The J57 featured a dual-rotor axial-flow compressor. This allowed for low fuel consumption over a wide operating range and improved the sluggish acceleration previously characteristic of jet engines.

The J57 in Figure 22 is a YJ57-P-3, the first series to go into production. It is rated at 8,700 lbs thrust, and it served as the prototype for the higher-powered engines later used in B-52s. This was the sixteenth of the 95 P-3 engines built and was used in XB-52 testing.

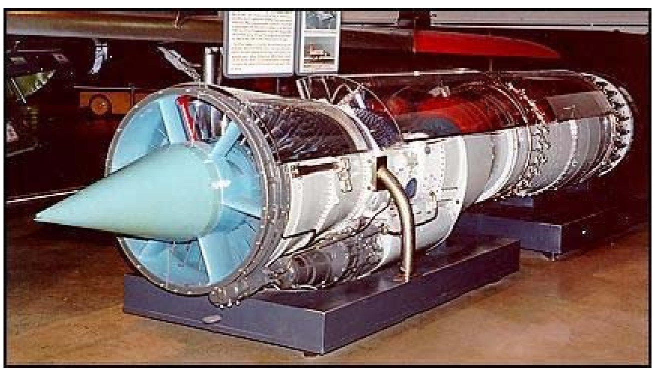


Figure 22. YJ57-P-3 Engine [31]

The nacelles were pod mounted and these were placed so as not to add to the drag rise at high Mach numbers. It also served as load alleviation and helped to reduce the stall. The struts of the nacelles were adjusted to avoid the possibility of flutter.

The J57 led to the larger J75 and to the re-fanned TF33, which is used on the B-52H. The TF33 is shown in Figure 21.

Figure 23. Pratt and Whitney TF33 turbofan used on the B-52H [29]

6.3.2.1 Starter System

Each engine is equipped with a turbine driven starter. The starter turbine is equipped for two types of operation. Either low pressure bleed air is obtained from a ground source or from a running engine through the bleed air system, or a solid propellant cartridge is burned to produce high pressure air. The starter operation is similar for both methods, except the high pressure bleed air is much hotter than the low pressure bleed air. Each starter unit consists of a turbine, gear train, overrunning clutch with a speed sensor, and an overspeed disengagement mechanism. Once engine rpm exceeds the starter rpm, the overrunning clutch disengages to prevent the starter turbine from running overspeed. If the clutch fails, the overspeed disengagement mechanism isolates the turbine from the gear train. Attached to the starter turbine is an aerodynamic brake which prevents the turbine from running overspeed.

The primary purpose for the cartridge starting system is to allow the B-52 to operate where ground services, including air and electrical power, are not available. For this reason, each B-52 carries eight spare cartridges. All eight engines can be started simultaneously using cartridges and can also be started from a single battery if necessary. [27]

6.3.2.2 Intake and Compressor

The J57 family of engines is of the two-shaft turbojet type. The intake is annular, with radial struts supporting the centre housing front main bearing, with fixed inlet guide vanes. The compressor bleed air provided anti-icing.

A nine-stage axial-flow low pressure (LP) compressor is located on the inner of two concentric shafts. The seven-stage axial-flow high pressure (HP) compressor is located on the outer hollow shaft. The shaft runs on roller bearings fore and aft (thrust) and is splined at the rear end to the LP turbine shaft. The rotor blades are made up of nine steel discs, and blades are all steel. The pressure ratio of the HP compressor is 12.5 with a mass flow of 200 lb/s. [39]

6.3.2.3 Combustion Chamber and Turbine

The combustion chamber of made out of an outer annular steel casing enclosing eight alloy interconnected flame tubes, and has two igniter plugs. Combustion and cooling air are introduced via the central tube as well as through the outer walls.

The engine consists of single-stage high-pressure and two-stage low-pressure turbines in tandem on concentric drive shafts, the outer shaft on the a ball-bearing forward of the HP turbine wheel and the inner on the a ball-bearing aft of the LP turbine wheels. The guide and stator vanes, turbine wheels and blades and the casing are all made of steel. [39]

6.3.2.4 Oil System

The oil system is a closed system with a main gear-type pressure pump that feeds bearings through calibrated orifices. Scavenger pumps return oil through fuel-cooled hear exchanger to the engine tank. The oil specification is Synthetic Turbo Oil (ETQ-15), or MIL-L-7808. [39]

6.3.3. Fuel System

The fuel system of the B-52 employs four main integral wing tanks and eight auxiliary tanks to carry between 35,600 gallons (B52-A) and 48,030 gallons (B-52H) of usable JP-4 fuel. Originally, the fuel tanks were comprised of flexible, self-sealing bladders. A redesigned wing allowed the B-52G and H models to increase internal fuel volume by using built in wing tanks, or a wet wing, instead of the fuel bladders.

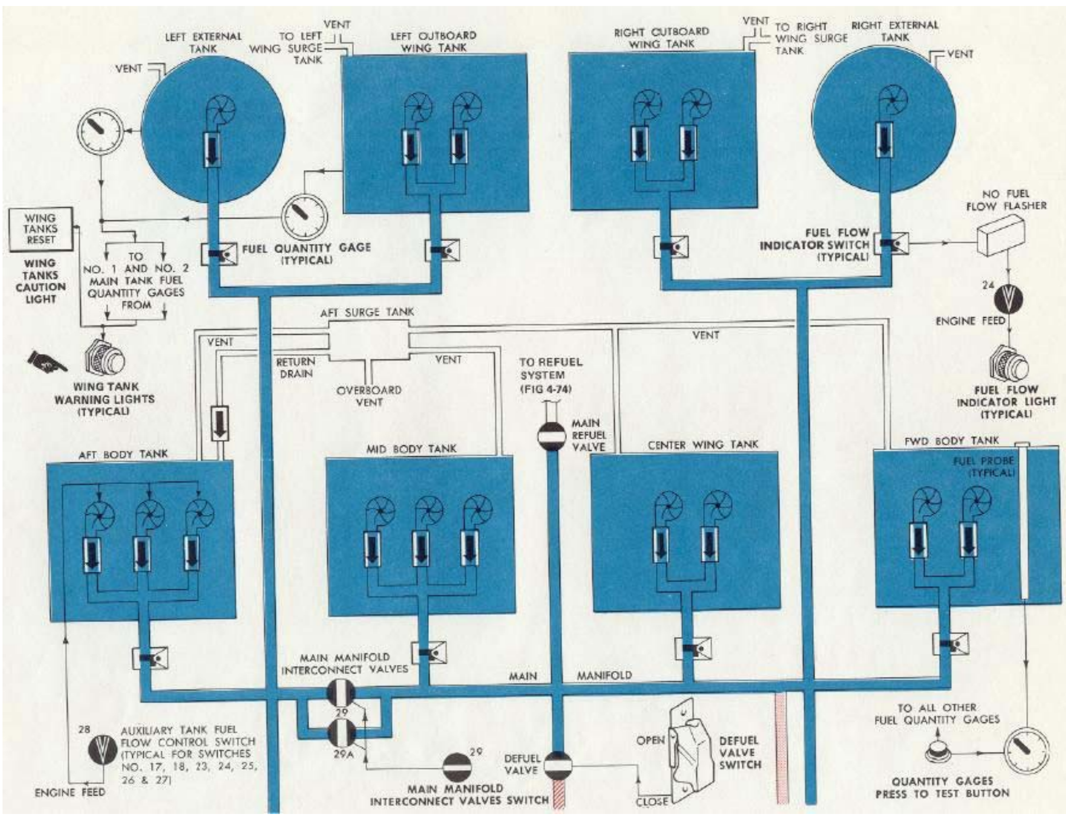
Each main integral wing tank has 4 boost pumps and is designed to provide fuel to two engines. The two outboard wing tanks and the center wing tank are also integral tanks. The other auxiliary tanks include three fuselage tanks: forward, middle, and aft, and two nonjettisonable external wing tanks. The fuel tank capacities of the B-52H are shown in Table 4.

Table 4. Fuel Tank Capacities, B-52H [27]

Tanks	No.	Usable Fuel (Each)		Fully Serviced (Each)	
		Pounds	Gallons	Pounds	Gallons
No. 1 and 4 Main	2	31,843	4,899	31,883	4,905
No. 2 and 3 Main	2	44,259	6,809	44,421	6,834
Mid Body	1	46,410	7,140	45,501	7,154
Forward Body	1	13,319	2,049	13,345	2,053
Aft Body	1	55,192	8,491	55,237	8,498
Outboard Body	2	7,495	1,153	7,540	1,160
Center Wing	1	20,982	3,228	21,060	3,240
External	2	4,550	700	4,583	705
Usable Fuel Totals					
Tanks	**Pounds**	**Gallons**			

No. 1,2,3, and 4 Main	152,204	23,416	• Fully serviced quantities include both trapped and drainable fuel • The tanks will have the quantities shown under conditions of ICAO standard day with fuel density of 6.5 pounds per gallon
Mains, Mid, Forward, and Aft Body	267,125	41,096	
All Tanks	312,197	48,030	

During flight, the main manifold is used to bring fuel from the auxiliary tanks to the engines, but it is used to direct fuel during refueling and can also be used to transfer fuel from auxiliary tanks to the main tanks. Auxiliary fuel can be used to run the engines by pressure override, because the boost pumps in the auxiliary tanks have higher capacity than those in the main tanks. The fuel system architecture of the B-52H is shown in Figure 24.



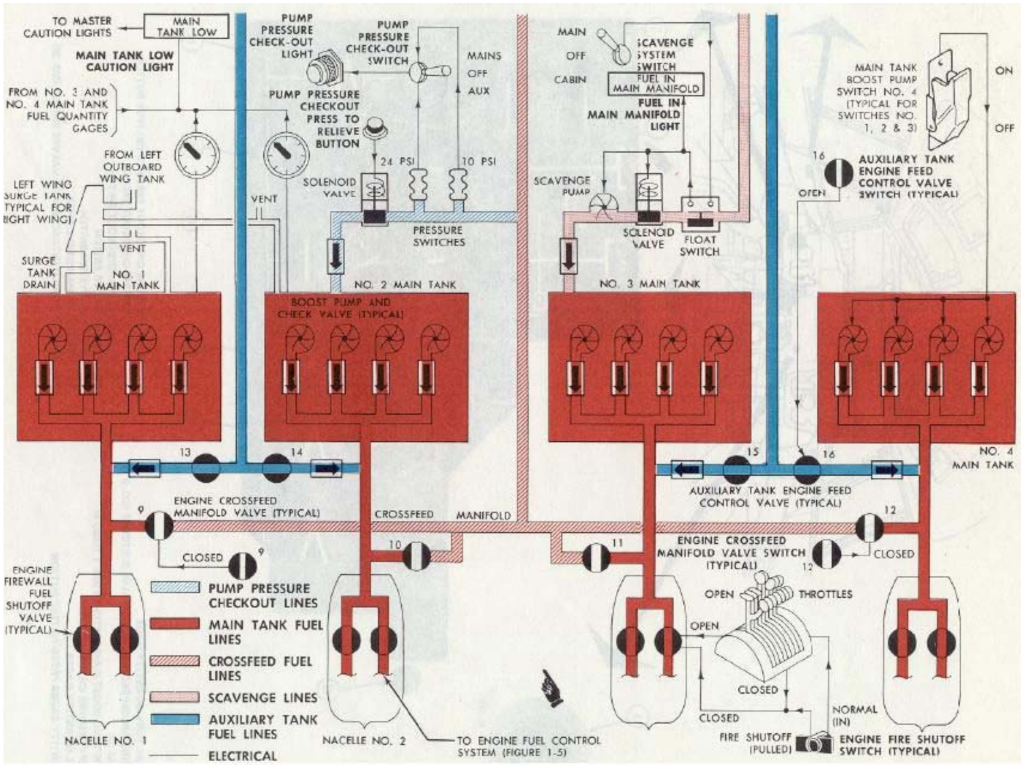


Figure 24. B-52H Fuel System [27]

Body fuel tanks are vented to a surge tank aft of the aft fuselage tank. The surge tank vents to the outside on the underside of the fuselage, aft of the rear wheel well. Each wing tank has a vent line, and the three vent lines on each wing connect to a wing surge tank in each wingtip. Each external tank is vented on the aft outboard side of the tank strut. [27]

6.3.3.1 Mid-Air Refueling

The B-52 is equipped for mid-air refueling from a boom-type tanker aircraft such as the KC-135 Stratotanker. An air-refueling slipway and receptacle is located on top of the fuselage, just aft of the cockpit. The refueling system, shown in Figure 25, is an extension of the fuel system, and can be used for both airborne and ground based refueling.

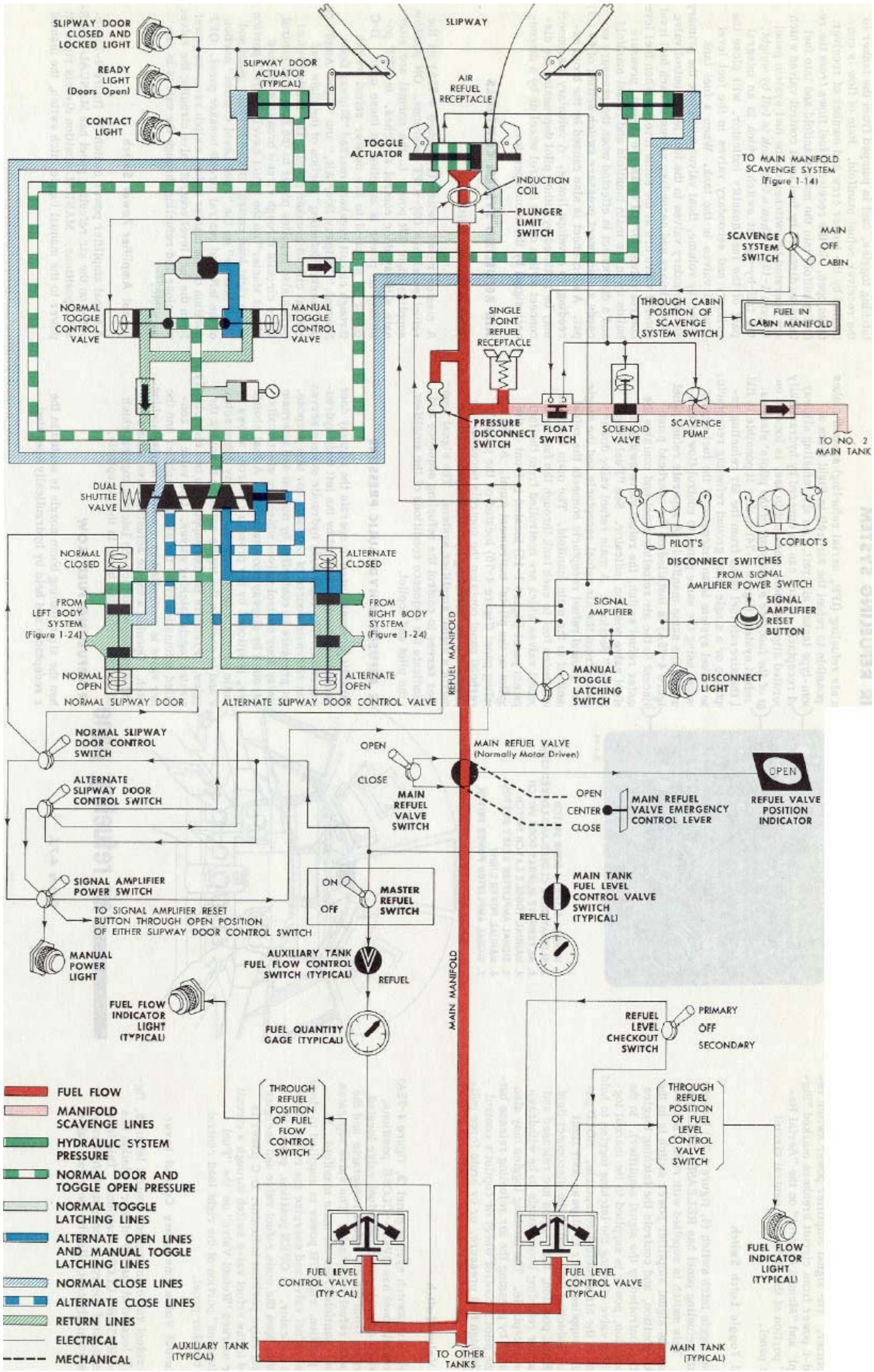


Figure 25. B-52H Refueling System [27]