NASA
S2-02
254517

HISTORICAL REVIEW OF MISSILE AERODYNAMIC DEVELOPMENTS

M. Leroy Spearman
Senior Technical Specialist
NASA Langley Research Center
Hampton, VA 23665-5225

Abstract

The earliest form of a missile was probably a rock, which, when hurled through the air, would follow a curved ballistic path. This paper will attempt to trace the development of missiles from early history up to about 1970. Early unpowered missiles beyond the rock include the spear, the bow and arrow, the gun and bullet, and the cannon and projectile. Combining gunpowder with projectiles resulted in the first powered missiles. In the early 1900's, the development of guided missiles was begun. Significant advances in missile technology were made by German scientists during World War II. The dispersion of these advances to other countries following the war resulted in accelerating the development of guided missiles. In the late 1940's and early 1950's there was a proliferation in the development of missile systems in many countries. These developments were based primarily on experimental work and on relatively crude analytical techniques. This paper will consider some of the missile systems that were developed up to about 1970; on some of the problems encountered; on the development of an experimental data base for use with missiles; and on early efforts to develop analytical methods applicable to missiles.

Early History

The earliest form of a missile was probably a stone which, when hurled through the air, would follow a curved ballistic path from the launching point to the impact point. The use of such a missile is described in the Holy Bible where the slaying of Goliath by David is described (I Samuel 17;49-50). David prevailed with a sling and a stone and there was no sword in the hand of David. This event represents a form of a standoff engagement (as opposed to hand-to-hand combat) in which a mobile launcher was used -- David, and his arm and sling; a ballistic missile — the stone; and initial guidance -- David's eyes for tracking, his muscle for propulsion, his brain for coordinating, and the power of God. Other unpowered and unguided ballistic missile standoff weapons include the spear, the bow and arrow, the gun and bullet, the hand grenade, and so on.

Some historians have recorded the use of incendiary materials in combination with early missiles to form fire pots, fire lances, and flaming arrows. Greek soldiers used such devices, known as "Greek fire," which was reported to have caused utter dismay to Arab attackers at Constantinople in the 7th century. The Chinese were reported to have flame-throwing devices by the 10th century that consisted of bamboo tubes filled with explosive powder. This may have been the first use of solid-propellant rockets. Details of these rockets reached Europe by the 11th century and were used in the war between Venice and Genoa in the 14th century where a previously impregnable defense tower was destroyed by a rocket. The use of gunpowder and the application to rocket-type devices was the subject of many investigators including the German, Albertus Magnus, and the Englishman, Roger Bacon, in the 13th century. During the 15th century, Leonardo da Vinci prepared drawings of rockets and a Venetian, Giovanni da Fontana, described rocket-powered torpedoes that could skip along just above the water surface or even go below the surface on the way to the target. In the 16th century, a German, Conrad Haas, made sketches of multistage rockets in which the first stage consumed itself so that separation of the stages was not necessary. Haas also developed a swept-back guidance fin and, in another instance, sketched a house-like structure on a rocket that might be interpreted as a preconception of a future manned rocket-propelled flight. Rockets were also developed in India where they were used in several wars with the French and with the British before the end of the 18th century. The Indian rockets weighed from about 6 to 12 pounds and, in addition to ballistic flight, could be fired along a nearly horizontal path close to the ground. The Indian rockets were described as being simple, easily transported, inexpensive, easily operated, and readily producible-traits that are desirable today. Although they were not especially accurate, they could be fired in great numbers. In addition to being capable of killing troops, these rockets were especially effective in harassing, in startling troops and horses, and in setting off ammunition carts.

A British army colonel, William Congreve, was quite impressed by the Indian missiles and began experimenting with rockets in the early 1800's. Congreve rockets were stabilized to some extent by the addition of sticks that extended rearward with the required length of the stick depending on the size and weight of the weapon. This type of stabilization is still in use today on display skyrockets. Congreve also recognized that the continual change in weight and center of gravity in flight must be taken into account. Congreve rockets also contained gun powder mixed with metallic particles that resulted in explosion upon impact. Congreve recognized some of the fundamental features of rocket systems in proclaiming "the very essence and spirit of the rocket system is the facility of firing a great number of rounds in a short time, or even instantaneously, with small means" and "the projectile force is exerted without reaction upon the point from which it is discharged"--giving rise to ship-mounted launch platforms and eventually to air-launching and man launching. Ship-launched Congreve rockets were used by the British in the Napoleonic wars and the city of Copenhagen was essentially destroyed in 1807 during a three-day siege in which from 25,000 to 45,000 incendiary rockets were fired.

One solution to eliminate the stick and improve the accuracy of the rocket was found to be through spinning the rocket in the manner of a cannon-launched projectile. William Hale, an Englishman, addressed himself to this problem in 1839 and developed a stickless spinning rocket that was given a rotary motion by directing part of the propellant exhaust through slanted exits. He received a British patent on the rotary rocket in 1844. He also received a U.S. patent for his spin-stabilized rocket and the process was sold to the U.S. Army Ordinance Department in 1846.

Near the end of the 19th century, a Swedish engineer, Wilhelm Unge, became interested in the rockets of Congreve and Hale. With the financial aid of millionaire Alfred Nobel, the inventor of dynamite, Unge began to explore means of improving the performance and accuracy of rockets. He did the first work on range extension through the use of cannon-launch for initial first-stage velocity. Drawing on the work of Nobel in double-based smokeless powder, Unge developed a propellant that had controlled burning; higher exhaust velocity; a stabilizer to increase storage life; a plasticizer to increase workability; and a binder to give greater mechanical strength to the grain. A rocket using such a propellant was flown by Unge in 1896. Unge also developed a spin-stabilized rocket in which the spin was produced by a spinning launcher so that angled thrust was eliminated. By the turn of the century, these rockets were reaching ranges of up to 5 miles with accuracy that competed with rifled artillery. Unge saw possible applications of rockets for surface-to-air (anti-balloon), ship-to-ship, and ship-to-shore. The Swedish military was not interested, and in 1908, Unge's patents were bought by Krupp in Germany.

Twentieth Century

Pre-World War I Era

In 1903, a Russian schoolteacher, Konstantin Tsiolkovsky, published a paper on space travel in which he advocated the use of liquid-fueled rockets for propulsion. Tsiolkovsky's work revealed the principle of mass ratio and that the performance capability of a rocket was limited regardless of size. His formula suggested that rocket performance could be maximized by using the best fuel for increased exhaust velocity and by reducing the empty weight so that more fuel could be carried. For many years the paper remained in obscurity.

Elsewhere throughout the world, almost no attention was shown in rockets in the early years of the 20th century. In fact, in the 1898 edition of "Dictionnaire Militaire" these words are recorded--"After having enjoyed, for more than half a century, a vogue that often touched of exaggeration, the war rocket today is almost completely abandoned. It is nevertheless necessary to treat the subject not only for historical reasons but in the hope--not yet abandoned by everyone--that in the future the device will be resurrected because of its simplicity and ease of deployment."

World War I Era

With the outbreak of World War I (1914-1918), some attention was once again paid to the rocket. Rockets were used to launch parachute flares and to transport messages from one location to another. The French also adapted the stick-guided powered rocket for tube-launching from airplanes engaged in anti-balloon operations. The process was somewhat successful when the rockets were fired in barrages according to set procedures. One quote from the procedure that may be of interest is as follows--"Extremely Important Remark: The departure of the rockets does not follow immediately the touch of the electrical button, and the delay varies from one rocket to another. Therefore, it is absolutely necessary to continue to hold the sight and the descent until the discharge of the last rocket (about one second). If one redresses or turns too quickly, the last rockets will go in different directions and give a dispersion that is altogether inadmissible."

A completely different path in guided flying weapons began just before 1914 when British Professor A. M. Low started work on a top secret project called a Flying Target, or F.T. The F.T. was a small, radio-controlled airplane designed to combat German Zepplins as a form of a flying bomb. One version was also to be flown against ground targets with guidance from a parent airplane as a true air-to-surface guided weapon. Several types were built by Low and his associates; by De Havilland; by Sopwith; and by the Royal Aircraft Factory. The R.A.F. produced 6 graceful monoplanes with aerials fitted chord-wise on the wing and on the aft body. The weapons were launched from a lorry with a compressed air catapult which, in itself, was an idea ahead of its time. Although flight experiments were successful, no operational use was ever made of the weapon. Flight experiments continued and, in 1921, several of the monoplane weapons were flown from the aircraft carrier, H.M.S. Argus with takeoff under their own power from a trolley undercarriage. Low went on to build radio-controlled rockets in 1917 and these appear to be true ancestors of similar devices that did not emerge until World War II and were claimed as the invention of others.

Another interesting development during World War I was the Kettering Aerial Torpedo or "Bug." The Bug was invented by the American, Charles F. Kettering and built by the Dayton-Wright Airplane Company in 1918 for the U.S. Army Signal Corps. The unmanned Bug was a propellor-driven biplane with a speed of 120 mph and a range of 75 miles. Takeoff was accomplished under power from a dolly running on a track. Guidance to the target was provided by a system of onboard preset vacuum-pneumatic and electrical controls which, after a predetermined time, would shut off the engine, release the wings, and cause the Bug to fall to the target where its 180 pounds of explosive was detonated on impact. Tests were successful but the war ended before the Bug could enter combat. About 50 Bugs were built and some testing continued but, in the early 1920's, a scarcity of funds resulted in cancellation of the program and the progress of guided missiles was destined to wait for several more years.

Post World War I Era

The basis for modern rocketry was being laid independently in the early 1920's by Hermann Oberth, a Hungarian-German, and Robert H. Goddard, an American, who were both experimenting with liquid-fueled rockets. Oberth's book, "The Rocket Into Interplanetary Space" published in 1923, provided the impetus for experimental rocket work in Germany that lead to the formation of the German Society of Space Travel in July 1927. This group, known as the German Rocket Society, grew to a worldwide membership of more than a 1000 by 1930, including a young engineering student, Wernher von Braun, who was to become quite prominent in the field of rocketry in years to come. Oberth successfully fired a liquid-fueled rocket in July 1930.

In the U.S., Goddard prepared a paper in 1919 entitled "A Method of Reaching Extreme Altitudes," in which he alluded to the possibility of reaching the moon. Goddard, having experienced some problems with grain imperfections in solid rockets, began experimenting with liquid rockets about 1920. By 1935 his rockets had reached altitudes of 75,000 feet and speeds of over 700 mph and he was generally recognized as a world leader in rocket science. American enthusiasts formed the American Interplanetary Society in 1930, with the name later being changed to the American Rocket Society.

In the U.S.S.R. the early work of Tsiolokvsky was subsequently followed by such contributors to rocketry as Tsander and Kondratyuk. The Leningrad Dynamic Laboratory was formed in 1928 and built a series of monopropellant and bipropellant liquid rockets in the early 1930's.

A German, Johannes Winkler, who experimented with both solid and liquid rockets was successful in launching the first liquid-fuel rocket in Europe in March 1931. Another German, Rudolf Nebel, who had been an assistant to Oberth, headed a rocket study team formed in 1930 that included von Braun. The group developed a water-cooled liquid-fueled rocket motor that was test flown nose-mounted and towing fuel tanks up by the fuel lines. This work attracted much attention and the German army became especially interested since it appeared that rocketry offered a legal approach to a long-range weapon that would not specifically violate the restrictions placed on the range of classical artillery. The army supported work was conducted in great secrecy at the Army artillery range at the Kummersdorf Proving Ground. The Army brought von Braun to Kummersdorf under a research grant that permitted him to earn his doctorate while working on secret Army projects involving the combustion processes in a liquid-propellant rocket motor. At the age of 20, von Braun became chief of the experiment station. In late 1933 the group under Von Braun successfully tested a 660-pound thrust motor that was regeneratively cooled by its own alcohol flow. In 1934 the group successfully launched an A-2 rocket that was designed with a liquid motor and a gyroscope stabilizer located near the center of gravity.

World War II Era

Adolph Hitler came into power in Germany in 1933 and, having become interested in rockets as weapons in 1936, initiated the construction of a huge Army/Luftwaffe rocket research center at Peenemunde on the Baltic Sea. In April 1937, the Kummersdorf group moved in and von Braun, at the age of 25, was named the technical director of the Army complex. Advanced rocket developments continued beyond the A-2 with both failures and successes. Wind tunnels, including supersonic tunnels, as well as an elaborate guidance and control simulator were used extensively in the developments to answer the many unprecedented questions related to flight at speeds up to five times the speed of sound. The A-4 rocket was developed in response to an Ordinance Department requirement for a field weapon with a large warhead and a range substantially greater than that of artillery. Calculations indicated a rocket about 46-feet long, 5.2 feet in diameter, a launch weight of 26,000 pounds, a warhead of 2,200 pounds, a thrust level of 55,000 pounds, and a range of 270 miles. Thus the A-4, which was later to be known as the V-2 vengeance weapon and the forerunner of future ballistic missiles, came into being. The third launch on October 3, 1942, was a success and the rocket, after accelerating for 63 seconds, reached a Mach number of about 4.7, an altitude of 275,000 feet (52 miles), and a range of 116 miles. For the first time, a man-made object had left the atmosphere and reached the fringes of outer space. The first operational V-2 weapon was fired against London on September 7, 1944, and over the next year about 3,600 V-2's were used against London and Antwerp, Belgium.

A noteworthy development by the Luftwaffe at Peenemunde was a winged subsonic cruise missile powered by an air-breathing pulse-jet engine. This missile, which was to become known as the V-1 vengeance weapon, was catapult-launched, was controlled in flight by inertial guidance, and used a predetermined engine shutoff time when the weapon would dive with its 1870 pound warhead. The first V-1 was launched against London on June 12, 1944 and by March 1945 a total of about 9000 V-1's had been launched against London and another 12,000 against Belgium. The subsonic V-1 was more vulnerable than the V-2 but it was also less expensive and both weapons created considerable havoc.

Another development at Peenemunde was the A-9 which was a winged version of the V-2 intended to increase the range with an aerodynamic glide to follow engine burnout. A successful A-9 was flown to a Mach number of about 4 during the winter of 1944-45. Further plans for the A-9 included a manned version with a pressurized cockpit and a tricycle landing gear that was to have a range of about 400 miles at twice the speed of sound.

One other development of interest was the Wasserfall surface-to-air guided missile that the German's wanted in order to counter the growing Allied air threat in the winter of 1942-43. The requirements were simply stated: surface launch from zero velocity; a maximum velocity of about three times the speed of sound at an altitude of about 65,000 feet; to be controlled from the ground to a distance of about 31 miles or to be equipped with a target-seeking device; and to be able to overtake and out-maneuver enemy airplanes. Liberal use was made of the basic design features of the A-4 since that was the only vehicle that had negotiated the required speed and altitude range. Studies indicated a body diameter of 90 cm (35.43 in.) and a length of 810 cm (26.6 ft.). The maneuver requirements called for additional wind-tunnel testing and the investigation of new characteristics that included the following items:

- The tight turn requirement dictated a load factor of 12 g's which resulted in the use of a cruciform wing and tail arrangement as a means for obtaining rapid response in any radial plane. An annular (ring) wing was investigated in the wind tunnel but was not adopted because of excessively high drag.

- The large speed range required that attention be given to the variation of the center of pressure. Considerable tailoring of the wing and tail planforms was done in the wind tunnel with about 23 wings being studied before the final configuration was selected. The center of gravity variation with fuel consumption was also taken into account.

- The requirement for control over a speed range from zero to M = 3 both with and without power lead to the use of aerodynamic rudder controls. At low speeds after launch, control was maintained with jet rudders made of graphite that were mounted to the inboard end of the rudder shafts. The development of the rudder involved the testing of many shapes with both force and pressure measurements to determine the trade between size and deflection from the standpoint of control effectiveness, control hinge-moment, and trim drag.

- Roll control was studied since it was recognized that roll caused by manufacturing inaccuracies or induced by flow fields developed by extreme flight attitudes would adversely complicate the guidance system. Wing ailerons and differential rudder deflections were both investigated with differential rudder deflection being selected because the effectiveness was good, there was no interference flow field, and no separate actuator was required.

- Interference flow fields were investigated including the effects of panel-to-panel flow and wing-to-tail flow. These studies lead to the inline arrangement rather than interdigitated.

- The effect of the jet plume on drag and damping was investigated using a model with a compressed air jet.

- The investigation included pressure distribution tests and heat transfer tests since the extreme flight conditions were likely to produce problems of structural integrity and would necessitate the protection of the warhead, the tracking system, and an optical fuse.

The Wasserfall missile represents the extent to which the German scientist understood the problems and were able to develop a maneuvering, supersonic, surface-to-air, guided missile system over 4 decades ago. The war ended before the Wasserfall could be placed in service but 44 test flights had been made in which the missile was maneuvered from the ground with a control stick. A fully automatic hookup to an analog computer which developed steering signals from a target-tracking and missile-tracking radar was partially completed and an optical proximity fuse had been developed.

Although the Wasserfall did not become operational during the war, other less sophisticated German missiles did. Guided missile warfare may, in fact, have begun on August 27, 1943, when a German radio-controlled, rocket-powered Henschel HS 293 air-to-surface missile sank the British ship HMS Egret. Henschel work also included wire-control and TV-control; a sea-skimmer; steep-dive missiles and underwater attack missiles; the monoplanar $M = 1.5$ Zitteroschen that may have been the first winged supersonic missile; the Schmetterling HS 117 surface-to-air missile; and the HS 298 monoplanar concept that is thought to be the world's first air-to-air missile.

Other German missile developments included some glide-bomb and glide torpedo types by Blohm and Voss such as the BV 143 and BV 246 which were small airplane-like configurations that explored various guidance and control systems including autopilots, radio, infrared, beam riding, and radar. A German research project, the Feuerlilie, intended to be a surface-to-air missile was also tested extensively during 1941-1944.

U.S. missiles developed during World War II included the GB series of glide bombs that initially were standard 2000-pound bombs fitted with a wing and twin tail booms that supported a horizontal tail and twin vertical tails. Many unguided GB's were launched as ASM's against German targets, generally with poor accuracy. Later modifications to the GB's incorporated guidance changes that included TV, IR, light-contrast, and direct visual with radio. Another type, the BQ series, was designed to be ground-launched as an SSM. These were airplane-like designs and, in some cases, were actually unmanned airplanes that were completely filled with explosives and radio-guided from a mother airplane to the vicinity of the target.

Other U.S. missile programs included the Bat, an Army/Navy antishipping miniature airplane with radar homing that successfully sank many Japanese ships. Another, the Gargoyle, the first missile made by McDonnell, had a 1000-pound warhead, a range of about 5 miles, a speed of 690 mph, and was intended for use as an ASM. Although flying in 1944, the Gargoyle never became operational and remained a research program.

The U.S.S.R. developed a family of solid-propellant, short-range, tactical weapons and made extensive use of them in World War II land battles. Among the better known for their devastating effect was the Katysusha (Stalin's organ pipes) and the KgAT antitank missile.

The British pursued several missile projects during World War II but with little enthusiasm. These projects included the Miles Hoop-la, a propeller driven monoplane built around a 1000-pound bomb for an ASM role; the Brakemine, a beam-riding radio-controlled monoplanar SAM; and the Fairey Stooge, an airplane-like ship-launched SAM. Although these projects showed promise, they were all abandoned.

Post World War II

In the spring of 1945 with the Soviet Second White Army about to occupy Peenemunde, many of the top German scientists there, including von Braun, choose to fall into American hands and moved to Bavaria to await capture. So it was that under the U.S. Operation Paperclip, von Braun and 120 other hand-picked scientists were brought to Ft. Bliss, Texas, by the summer of 1946. Soon they were to resume flight testing at the White Sands Proving Grounds in New Mexico using captured V-2 rockets, 68 of which were launched during a 5-year program.

The USAAF sought proposals in October 1945 for a guided missile development program. One of the successful bidders was Convair, whose proposal, the MX-774, appeared to be a scaled down V-2. There were some innovations, however, such as the use of the outer shell as the wall of the fuel tank (thus saving weight) and the use of gimbaled motors to provide thrust and control (thus eliminating tail fins). Three MX-774's were launched at White Sands in the last half of 1948 from which valuable lessons were learned that helped lead to the selection of Convair in 1951 to begin the development of the first free world ICBM, the Atlas, which first flew a full-range flight in excess of 6000 miles on November 28, 1958.

On February 24, 1949, a two-stage Bumper-Wac (a U.S. Corporal second-stage rocket on a German V-2 first-stage) was launched to an unprecedented altitude of about 250 miles. The U.S. ballistic missile program was beginning to take shape. In 1950, the Paperclip group, augmented by about 400 Americans, was moved from Ft. Bliss to the Redstone Arsenal in Huntsville, Alabama which was perceived as becoming the future home of Army guided missiles.

The German V-2 was also exploited in the U.S.S.R. where a reengineered version, the M-101, with a Soviet rocket motor was placed in production. This work was soon to lead the Soviet's to a position of world leadership in large ICBM's (first being launched in August 1957) and to the booster that placed the world's first satellite, Sputnik, in orbit in October 1957.

Both the U.S. and the U.S.S.R. exploited the German V-1 as a forerunner of monoplanar cruise missiles to come. The U.S. program, called the JB series (for jet-bomb), also included two Northrop flying-wing designs-the JB-1 and the JB-10. The Americanized V-1 was designated the JB-2 and about 330 were built, some of which were sled-launched from Holloman and some were air-launched at Eglin. A Navy ship-launched version of the JB-2 was called the Loon. The U.S.S.R. produced several hundred V-1 types known as the J-1. This was followed by the J-2, powered with a turbojet engine (patterned after a British engine), and a submarine-based version J-3 was also postulated.

U.S. Missile Activity, Late 1940's Through the 1960's

Among the missile development programs in the late 1940's were the following:

- o The Gorgon family of missiles by Martin were begun in 1946 to respond to a Navy desire to develop weapons for the roles of SAM, SSM, ASM, and AAM. The first versions were canard-monoplanes with both jet and rocket types. Later versions were aft tail concepts with an underslung ramjet engine. The project was terminated in 1953.

- o Firebird, started in 1947 by Ryan, was the first post-war AAM to reach the flight test stage in the U.S. The Firebird had interdigitated cruciform wings and tails. Although never produced, the missile was the forerunner of things to come.

- o The Kingfisher, developed in 1948 by McDonnell as a Navy air-launched ASW, had small monoplanar wings, a butterfly tail, and a pulsejet engine.

In the late 1940's and moving into the 1950's and the 1960's, the advent of guided missile technology was such that a tremendous proliferation of missile systems appeared within the services and throughout the industry and academic fields with almost everyone having a missile study or contract of some type. Among the missile systems that appeared in the U.S. during this time period were the following:

- o Bullpup, among the first operational ASM's, was developed by Martin in 1954. Many versions were conceived but the basic concept was the incorporation of standard existing bombs into a roll-stabilized airframe with cruciform, fixed rear wings and cruciform canard controls.

- o Northrop SM-62 Snark, an airplane-like jet-powered intercontinental cruise missile capable of carrying a nuclear warhead for 6300 miles at a Mach number of 0.93. The Snark had a high aspect ratio swept wing and no horizontal tail. The Snark was operational with SAC from 1957 until 1961 when it was deactivated in favor of ballistic missiles.

- o North American SM-64 Navaho, a significant step forward in strategic cruise missiles, was designed to carry a nuclear warhead a distance of 6325 miles at a Mach number of 3.25.

The essential design data required for such an advanced concept were obtained through flight tests of a supersonic research vehicle designated the X-10. The X-10 was powered by two jet engines, was capable of M = 2 flight, was radio controlled, and, with a retractable gear, was recoverable. The resulting Navaho design was a delta wing-canard configuration with twin ramjet engines. Control was provided by the canard for pitch, an all-moving vertical tail for yaw, and pivoting wing-tips for roll. Although many successful flights were made and much was learned about ramjet propulsion, canard configurations, supersonic stability and control, cryogenic fuel, honeycomb structures, and many other items of advanced technology, the program ended with cancellation in July 1957 after being severely criticized by the media as a waste.

- IRBM/ICBM's that came into favor over cruise missiles in this time period were Jupiter, Thor, Atlas, Titan, Minuteman, Polaris, and Poseiden.

- Martin TM-61 Matador, a tactical cruise missile with a highly swept wing, a T-tail, and a single jet engine fed by a lower surface flush inlet. Phased out in 1959.

- Martin TM-76 Mace, a cruise SSM similar to Matador but updated. Operational during the 1960's.

- Boeing CIM-10 Bomarc, an airplane-like interceptor with a monoplanar delta wing, a conventional tail, and powered by two ramjet engines. Designed for intercepts at ranges up to about 260 miles at altitudes up to 80,000 feet and speeds up to M = 3.95. Control was proved by pivoting the wing tips, pivoting the upper portion of the vertical tail, and deflecting the all-moving horizontal tail. Operational from 1961 to 1972.

- The Nike family of air-defense missiles including Ajax, Hercules, and Zeus, developed by Western Electric and Douglas. The Ajax and Hercules were among the first operational missiles in the U.S. to use a cruciform configuration.

- Terrier for Navy ship defense was an outgrowth of the Applied Physics Laboratory (APL) Bumblebee program in which a large amount of missile data was obtained at the Ordnance Aerophysics Laboratory (OAL), Daingerfield, Texas. First produced by Convair-Pomona. Terrier was rocket powered and was followed by the rocket powered Tartar and the ram-jet powered Talos. These three were commonly referred to as the triple-T.

- Sparrow, originally developed as an AAM by Sperry and Douglas in the mid-1950's, has been continually modified and is still in use by both the Air Force and the Navy as the AIM-7.

- Falcon, developed as an AAM from the GAR program by Hughes in the mid-1950's, was the missile component of the integrated weapon system of the Convair F-102 interceptor. With many modifications, the Falcon is still operational as the AIM-4.

- Hawk, developed by Raytheon in the mid-1950's as an Army mobile air-defense missile system, has a geometric arrangement similar to the Falcon. Having been modified many times, Hawk is still in service.

- Sidewinder, developed by the Naval Weapons Center and Philco in the mid-1950's as an AAM, is, after many perturbations, still in service with both the Air Force and the Navy as the AIM-9.

- Hermes, first major U.S. missile program conducted by Army von Braun group and General Electric, was based on the German Wasserfall. Test flown at White Sands but was never operational.

- Corporal, Army/JPL/Firestone radio-commanded battlefield SSM, based on German V-2 technology.

- Sergeant, follow-on to Corporal, with inertial guidance.

- Redstone, SSM developed by the German group, was the system that launched the first American astronaut into sub-orbital flight in May 1961.

- Honest John, Army/Douglas battlefield SSM, the first post-war operational American missile was a simple spin-stabilized unguided rocket.

- Little John was an Army/Emerson effort to produce a smaller, lighter version SSM than Honest John.

- Lacrosse, Army/Cornell/Martin close-support SSM, had large swept cruciform wings and aft tails.

- Regulus I, subsonic, and Regulus II, supersonic, jet-powered long range cruise missiles developed by Navy/Chance Vought in the mid-1950's for ship-launched surface-to-surface missions.

- Rascal, USAF/Bell, was based on the X-1 design and was intended for long-range (100 miles) air-to-surface missions.

- Loki, Army/Bendix, unguided barrage-type fin-body air defense rocket based on the German Taifun.

- Davy Crockett, Army developed spin-stabilized Jeep-mounted SSM.

- Lark, Navy/Fairchild, subsonic SAM intended for ship defense.

- Oriole, Navy/Martin, a long-range ramjet-powered AAM with a 20 mile range at $M = 3$.

- o Meteor, a Navy/MIT/Bell AAM, which demonstrated an advanced guidance system and achieved M = 3 flight was subsequently cancelled.

- o Rigel, Navy/Grumman long-range SSM with ramjet propulsion.

- o Petrel, Navy/Fairchild air-to-underwater missile that was airborne with a jet engine and upon entering the water, shed it's wings and tail and homed on the target as a torpedo.

- o Eagle, to be developed by Bendix/Grumman, was the missile component of the Missileer weapon system initiated by the Navy in 1957 for fleet air defense. The system was to consist of a subsonic airplane that would serve as a stand-off launch platform for the missiles that were to fly at M = 4 for a range of about 100 miles. The controversial program was subsequently cancelled in 1960 but the technology was to find a place in missiles to come later.

- o Phoenix, an advanced long-range AAM currently operational as the AIM-54 on Navy F-14's. Developed by Hughes beginning in 1960, the missile configuration bears a resemblance to the Falcon family. Predecessor concepts that were somewhat similar to Phoenix were the AIM-47 Falcon, that had been intended for use with the proposed F-12 interceptor, and the Eagle.

- o Standard, surface-to-air shipboard missile developed in the mid-1960's by General Dynamics-Pomona was based on the Terrier/Tartar family. Currently operational in various forms.

- o Lance, a mobile battlefield SSM development begun by LTV in 1962 to replace Honest John and Sergeant, is currently operational.

- o Pershing, a mobile battlefield SSM development begun by Martin in 1958, utilized a two-stage system to provide a greater range than Lance.

- o Maverick, a tactical ASM development by Hughes that was begun in 1965. The configuration is similar to the Falcon family.

- o Hound Dog, a strategic cruise ASM begun in 1957 by North American in response to a USAF requirement to enhance the penetration capability of the B-52. North American made use of the technology generated by the X-10 and Navaho program that had just been cancelled. The Hound Dog was similar to the Navaho with a delta wing-canard arrangement and, powered by an underslung podded jet engine, was capabile of M = 2 flight. Hound Dog was operational with SAC from 1961 to 1976.

- o Skybolt was developed by Douglas in 1959 to be a B-52-launched ballistic missile to achieve greater penetration capability than Hound Dog. The program was cancelled in late 1961 although a full-range (1,150 miles) flight with perfect guidance had been achieved.

- o SRAM (Short Range Attack Missile) developed by Boeing in the mid-1960's for use on the B-52 and later the FB-111. Currently operational.

- o Chaparral, developed by Philco-Ford in 1965 as a field-mobile Army air defense system. The concept is basically derived from the Sidewinder airframe.

- o Redeye and Stinger, tube-launched, man-portable IR air-defense missiles developed by General Dynamics-Pomona.

- o Patriot, developed by Raytheon/Martin as a field-mobile Army air defense system. The Patriot missile is a body-cruciform tail configuration with an ancestory dating from the mid-1960's as the Plato program, followed by FABMDS (field army ballistic missile defense system, then AADS-70 (Army air defense system for the 1970's), then SAM-D (surface to air missile-development), and now Patriot.

While it is recognized that some of the missile systems developed from World War II until about 1970 have been omitted, it should be evident from the ones that have been included that missile development was fervent.

Development Techniques

Much of the early missile development was clearly facilitated by the German influence; much was developed from test flight; and some was backed by wind tunnel programs such as the APL/NOL Bumblebee program. Missile research within NACA was nebulus at best in the late 1940's. At about that time, however, and into the 1950's many missile research programs were undertaken at both the Langley and the Ames research centers of NACA/NASA. Most of the effort was expended in experimental wind-tunnel investigations and some in free-flight rocket-model tests. In the 1950's, some analytical and semi-empirical estimating techniques were being developed for use with missile concepts. Some of this work that should be mentioned was produced by a team of researchers at NACA-Ames that included Jack Nielsen. Several papers on this work were published in the 1950's and a book entitled "Missile Aerodynamics" by Nielsen was published in 1960. The procedures developed were reasonably useful for design purposes but were somewhat time consuming. In addition, for best results, the procedures often required the use of empirical correlation factors. These factors generally came from experimental test data which, in effect, resulted in an increase in the amount of test data being obtained from generalized research models rather than from tests of specific configurations. Even so, experimental data was generally required when detailed results were required or when regimes such as high angles of attack were to be explored or regions of combined pitch and roll.

An example of the use of experimental wind-tunnel data to clarify a problem area occurred with the Nike-Ajax missile. Flight tests of the Ajax often terminated with the missile tumbling out of control when maneuvers were done near M = 2 at high altitudes. The phenomena had become known as "low-q tumbling" and was thought to be associated with high altitude. The behavior had not been predicted by estimating procedures so wind tunnel tests of a simulated Ajax model were conducted in the early 1950's in the 4- by 4-foot supersonic pressure tunnel at NACA-Langley. The tests revealed that the tumbling was caused by an extremely nonlinear variation of pitching-moment with angle of attack that resulted in a pitch-up instability above an angle of attack of about 10 degrees. The nonlinearity was traceable to the increase in lift contributed by the forebody of the very slender body (an ogive-cylinder with a length-diameter ratio of almost 20) and was a characteristic well beyond the capabilities of the estimating procedures of that time. This investigation was among the earliest in which relatively large-scale missile models were used in a supersonic tunnel. The early availability of a test model was possible by converting an existing model of a Langley D-22 ramjet research vehicle. This model became that progenitor of a series of generic research missile models that were used to study the effects of many geometric variations such as body length, wing and canard size, wing and canard planform, forebody and afterbody shape, and so on.

An example of the advantage of model size was demonstrated during the development of the Regulus II air-breathing supersonic cruise missile. This configuration had a sugarscoop inlet located about midway back on the underside of the body. Early flight tests indicated an inability to achieve sufficient control power to trim at cruise lift--an unexpected result based on wind-tunnel tests. It was noted that the early wind tunnel tests had been made in a small tunnel using a small model wherein it was necessary to fair over the underslung inlet. Subsequently, a larger scale model which provided for internal flow was built for testing in the Langley 4-foot tunnel. These tests, when compared to the early tests, revealed that a substantial increase in longitudinal stability occurred when the inlet flow went through the model rather than being diverted around the model.

Model and tunnel size was also an important factor in studies of store carriage and separation. Many experimental studies were made in the Langley 4-foot tunnel with a dual-sting mount being used to support the carrier airplane and the store. These data were used to support efforts to obtain useable analytical techniques.

Model size also facilitated the use of remotely deflected controls and instrumented wing and tail panels. This capability, in turn, provided a data base for use in developing analytical methods for determing panel loads and control hinge-moments.

During the 1960's, the analytical techniques applicable to missile configurations were becoming more useable and, when used in conjunction with experimental studies, resulted in more efficient and effective investigations of missile concepts. Two missile programs of the 1960's that benefited from the combined use of experiment and theory were the Improved Hawk, with a new wing and control arrangement, and the Patriot in the design of the tail planform.

Concluding Remarks

It is fairly clear that the study and the use of missiles goes back several centuries. Insofar as the missile as we know it today is concerned, the impetus came primarily from World War II and, in particular, from German scientists. Immediately following the war, there was a proliferation of missile activity in many parts of the world. While this paper is primarily concerned with U.S. activity, it should be pointed out that a considerable amount of missile development has occurred in other countries, in particular, the Soviet Union, and in several countries of the free world. Most of the missile developments during the time period following World War II on through the 1960's were based on experience, on flight test, and on wind tunnel experiments. Analytical approaches were attempted in the early 1950's and, although initially inadequate, were beginning to become reasonably useful in the design process by the late 1960's.

Bibliography

The Rockets Red Glare. Wernher von Braun and Frederick I. Ordway III, Anchor Press/Doubleday, Garden City, New York, 1976.

Rockets and Missiles. Bill Gunston, Cresent Books, New York, 1979.

Jane's Pocket Book of Missiles. Edited by Ronald Pretty, Collier Books, Macmillian Publishing Co., Inc., New York, 1976.

Historical Development of Worldwide Guided Missiles. M. Leroy Spearman, NASA Technical Memorandum 85658, June 1983.

An Overview of Some Monoplanar Missile Programs. M. Leroy Spearman, NASA Technical Memorandum 86330, December 1984.

Figure 1.- Early ballistic missiles.

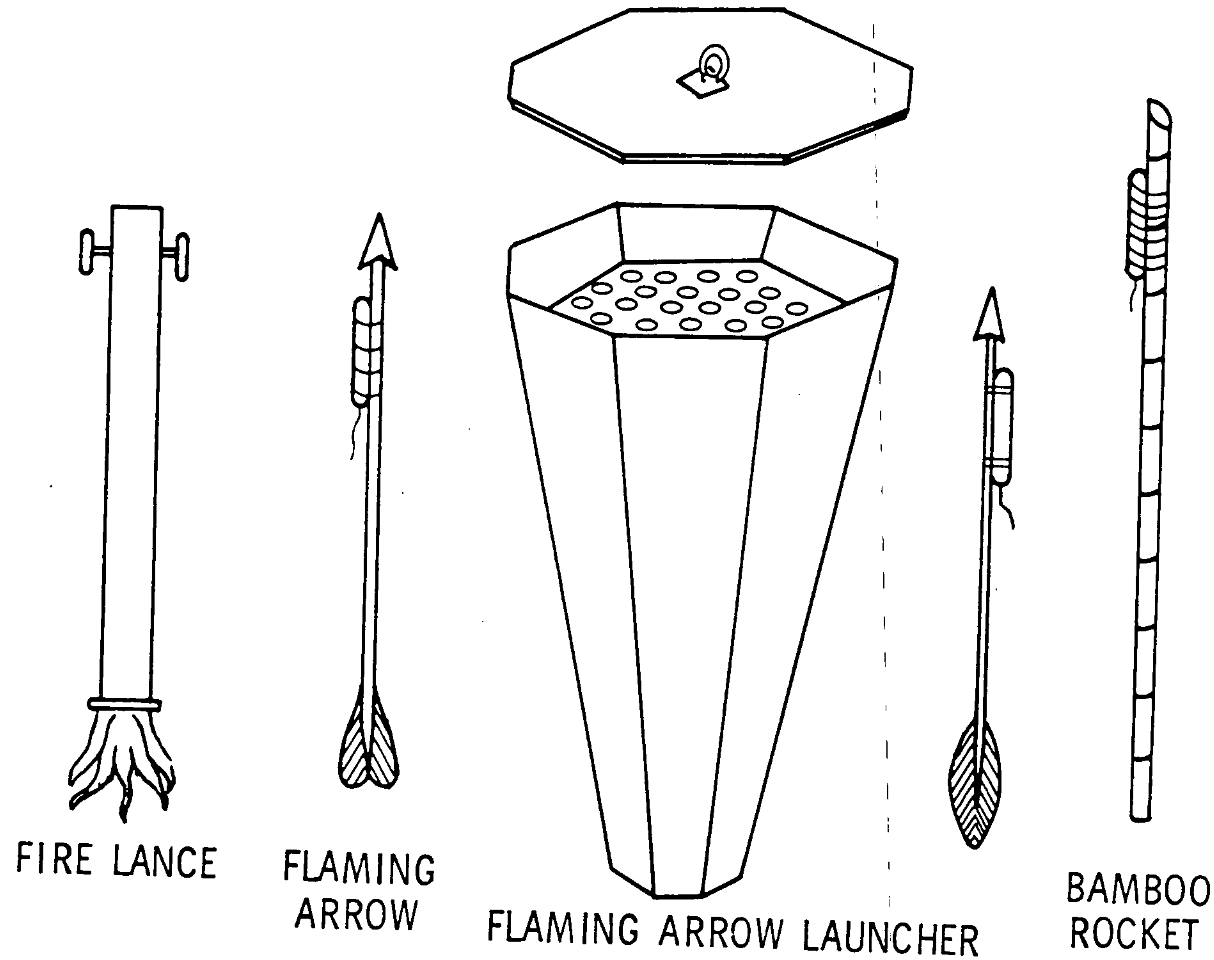

Figure 2.- Early rockets.

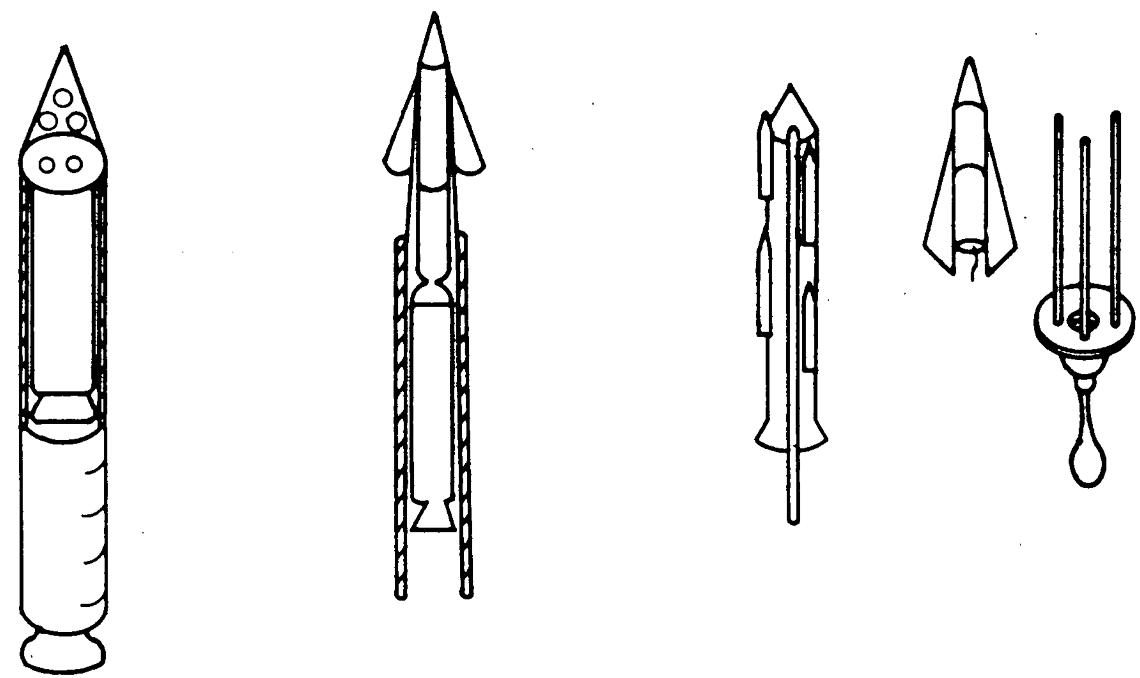

Figure 3.- Multistage rockets.

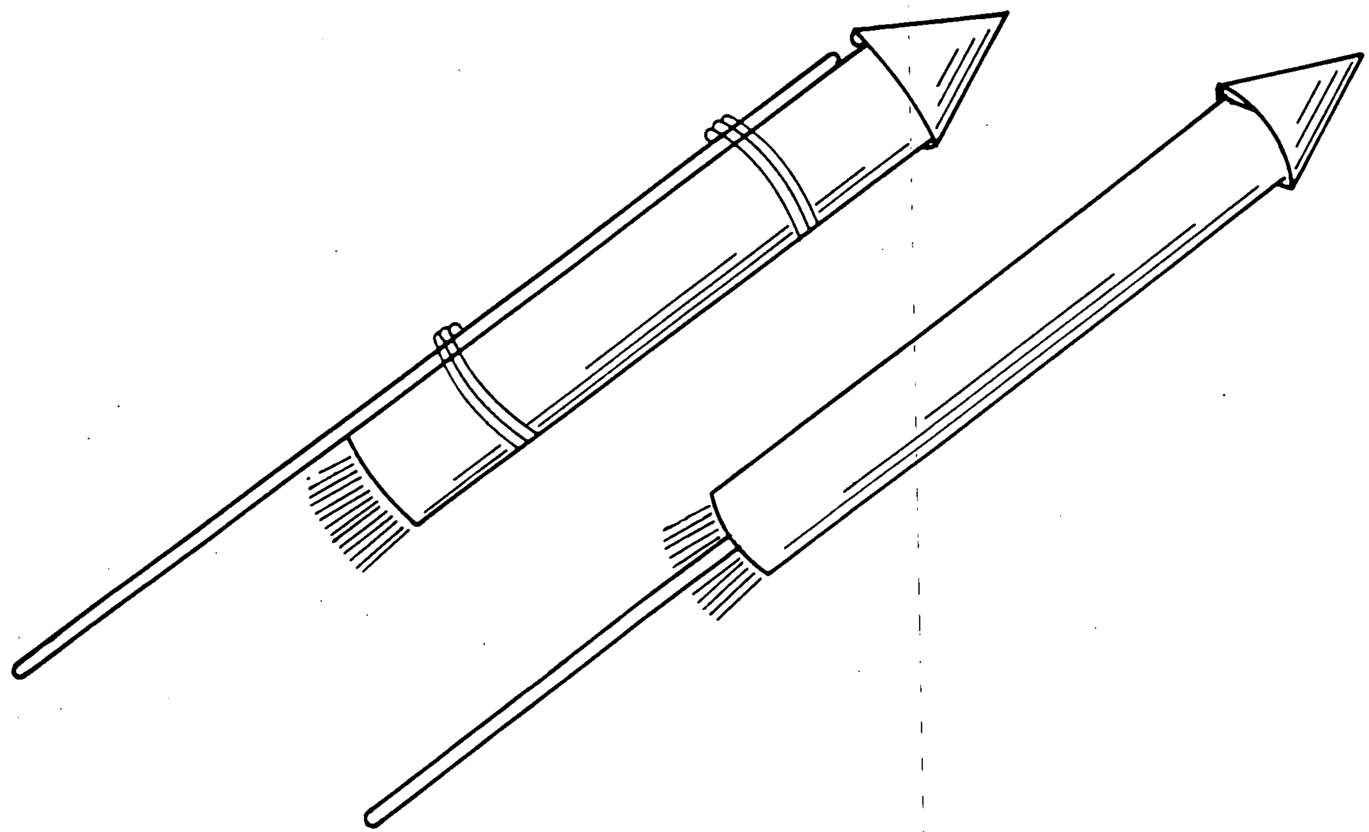

Figure 4.- Congreve stick rocket.

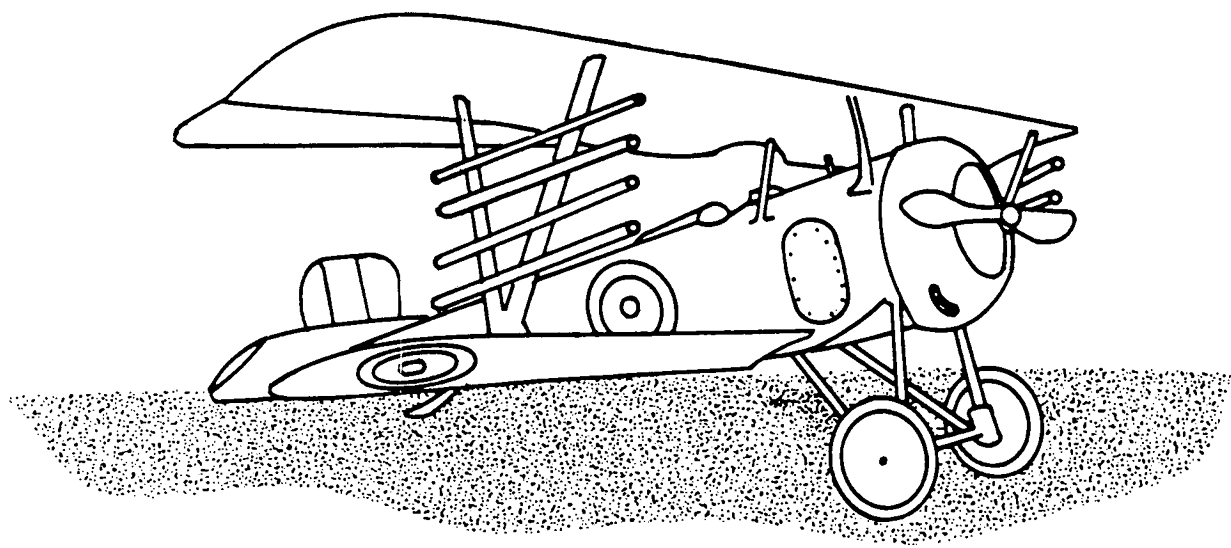

Figure 5.- Nieuport fighter with rocket tubes.

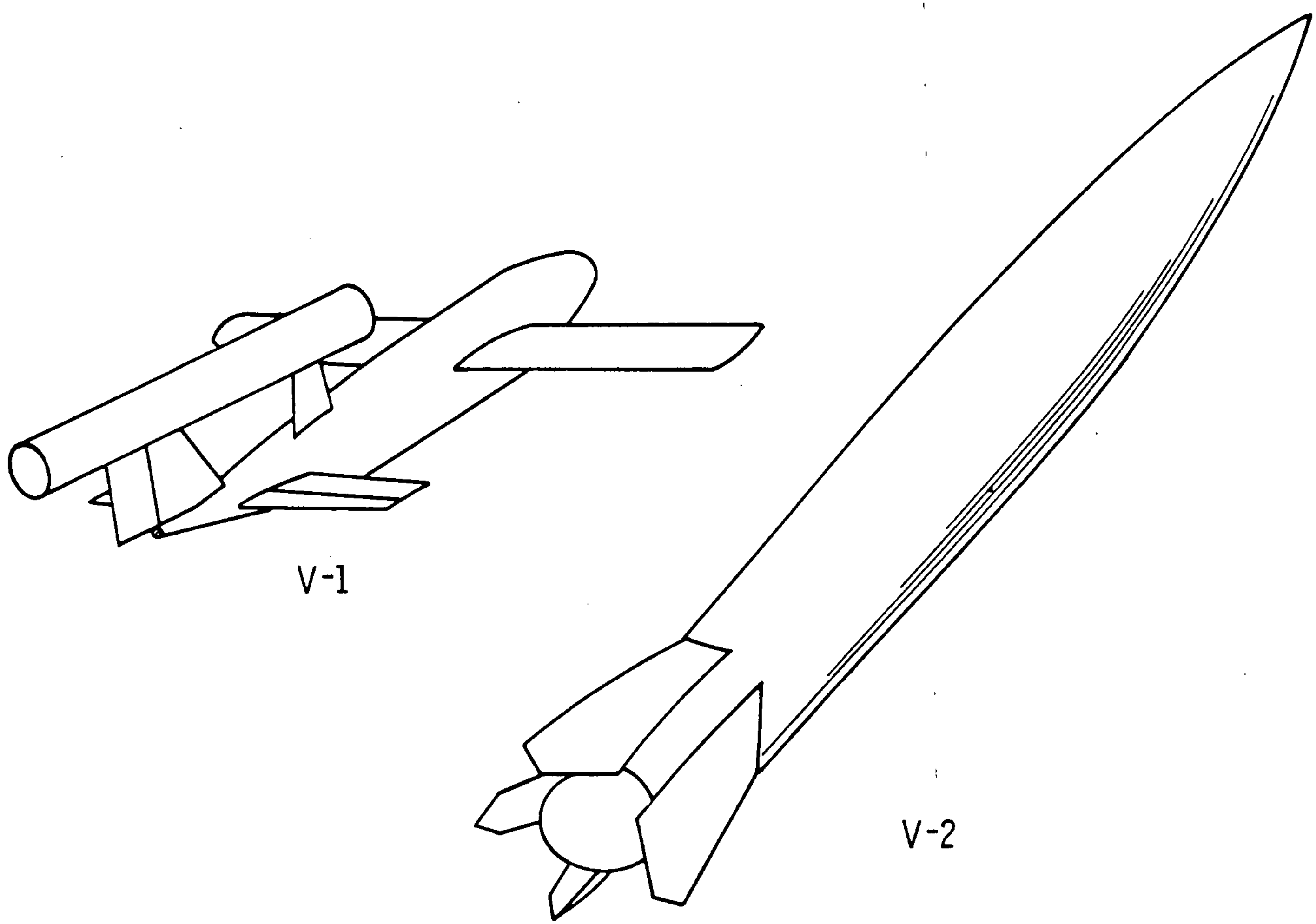

Figure 6.- Vengeance weapons.

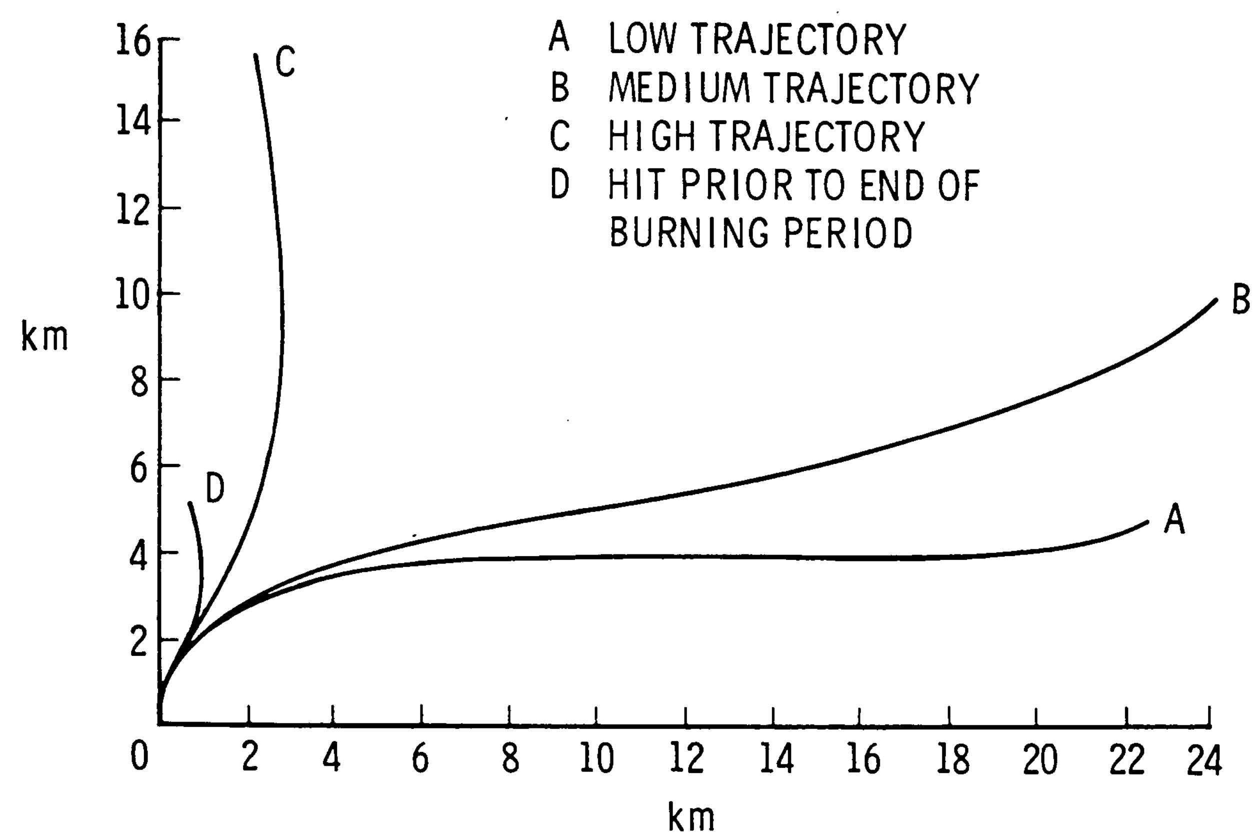

Figure 7.- Trajectories for air defense missile.

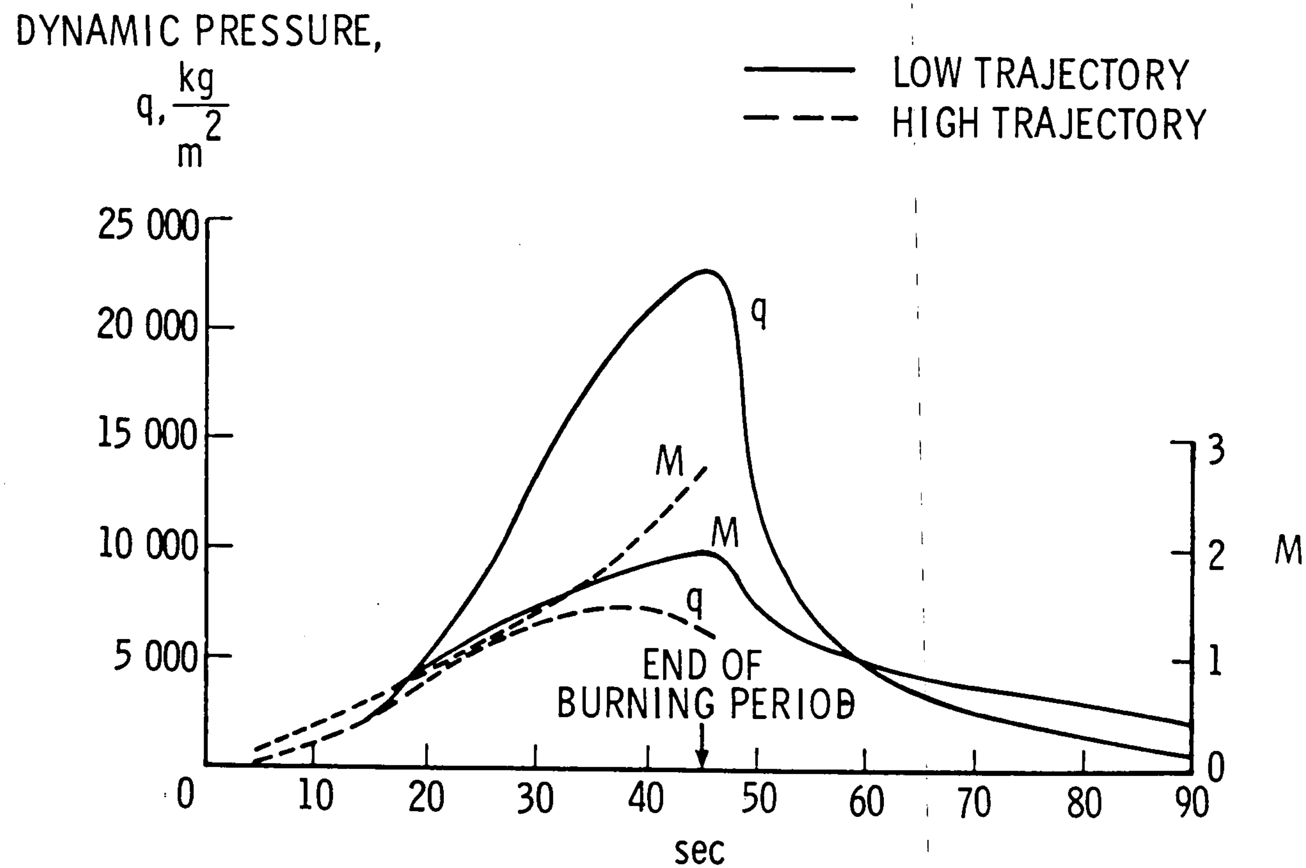

Figure 8.- Flight conditions for air defense missile.

- MANEUVERABILITY TO EXCEED TARGET BY FACTOR OF 2 TO 6
- LOW INDUCED DRAG
- CONSTANT CENTER OF PRESSURE LOCATION
- RAPID RESPONSE
- LOW HINGE-MOMENTS
- POSITIVE STABILITY
- FREEDOM FROM ROLL
- STRUCTURAL LOADS
- SKIN TEMPERATURE
- JET PLUME EFFECTS
- PROXIMITY FUSE

Figure 9.- Characteristics considered for air defense missile.

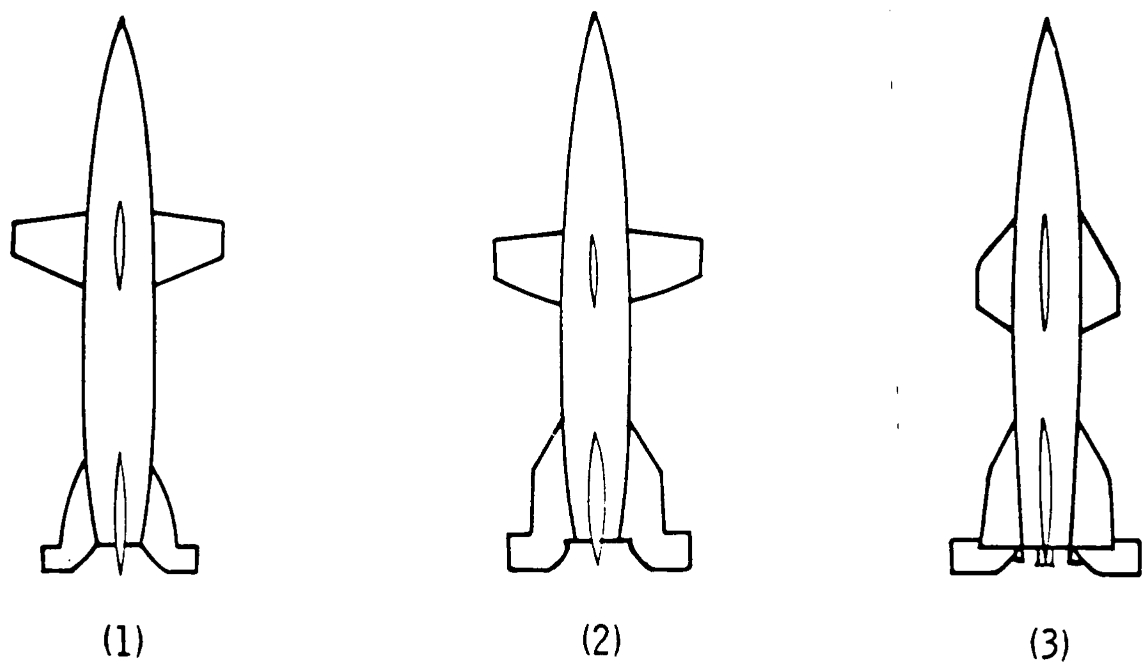

Figure 10.- Wasserfall configuration variations.

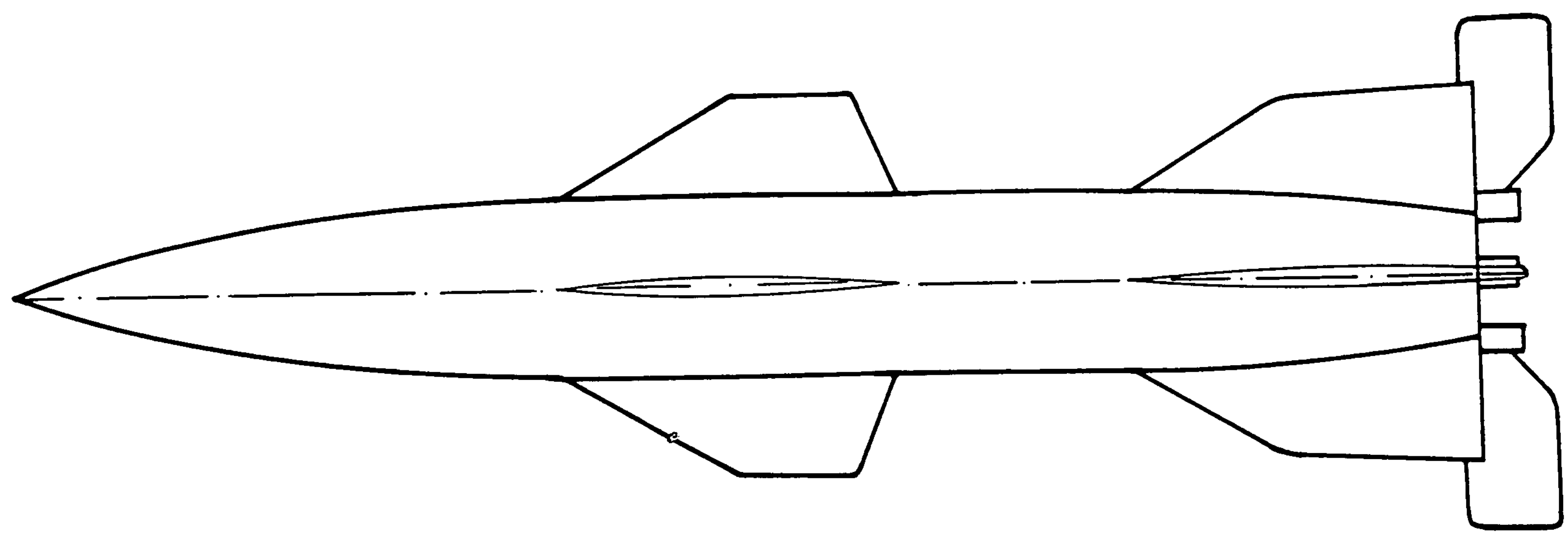

Figure 11.- Wasserfall configuration.

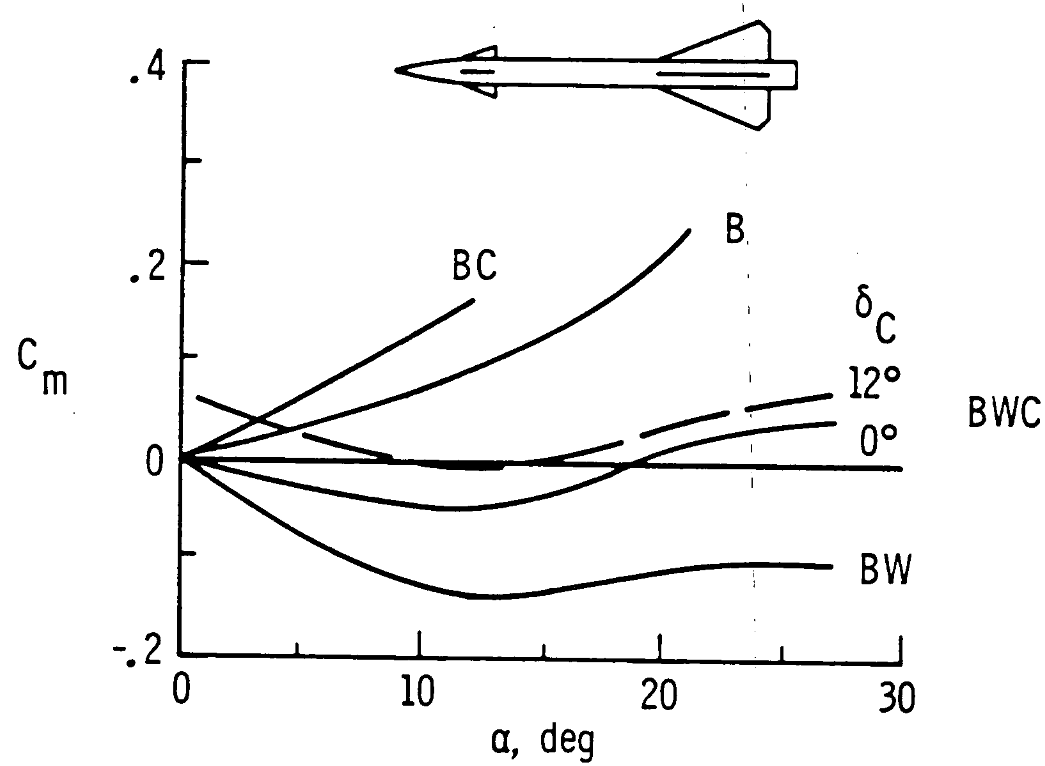

Figure 12.- Pitching moment characteristics for delta-wing-canard missile model, $M = 2$, $l/d = 19.1$, c.g. = $0.67l$.

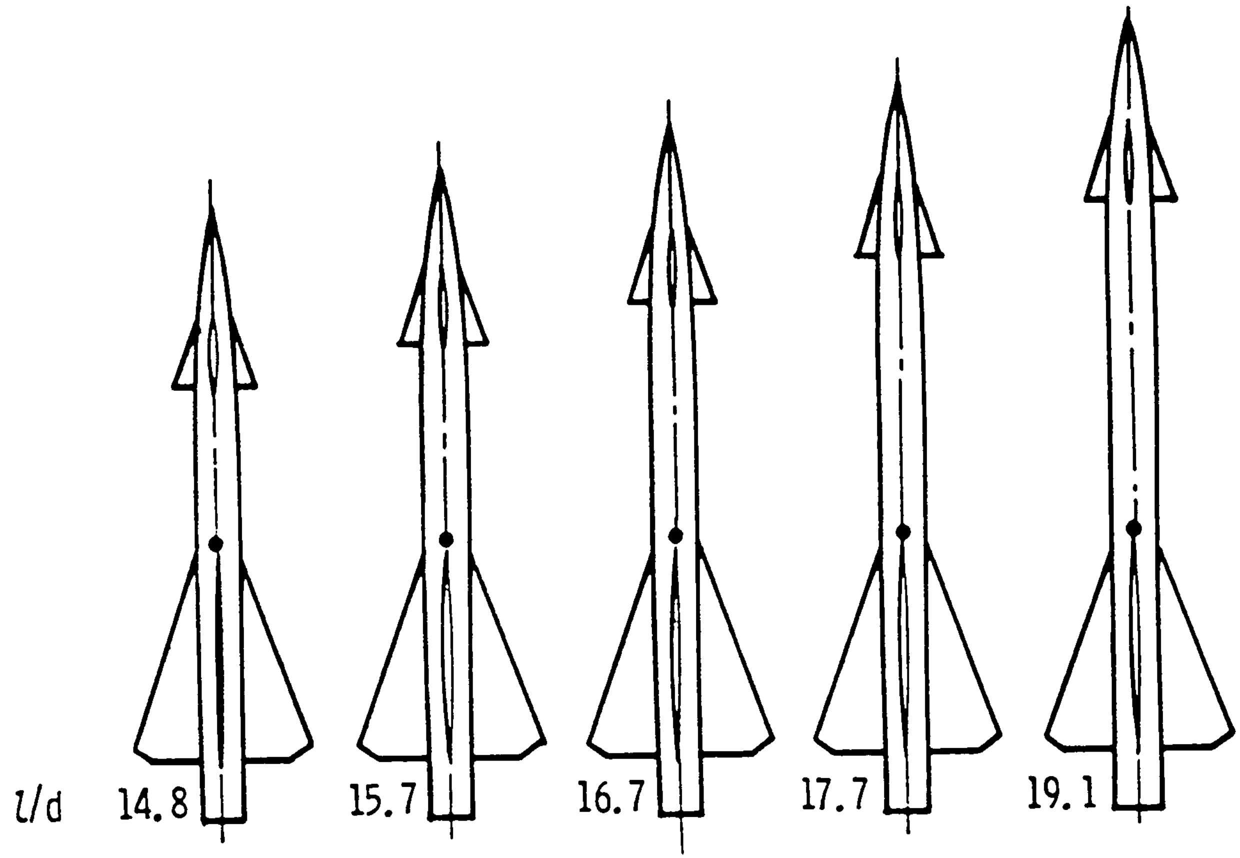

Figure 13.- Canard missile body length study model.

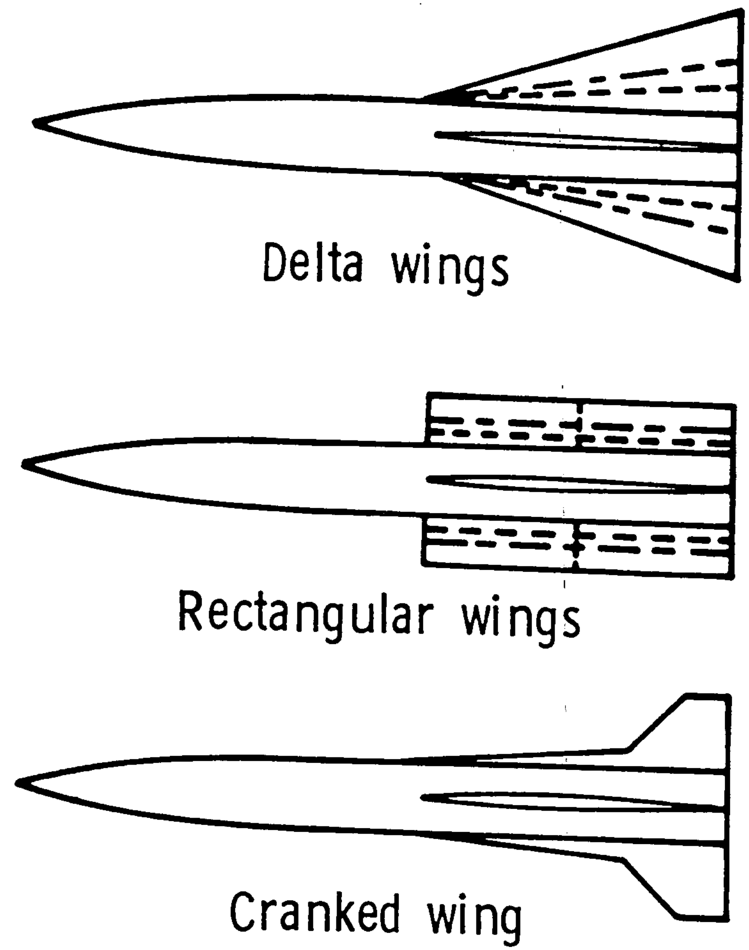

Figure 14.- Wing planform models.

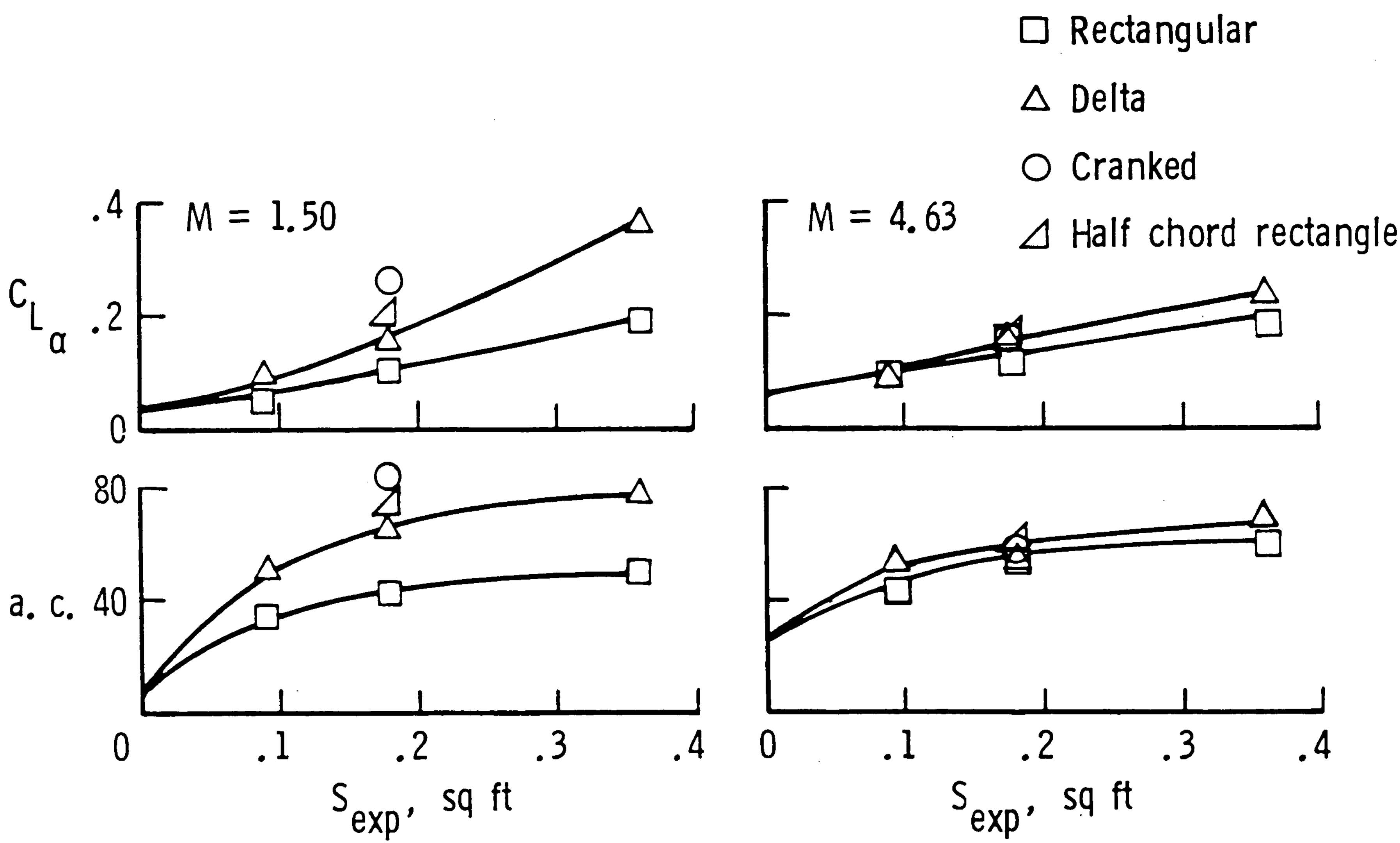

Figure 15.- Variation of C_{L_α} and a.c. with exposed wing area for various wing planforms, M = 1.50 and 4.63.

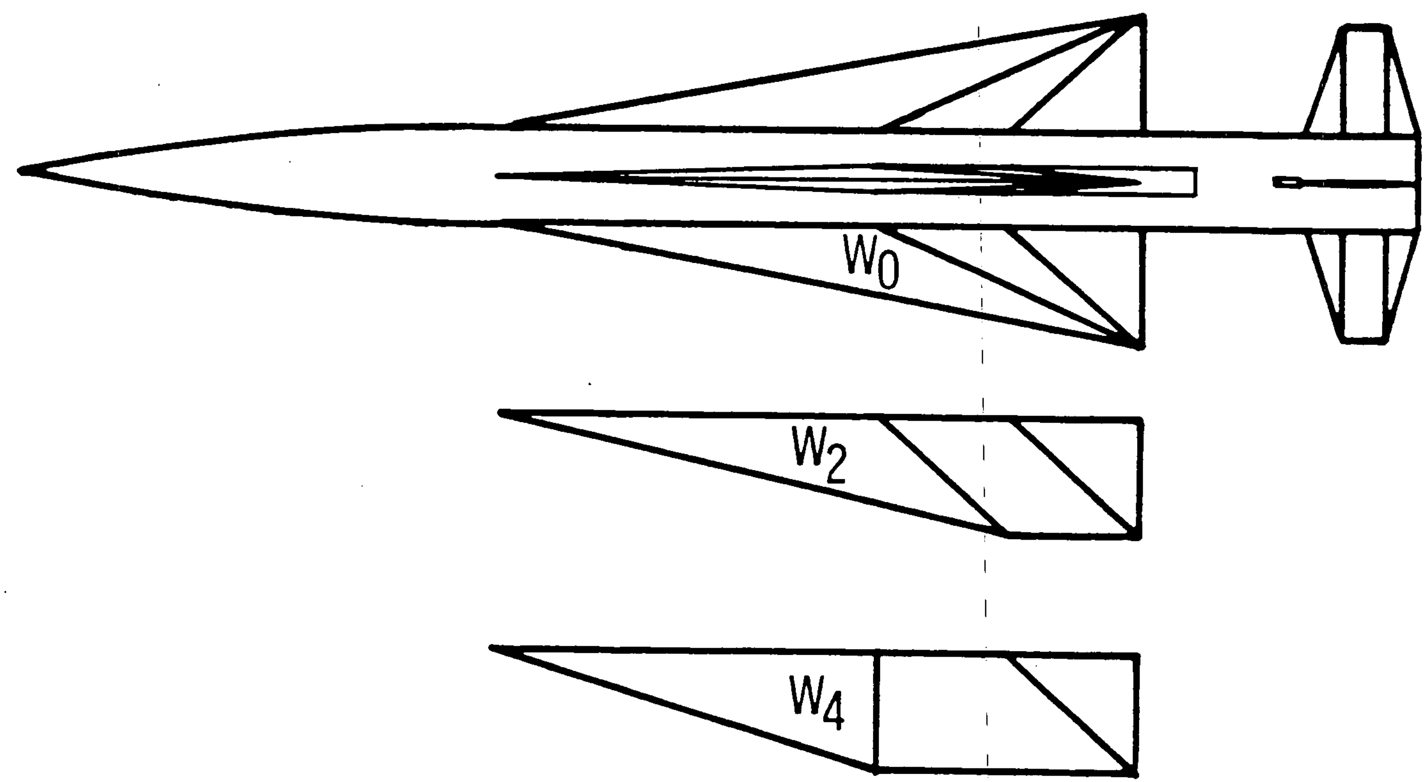

Figure 16.- Wing-body-tail model having planform variations with a constant wing span.

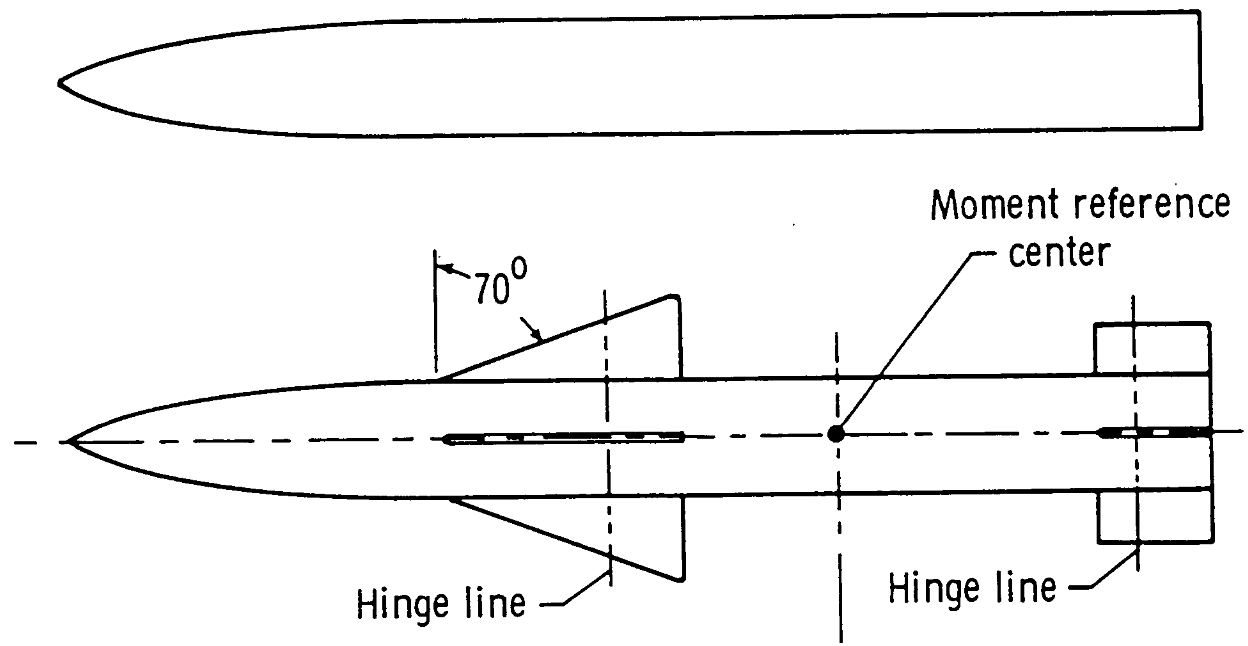

Figure 17.- Body with wing and tail controls, l/d = 10.17.

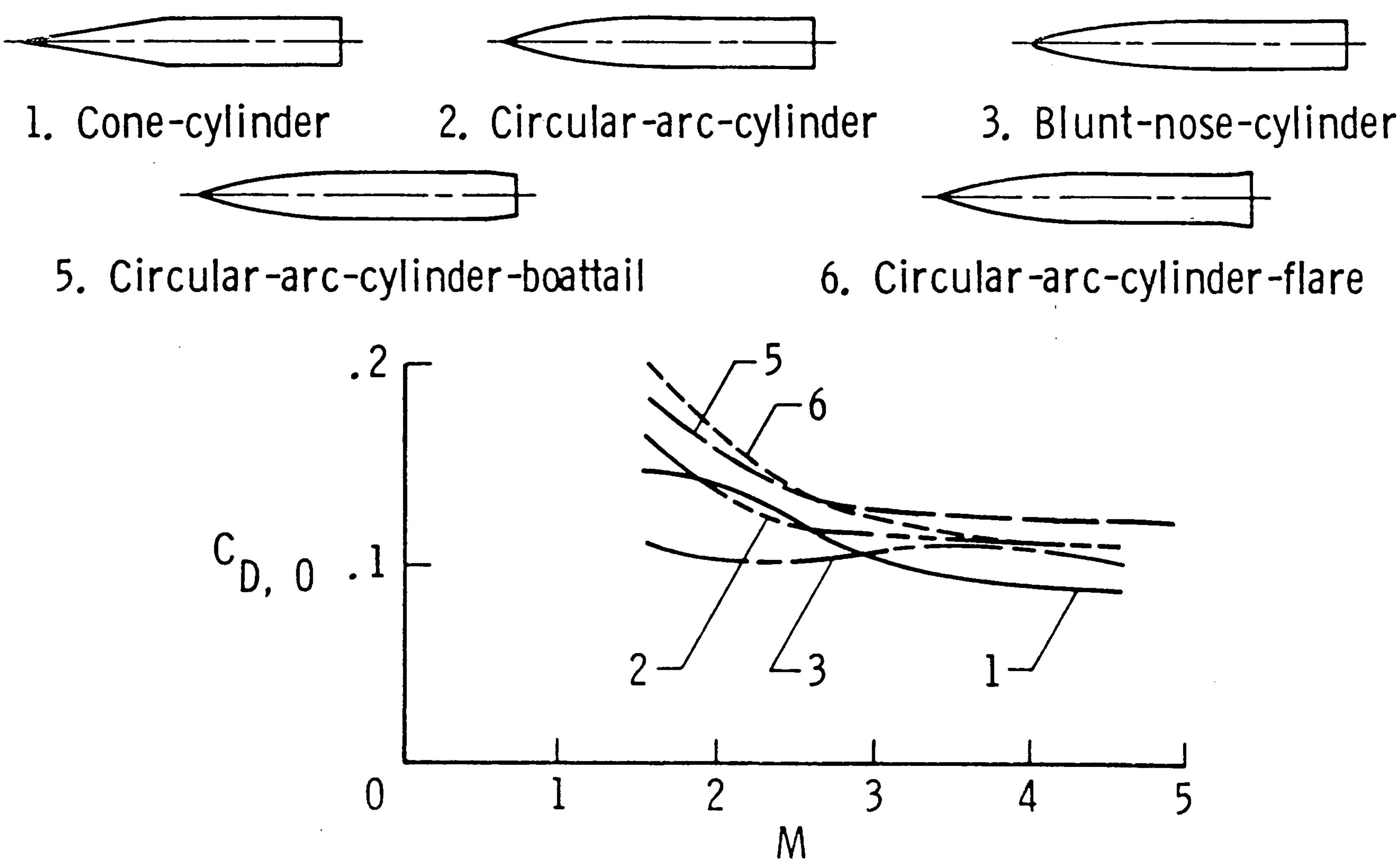

Figure 18.- Minimum drag variations for various forebodies and afterbodies.