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BUMBLEBEE MISSILE AERODYNAMIC DESIGN: A CONSTANT IN A CHANGING WORLD

This article discusses the development of the basic Terrier, Tartar, Standard Missile tail-control aerodynamic configuration as an example of Project Bumblebee technology not yet outdated. Solution of the problem of reverse roll at supersonic speeds is highlighted as a step toward final aerodynamic design. It is emphasized that tail control provides a noncritical aerodynamic configuration that can be efficiently divided into functionally separate elements (i.e., sectionalized) to facilitate development, production, and testing. As a result, it has been possible to implement a remarkable degree of interchangeability of parts between large- and small-ship missiles and to simplify the introduction of new missile capabilities. Pertinent systems engineering approaches and techniques are outlined. Similarities among worldwide aerodynamic designs are indicated.

INTRODUCTION

The fiftieth anniversary of the Applied Physics Laboratory provides a welcome opportunity for reminiscing about the historical role of APL in the development of supersonic surface-to-air guided missiles. It is quite natural to recollect with pride that many of the most significant achievements in the field can be attributed to APL. It is also appropriate and gratifying to note that APL scientists and engineers are continuing to make unique and timely contributions to the design of guided missile systems at a time when technology is changing rapidly and many organizations are involved. But there is a pertinent and intriguing question not often considered. Are there specific APL-originated ideas or missile design approaches from the early days—the pioneering days—that are not yet outdated? Is it possible to identify achievements of the distant past that have current significance in spite of the phenomenal advances in technology that have been made over the years?

In this article, primary consideration is given to only one aspect of guided missile design: the basic aerodynamic/dynamic configuration. It is evident that most modern supersonic guided missiles employ tail control; four tail surfaces are typically used in a cruciform arrangement to provide all aspects of pitch, yaw, and roll control. Some missiles have fixed forward lifting surfaces (wings or "dorsal fins") and some are wingless, but tail control is now the prevailing choice for high-performance missiles. Yet tail control was by no means the initial direction of guided missile development; at APL, and elsewhere in the world, primary emphasis was on the use of forward control surfaces, either large wings or smaller "canards." At APL, however, early interest in high levels of performance led toward tail control; more than 40 years ago, APL originated the aerodynamic design approach that is now in worldwide use.

To put the tail-control development story in perspective, it is necessary to emphasize that supersonic aerodynamics appropriate to missile design was truly in its infancy at the inception of the Bumblebee project in 1945. Simple linear theories were available for bodies of revolution or thin wings in isolation, but basic aspects of wing–body–tail (or even wing–body) interactions were a mystery; there was no hope of calculating stability and control parameters to the required degree of accuracy. Very limited wind tunnel lift and drag data obtained from tests in small tunnels in Europe and the United States were available for projectiles and airfoils, but there was no supersonic wind tunnel capable of providing adequate data (including essential stability and control measurements) for missile design. In fact, there was no general agreement (even at APL) that any affordable wind tunnel would ever provide data relevant to flight conditions (at representative Reynolds numbers). In 1947, during a classic Wilbur Wright lecture, Theodore von Kármán would still be referring to supersonic aerodynamics as "a collection of mathematical formulas and half-digested, isolated experimental results."[1]

STV–2 FLIGHT TESTS AND REVERSE ROLL

It was necessary to make exploratory flight tests in the late 1940s to establish the most fundamental aerodynamic design characteristics and to measure (telemeter) as many flight data as possible. The first APL supersonic control test vehicle (STV-2) is shown in Figure 1. The large aft lifting surfaces (tails) were fixed; the forward movable surfaces (termed wings, though relatively small in area compared with the aft surfaces) provided pitch and yaw control; and small flippers (rollerons) located between the wings were designed to furnish roll control. Results of a

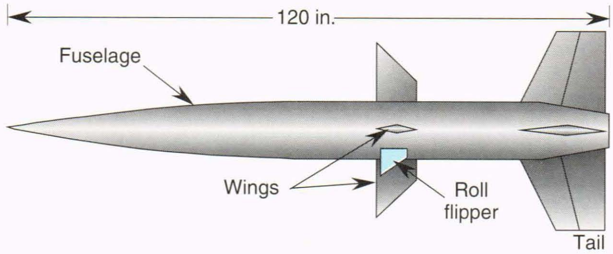


Figure 1. STV-2 aerodynamic configuration.

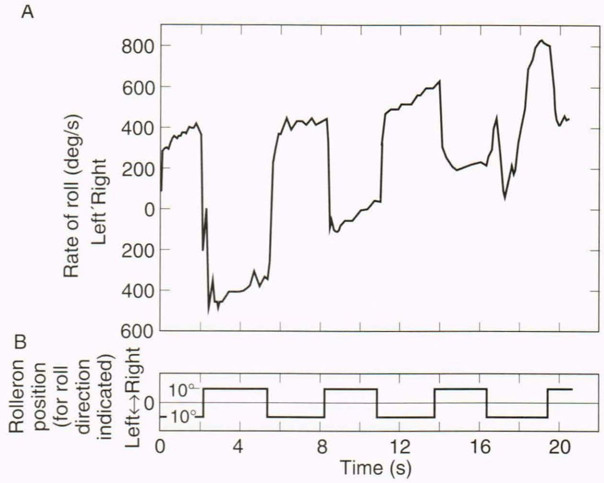


Figure 2. STV-2 Serial No. 24 telemetering data. **A.** Rate of roll versus time. **B.** Rolleron position versus time.

representative flight are shown in Figure 2; roll was indeed achieved on schedule, but—and it seemed incredible at the time—the direction of roll was opposite to the sense predicted from theory and subsonic experience.[2]

During the next few months, the STV-2 flight-test investigations of roll control were continued.[3] Two additional tests were conducted with the initial aerodynamic configuration, corroborating the previous data. Two flights were made with the roll flippers moved forward of the wings (to minimize flipper–wing interactions), and one was carried out with the rollerons removed and the small wings used to provide roll; during all three flights, the direction of roll was reversed at supersonic speeds.

Another flight test did provide roll results compatible with subsonic experience, however—one that led the way into the future. In this test, the tail surfaces were differentially deflected (with the forward rollerons removed), and roll performance was entirely consistent with expectations. It was immediately apparent that predictable roll control could be achieved by use of aft surfaces, even in the nonuniform flow field created by the wings.

SUPERSONIC WIND TUNNEL DEVELOPMENT AND TESTING

In the meantime, remarkable progress had been made toward the development of a suitable supersonic wind tunnel. Early in 1945, shortly after the beginning of Project Bumblebee, it had been decided that construction of a major test facility should be undertaken to provide for a large supersonic wind tunnel (as well as a "burner" laboratory to permit testing of large-scale ramjets under conditions of supersonic flow). For the wind tunnel, a test section area of "at least three square feet" was selected for testing of models "at least as large as tenth-scale, to facilitate making the complicated and precise models anticipated," and operation at relatively high pressures was specified as a requirement to provide acceptable Reynolds numbers. The defined power and compressor requirements were enormous (about 15,000 lb/min of air at a pressure of 30 lb/in^2 gauge), and the appropriate compressor and power-production facilities had to be identified and made available in a wartime environment.[4]

It did prove possible, however, to locate a standby blast furnace (at the Daingerfield, Texas, plant of the Lone Star Steel Company) with a blower capable of furnishing half of the required flow. The Navy arranged for the necessary access, and the Reconstruction Finance Corporation found a second blower of equal capacity that could be transferred to Daingerfield. Assistance in the overall design of the wind tunnel was obtained from the California Institute of Technology along with the detailed design of the nozzles intended to provide uniform flow in test sections of 19 × 27.5 in. for Mach (M) numbers ranging from 1.25 to 2.50. Construction of the Ordnance Aerophysics Laboratory (OAL) was started in June 1945, and initial exploratory tunnel tests with a full-scale nozzle were being run by June 1946. By March 1947, calibration of the $M = 1.73$ nozzle had been completed, demonstrating unusually uniform flow conditions (see Fig. 3), and a highly accurate rolling-moment balance system had been developed by the Consolidated Vultee Aircraft Corporation (CVAC), which was responsible for operation of the OAL facility under the technical direction of APL.

In March 1947, wind tunnel tests confirmed the reverse-roll results of the prior STV-2 flight tests (see Fig. 4); additional tests demonstrated the suitability of aft roll-control surfaces.[5] To minimize overall configurational changes for STV-2, it was decided to effect roll control by employing roll flippers located at the extremes of the tail surfaces (see Fig. 5), and flight success was immediate. In August 1947, roll stabilization at supersonic speeds was accomplished, and in March 1948, successful beam-riding guidance was demonstrated in a memorable flight.[6]

THE PHYSICAL EXPLANATION OF REVERSE ROLL

It is notable, however, that selection of the final STV-2 design (with aft roll-flipper control) had been made without a physical understanding of the phenomenon of reverse roll at supersonic speeds. Finally, after many false leads had been pursued, the breakthrough explanation occurred in June of 1947 between sessions of an Aerodynamics Panel meeting at OAL. The initial clues were negative in nature. It proved possible to deduce—conclusively—that no existing aerodynamic theory (wing upwash/downwash, body upwash effects, etc.) could possibly account quantitatively for the indicated results. It therefore became evident that an entirely new aerodynamic concept was required. When a particular possibility was identified by the author—late at night—it seemed so obviously correct

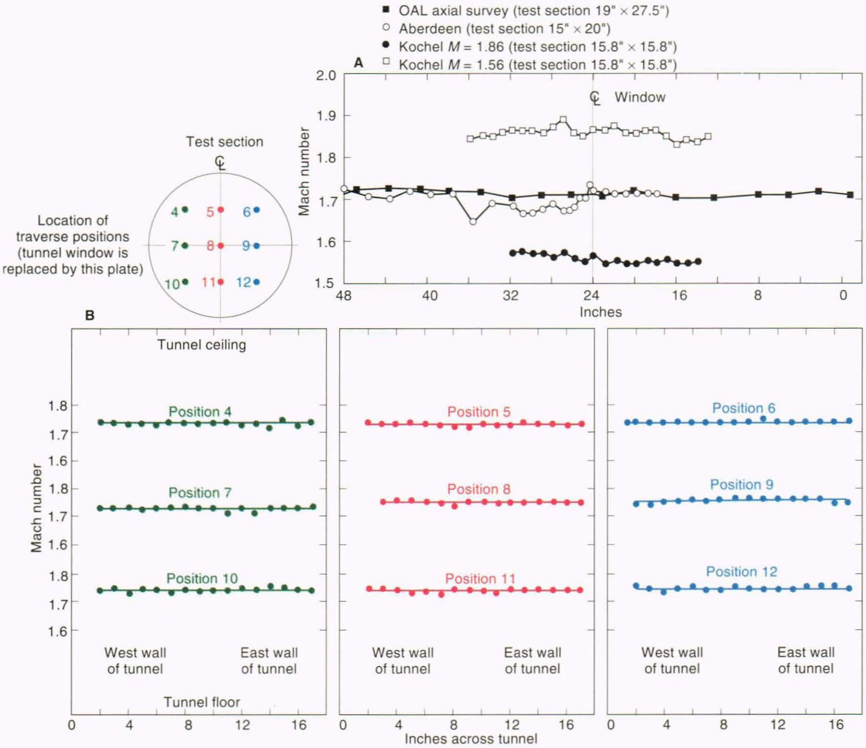


Figure 3. Mach number variations in supersonic wind tunnel test sections. **A.** Axial static pressure survey results for the Ordnance Aerophysics Laboratory (OAL), Kochel (Germany), and Aberdeen wind tunnels (Mach number versus nozzle abscissae). **B.** Uniformity of Mach number in test section (M = Mach number).

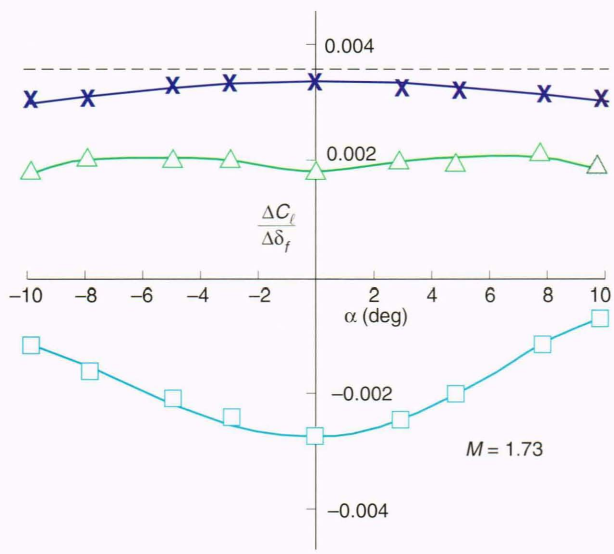


Figure 4. Wind tunnel roll-control data for the STV-2 test vehicle. ($\Delta C_\ell/\Delta\delta_f$ = rolling moment per degree of flipper differential deflection; α = body angle of attack; dashed line = theory, assuming no interference; x = roll-flipper effectiveness, wings and tails off; Δ = roll-flipper effectiveness, wings on and tails off; □ = roll-flipper effectiveness, complete configuration; M = Mach number.)

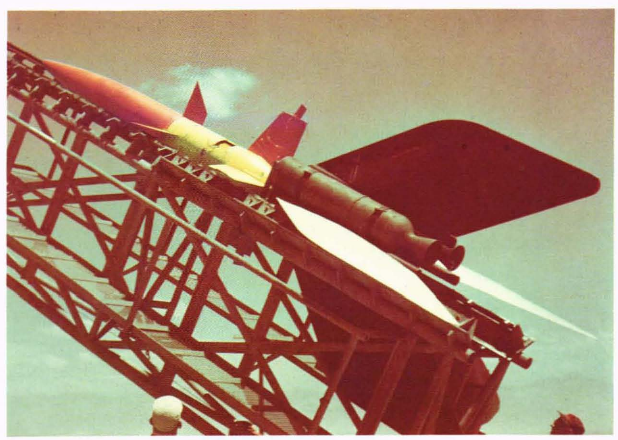


Figure 5. STV-2 test vehicle on launcher.

that immediate steps were initiated to provide experimental verification in the OAL wind tunnel. A simplified diagram of the nonconformist idea—which seems entirely obvious in retrospect—is presented in Figure 6. It seemed apparent that a strong interaction of pressure fields at the wing–body juncture must be occurring in direct contradiction to existing theory.

A postmidnight telephone call led to reopening of the wind tunnel facility and, with the essential cooperation of the CVAC tunnel operators, to an all-night effort to arrange a demonstration for the Panel on the following morning. Perhaps for the first time, two subsonic wind tunnel techniques were used to furnish a visual (and photographic) representation of supersonic flow patterns. In one approach, an oil-and-lampblack mixture was placed inside of a "Tinkertoy" model so that flow through model joints would occur when the model was exposed to the low pressures present during tunnel operation; in the other, tufts (short silk threads) were attached to the model in appropriate locations.[7] The resulting photographs (see Figs. 7 and 8) have deteriorated with time, but they still show that the essence of the physical theory was effectively proved by the initial experiments. Clear evidence can be seen of an interaction of pressure fields emanating from the root sections of the differentially deflected surfaces, leading to swirl around the body in the

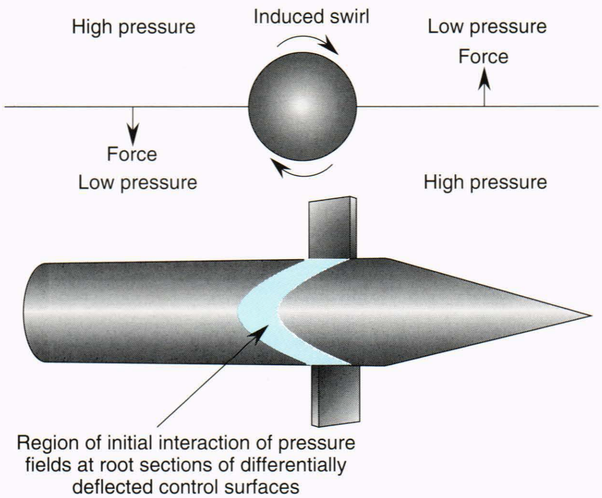
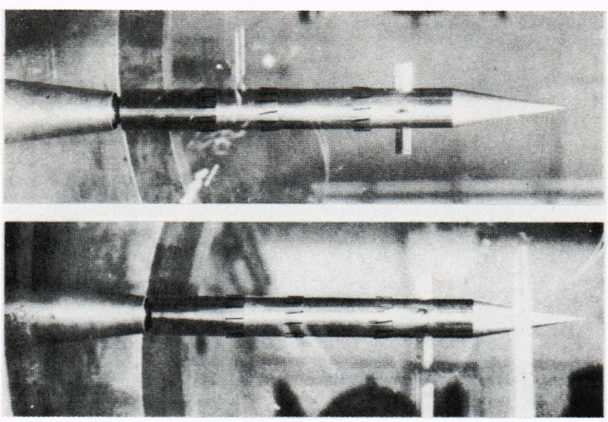


Figure 6. Origin of cross-flow and swirl from interaction of pressure fields at root sections of differentially deflected control surfaces.

A



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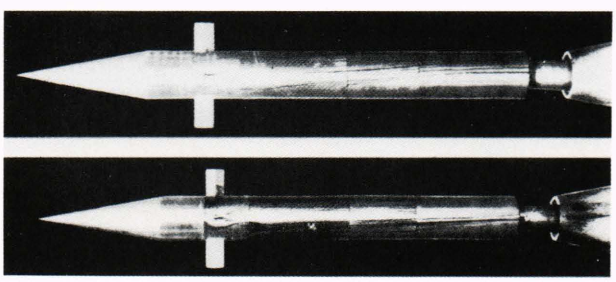

Figure 7. Photographs of tufts and oil-lampblack survey illustrating interaction of pressure fields. **A.** Tufts indicate swirl in the direction expected from the interaction of pressure fields at root sections of differentially deflected control surfaces. **B.** Oil-lampblack flow indicates swirl in direction expected from interaction of pressure fields at root sections of differentially deflected control surfaces. (Vertical flippers deflected 10° differentially, body angle of attack = 0°, Mach number = 1.73. Photographs taken from opposite sides of the tunnel.)

direction needed for reverse roll. (The swirl impinges on aft surfaces, causing the development of reverse rolling moments.) The field of swirl was evident for small flippers representative of the STV-2 design (see Fig. 7); crucially, in respect to the physical explanation, the swirl was also present for large-span differentially deflected surfaces (see Fig. 8) for which the flow at the root sections could not possibly have been affected (at supersonic speeds) by wing-tip phenomena.

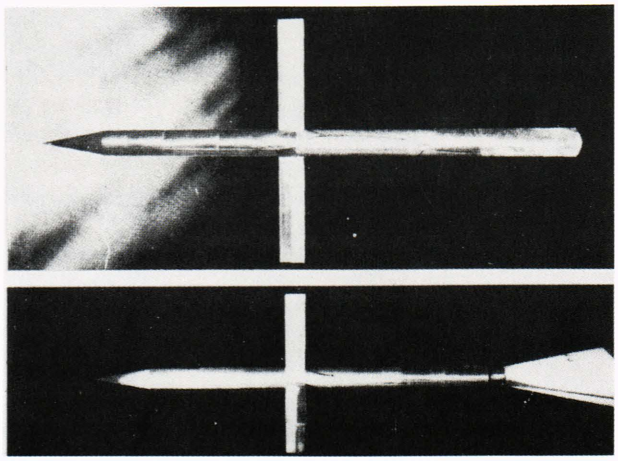

Figure 8. Photographs of oil-lampblack survey indicating swirl in direction expected from interaction of pressure fields at root section of differentially deflected wings. (Horizontal wings deflected 10° differentially, body angle of attack = 0°, M = Mach number. Photographs taken from opposite sides of the tunnel.)

Shortly after the flow patterns were identified, the results were confirmed by detailed pressure measurements, again in regimes that could not physically be affected by wing-tip flow.[7] Additional wind tunnel rolling-moment data were obtained for a wide range of configurations; typical results are shown in Figure 9. With aft surfaces substantially larger than differentially deflected forward surfaces, reverse roll is invariably encountered at supersonic speeds.

The reverse-roll story has been told in some detail to emphasize that supersonic aerodynamic theory was in a state of turmoil in the 1940s. In fact, after the Reference 7 paper had been delivered at a Bumblebee Aerodynamics Symposium in November 1948, reactions were mixed. A few well-recognized theoreticians in the United States and Europe denounced the reverse-roll (both flight and wind tunnel) results as impossible. Some time passed before it was generally agreed that the wind tunnel and flight results were correct and conclusive as presented, that the physical explanation was entirely valid, and that the relevant physical principles had previously been misinterpreted. In defense of those who reacted adversely, it should be mentioned that the OAL wind tunnel rolling-moment results could not be duplicated elsewhere at that time. The uniformity of OAL wind tunnel flow and the accuracy of OAL roll-measurement instrumentation were unique in the world. Furthermore, computational techniques available at the time could not possibly have predicted the rolling moment results, and it is interesting to note that—to the author's knowledge—modern methods have not yet been applied to this problem.

STV–3 AND TERRIER AERODYNAMIC DESIGN

For STV-3, which was intended as a forerunner of the Talos ramjet aerodynamic configuration, roll control was again achieved by use of rollerons at the tips of the fixed

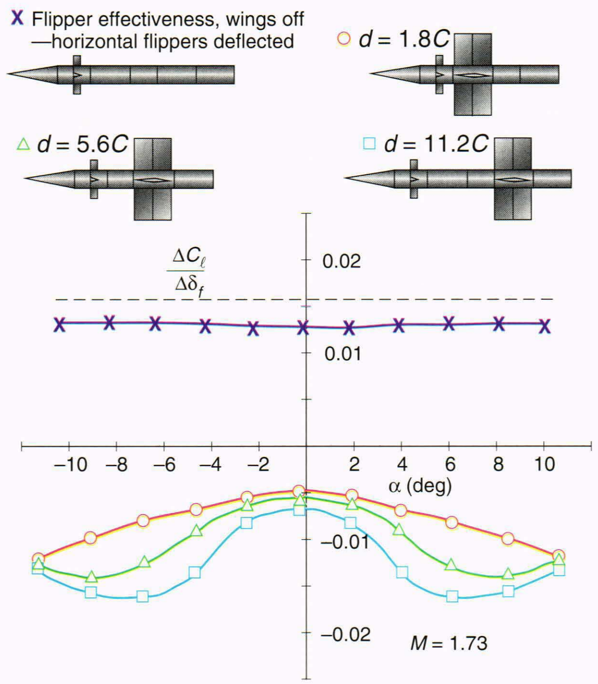

Figure 9. Effect of distance between rectangular flippers and rectangular wings (cruciform wings in line with flippers; horizontal flippers deflected). ($\Delta C_\ell/\Delta\delta_f$ = change in rolling moment per degree of flipper differential deflection; α = body angle of attack; dashed line = theoretical; d = distance from flipper trailing edge to wing leading edge; C = flipper chord length = 0.40 in.; flipper span = 0.60 in.; wing span = wing chord = 2.00 in.; body diameter = 1.00 in.)

tail surfaces, and pitch and yaw control were again (as for STV-2) accomplished by deflection of forward wings. By employing wings substantially larger than those of STV-2, it was possible to develop a viable design that would provide adequate maneuverability at low angles of attack, thereby simplifying in-process Talos ramjet propulsion development. For a ramjet, it is difficult to achieve appropriate air-inlet flow conditions at high angles of attack.

For STV-3, control-test-vehicle flights began in April 1948, and an extensive series of tests was conducted (throughout 1948) to establish correlation between wind tunnel and flight results. It was shown that predictions based on wind tunnel results had become dependable—assuming that considerations relating to nonrigid structures (structural dynamics) were appropriately taken into account (see Ref. 8). The STV-3 aerodynamic characteristics were defined in detail. As a result, when the decision was made in April 1949 to produce a tactical missile (Terrier) with solid rocket propulsion (to provide the earliest possible operational guided missile capability), it was prudent to proceed with minimal changes in the STV-3 configuration. Except for small changes in missile length and wing location and an increase in the size of the rollerons, the Terrier aerodynamic design (see Fig. 10) was virtually identical with that of STV-3.

TALOS AERODYNAMIC DESIGN

In respect to Talos design, it was initially decided that rollerons at the extremes of tail surfaces would be used

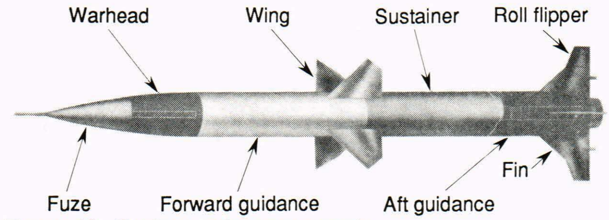

Figure 10. Terrier I major components.

for roll control (as for STV-3 and Terrier), but structural dynamics and control difficulties developed for the tail location on the ramjet tailpipe (the controls could not be directly coupled through the tailpipe). Fortunately, it was determined that, with a further increase in wing area (so that the wings were significantly larger than the tails), it would be possible to generate adequate roll control by differential deflection of the wings for the limited flight regime of Talos (nearly constant Mach number). It was also established that wing control would provide acceptable maneuverability throughout flight for the virtually fixed center-of-gravity location of the ramjet design. As a result, a well-understood aerodynamic configuration could be selected, known structural problems could be avoided, and a single control system could be used.[9]

INITIAL TAIL–CONTROL DEVELOPMENTS

Early in 1950, the need for a follow-on solid rocket missile of significantly higher performance (termed Terrier II) was identified, and an opportunity was provided to make a major change in aerodynamic design. By December of that year—on the basis of wind tunnel tests alone, since tunnel–flight data correlation had been clearly demonstrated—tail control had been selected.[10] It had been established that, for the desired high maneuverability, tail control would significantly improve controllability (much larger, more linear control moments; more linear static stability characteristics; reduced rolling moments due to pitch and yaw angles of attack). Since the center of gravity of the rocket motor could be located approximately at the overall center of gravity of the missile (not possible for wing control with solid rocket propulsion), center-of-gravity travel during flight could be minimized. Because stability variations with Mach number would also be limited for tail control, missiles could be designed for near-zero static stability and maximum speed of response while minimizing control system power requirements and drag due to maneuver.

By early 1951, a specific "final" Terrier II aerodynamic configuration had been chosen, essentially all required wind tunnel data had been obtained, a detailed Navy Ordnance Specification had been prepared, and work had started on the construction of four test vehicles with a view toward flights in early 1952 (employing Terrier I components where possible). The plans for Terrier II included both beamriding and homing guidance versions; the objective was to double the range of Terrier I while significantly improving both high- and low-altitude performance. To allow for the homing system dimensions and rocket characteristics that seemed to be needed, a diameter of 15 in. had been selected for Terrier II in contrast to 13.5 in. for Terrier I (see Fig. 11).

During 1951 and 1952, however, it became necessary to reduce hardware efforts directed toward Terrier II in order to concentrate on major developmental and production problems that had arisen for the original Terrier. Actually, the delays were beneficial because time was provided for additional studies as well as further component development. In late 1952, a complete Terrier II program review was initiated to assure that maximum advantage would be taken of all available research data and hardware components.

In May 1953, a major report was published,[11] providing in effect a composite design textbook for the future. Included were future program outlines for homing as well as beamriding guidance along with comprehensive aerodynamic and dynamic tail-control design data , extensive tactical analyses, detailed performance calculations, and illustrative discussions of shipboard installations. Selection of the original STV-4 aerodynamic configuration (with a large fixed wing) was confirmed as a best-bet design for homing, but a second tail-control configuration (wingless) was deemed to be of special interest. For the wingless design, it was evident that there would be even more desirable stability and control (and drag) characteristics as well as shipboard handling advantages (obviation of the requirement to install missile surfaces during the launching cycle). As shown in Figure 12, both configurations permitted ideal sectionalization (i.e., division of the missile into functionally separate elements to facilitate development, production, and testing).

The sole difficulty with the wingless missile related to the design and production of a radome that would meet guidance requirements for accurate homing while also withstanding the effects of high temperatures and rain erosion at supersonic speeds (speeds at which the impact of raindrops is similar to that of steel pellets). To realize small missile-to-target miss distances for a homing missile, it is necessary to achieve highly precise measurements of the rate of change of the line-of-sight from missile to target. For the type of guidance system involved, the measurements are made by tracking the target with a gimballed antenna system and measuring the motion of the antenna in space; the antenna system is mounted within a radome. Errors are introduced into the measurement process by aberrations in the radome that cause an apparent motion of the target as the missile moves in response to maneuver commands. As a result of these radome boresight errors, the true target position differs from the apparent target position, and the measured rate of change of the line-of-sight to the target differs from the true rate of change.

For a given missile configuration, the radome boresight error slopes that can be accommodated without significant degradation of miss distance are a direct function of the rate at which a missile develops lift with

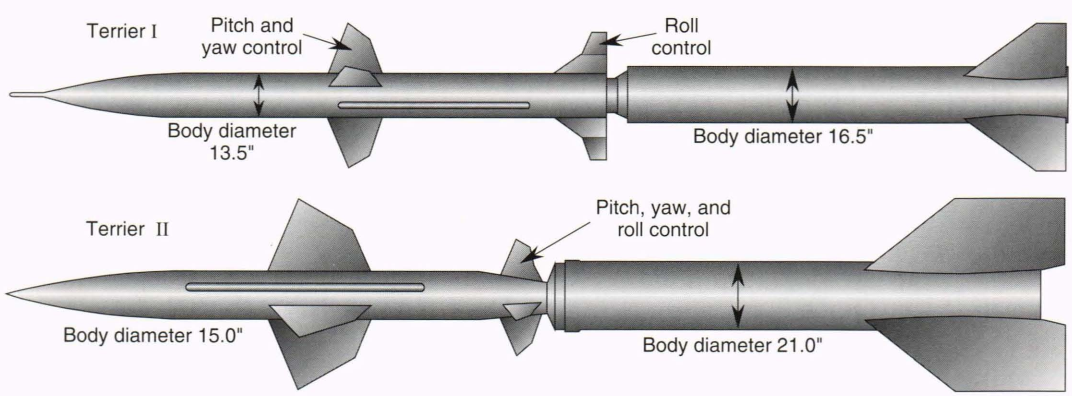

Figure 11. Comparison of Terrier I and Terrier II configurations.

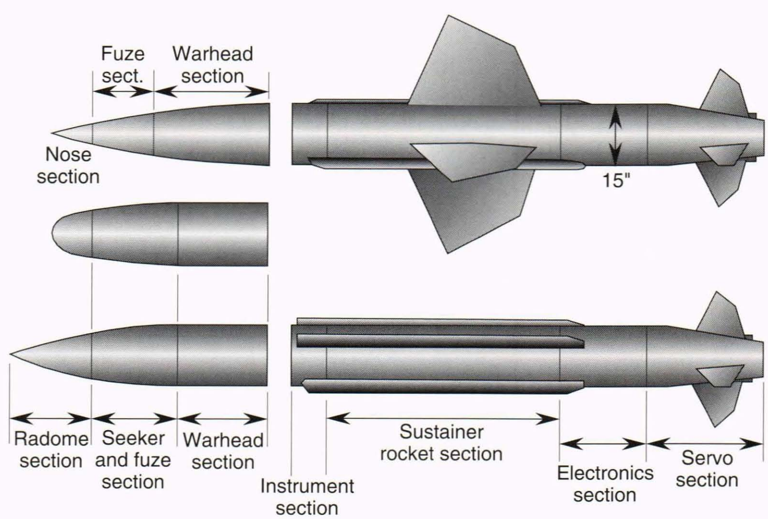

Figure 12. Winged and wingless Terrier II missiles.

increases in angle of attack. For the tail-control configuration with wings (and a high rate of lift development), the radome boresight error slope requirements (the characteristics essential to satisfactory homing) were considered to be consistent with design expectations for a radome of an acceptable (ogival) aerodynamic shape. For the wingless configuration, the requirements appeared at the time to be manageable only for an undesirable (high-drag hemispherical) nose shape.[11]

It was certain, however, that the wingless design would be preferable for beamriding guidance, and it seemed possible that ongoing radome research programs would lead to a radome design suitable for the wingless configuration. Two of the four previously designed STV-4 test vehicles were therefore converted to the wingless design. By October 1954, flights of both winged and wingless versions had been conducted with outstanding success, confirming in detail the preflight aerodynamics and control predictions from analyses and wind tunnel data.[12]

SELECTION OF THE PRODUCTION TAIL–CONTROL DESIGN

In the same time period, studies were undertaken of a compromise configuration, one that would improve the lift versus angle-of-attack characteristics of the wingless configuration—thus alleviating the radome design problem—while maintaining the shipboard handling advantages of the wingless approach. The concept involved using dorsal fins with span limited to the span of "folded" missile tails; the folded tails and the dorsal fins could then be retained on the missile body during the shipboard launching cycle, thus simplifying shipboard handling. The dorsal fins would furnish additional lift (potentially enough to make a significant difference in connection with the radome issue) and would also provide a further advantage in regard to stability and control. It appeared that the static stability of the airframe could be adjusted to required levels for different missile versions simply by altering the dorsal fin length.

Calculations for the designs with dorsal fins were very promising, indicating that the radome design issue might be successfully resolved for a highly desirable missile design. On the other hand, calculational techniques then available were not considered to be dependable for the parameters involved; consequently, the first relevant wind tunnel tests were awaited with intense interest. When the tests were conducted in November 1954, the results exceeded expectations.[13] The lift effects were greater than anticipated—to the extent that the radome boresight error slope requirements appeared to be achievable (within research expectations) even for a pointed radome. In addition, the wind tunnel stability and control data were entirely consistent with the very favorable estimates.

By late 1954, there had also been significant reductions in packaging volume requirements for homing guidance as well as notable improvements in rocket impulse. Putting all of the results together, it was realized that the advanced-missile diameter could be reduced to 13.5 in. to take maximum advantage of previous Terrier developments. A joint APL–Convair presentation (CVAC had become Convair, a Division of General Dynamics Corporation) was made to the Navy in December 1954, identifying the 13.5-in tail-control missile with dorsal fins as the ultimate program objective.[14] At that time, however, the Terrier Growth Program did include advanced wing-control missiles as potential production versions to provide interim levels of improved performance in the event that delays were encountered in meeting the tighter radome tolerances required for tail control. Navy acceptance of the program proposal was immediate.

During 1954, manufacture of another test vehicle series, STV-5, had been undertaken as a step in the winged Terrier II program (15-in. diameter). In accordance with the revised program plan, the STV-5 wings were replaced by dorsal fins, and the first control flight test of the new configuration was carried out, very successfully, in November 1955. By that date, impressive progress had also been made in radome design, and again there were program changes. In January 1956, in another joint APL–Convair presentation, it was recommended to the Navy—again with immediate Navy acceptance—that only tail-control missiles with dorsal fins be produced as elements of the Terrier Growth Program.[15]

TERRIER–TARTAR INTERACTIONS

In the meantime, yet another major program decision had been made. Over a period of years, studies had been directed toward the development of a "small-ship" missile (Tartar) that could be used on destroyers or as a secondary battery on larger ships. Initially, efforts had focused on the design of a new missile. By early 1955, however, an intensive study[16] had been conducted "to determine if the Terrier Improvement Program could also lead directly to the development of a missile suitable for use aboard small ships." As noted in the reference, "The outcome of the study was successful beyond initial expectations. A program based on the results of this study was approved by the Navy early in 1955 and all previous work reoriented accordingly . . . To a major extent, a single missile is being developed to meet both requirements for the Navy . . . It should be emphasized that this evolution is made possible by the Terrier concept of sectionalization and by the use of a missile configuration that is not sensitive to changes in missile dimensional and weight characteristics."[16]

The "Tinkertoy" approach to missile development and production (see Fig. 13) was outstandingly successful, both with respect to the several Growth Program versions of Terrier and with regard to Terrier–Tartar interactions. To streamline the development process, the Terrier program was given responsibility for primary aspects of aerodynamics, dynamics, and control system design for Tartar as well as Terrier,[17] and the Tartar program was made responsible for homing system and warhead design for Homing Terrier as well as for Tartar.[17,18] In general, problem solutions developed for one missile type could be employed for others.

SOLUTION OF THE RADOME PROBLEM

In 1957, an especially timely and noteworthy success was achieved in the radome research program. As men-

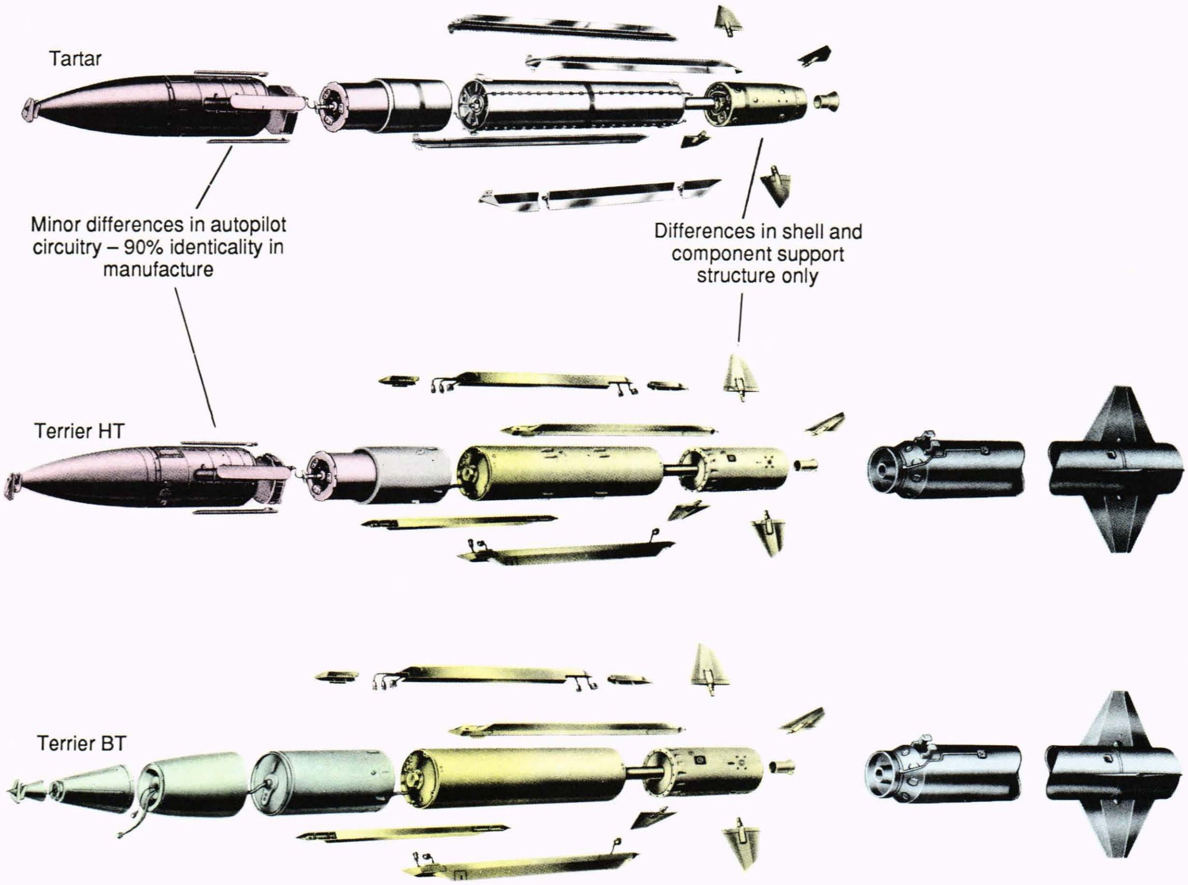

Figure 13. "Tinkertoy" approach to missile design.

tioned previously, to permit accurate homing with tail control, it was necessary to develop radomes that would meet electrical design requirements (very low values of radome aberrations) while also fulfilling mechanical design requirements (suitable structural characteristics under conditions of high flight temperatures and potential rain erosion). In the rain-erosion test program, samples of a new class of materials (termed cerams) were obtained from the Corning Glass Company—initially because of the promise of excellent mechanical properties. Prior to heat treatment, these materials behaved as high-melting-point glasses and could be fabricated into desired shapes by conventional glass-forming techniques; after forming, they could be heat-treated to change them from a glass to a fine-grained crystalline material. The material of greatest interest—a pyroceram—passed all mechanical tests, demonstrating remarkable rain-erosion resistance.

Fortuitously, it was determined that the electrical properties of the same material might also be unusually attractive if precise control of composition could be accomplished in production. Under Department of Defense sponsorship, a pilot production project was quickly established—first to develop production techniques and then to furnish flight radomes for Tartar and Terrier. Once again, the results exceeded all expectations. It proved possible to produce a material of requisite uniformity; as a result, radomes with outstanding electrical characteristics (including the required boresight error slopes) could be provided at low cost.[19] By this achievement, the major risk taken in the selection of the tail-control configuration with dorsal fins had been eliminated—and the Corning Glass Company had a new product available for commercial applications.

DESIGN FOR PRODUCTION

In all design areas, progress was made rapidly—though not smoothly. Structural dynamics problems (steady-state deflections and flutter) had led to STV-3 and Talos flight-test failures; flutter problems also developed for the Terrier/Tartar tail surfaces. Flutter theory was inadequate at the time, but ultimately the problems were solved by use of a straightforward dynamic balancing approach developed at APL.[20] Additional structural dynamics issues plagued the development of the first high-performance acceleration-feedback autopilots. Abstruse coupling modes, such as coupling between body longitudinal bending and tail torsional modes and between tail spanwise bending and roll system design parameters, were discovered in ground tests—degrees of interaction that were certainly not anticipated. For high angle-of-attack conditions, aerodynamic interactions among pitch, yaw, and roll modes of motion had to be accounted for in control system design.[19, 21, 22] Rocket shock, vibration, and flame-burst problems had to be solved; malfunction of components caused by extreme flight environments was common. Fortunately, flight failures were deemed to be necessary elements of the learning process, not reasons for program cancellation; management efforts could therefore be concentrated on program accomplishment, not on program defense. As a result, problems were solved expeditiously, schedules were maintained, and all design objectives were fully met.

For the beamriding tail-control Terrier (Terrier BT), pilot production began in mid-1958. By December 1958, all thirty of the missiles in the pilot program had been formally accepted by the Navy—12 months after the first successful tail-control flight with beamriding guidance and 18 months after the first successful control-test-vehicle flight with the dorsal fin configuration. Terrier BT was in full-scale, high-rate production early in 1959.[17]

INTERCEPT OF BALLISTIC TARGETS

Successful formal Navy evaluations of Terrier BT performance were conducted at the Naval Ordnance Test Station (now the Naval Air Warfare Center), China Lake, California, and on tactical ships; however, an additional, unusual flight-test program was carried out to provide flight demonstrations against potential tactical ballistic missile targets. For this program, Terrier I Beamriding/Wing Control (Terrier BW) missiles were converted by APL for use as targets (with wings removed); a missile-to-target miss-distance measuring system was included. The targets were launched from San Nicolas Island (off the coast of California, in the Pacific Missile Range) by a U.S. Marine Corps Battalion; the Terrier BT interceptor missiles were flown from the USS *Norton Sound,* a ship that had been converted for experimental Terrier flight tests. The Terrier BW missiles (targets) were flown on ballistic trajectories to altitudes of about 115,000 ft; the Terrier BT missiles were fired for planned intercepts during the downward phase of the target flights.

On August 16, 1960, an intercept was achieved at an altitude of 64,500 ft, with a measured miss distance of 56 ft—presumably the first intercept of a ballistic missile target by a supersonic guided missile. On August 18, a second ballistic missile intercept occurred at approximately 80,000 ft; the miss distance indicator malfunctioned, but a close miss or direct hit seemed to be indicated. In the same program, designated TOP HAT (Terrier Operational Proof, High Altitude Target), Terrier BT successfully intercepted (on August 17) a Regulus II Missile Drone flying at Mach 2 at an altitude of 44,000 ft,[23] foreshadowing programs to intercept airborne missile targets.

TERRIER–TARTAR INTERCHANGEABILITY

Production of the Tartar missile was started late in 1959; Homing Terrier (HT) production, in 1961. Because of the sectionalized nature of the missile designs and the noncritical aerodynamic configuration, improvements on a "block-change" basis could be conveniently introduced.[24] The Terrier/Tartar concept of interchangeability—the capability for substitutions and common usage of missile elements with no modifications or adjustments—resulted in striking advantages during development, production, and fleet utilization. For development: concentration of design talent on fewer components with concomitant reductions in documentation requirements and in the number of items to "debug" in ground and flight tests. For production: reduction in documentation requirements and in tooling for parts fabrication; quantity purchase of common items; standardization of assembly techniques; multiple usage of test equipment, inspection facilities, and gauges. For fleet utilization: quantity purchasing; reduced inventory of spares, test equipment, and assembly tools; common shipping and handling methods; reduced training time.[25] For the overall program: substantially reduced costs.

When production of Homing Terrier and the corresponding improved version of Tartar was fully integrated in 1961 (see Fig. 14), approximately 85% of the dollar value of the guidance, control, and airframe elements was in terms of directly interchangeable parts. Achieving the indicated levels of interchangeability entailed minor costs, for each of the missiles necessarily carried a small number of extra components and circuits as a result of requirements for a different missile. The costs of interchangeability were, however, entirely negligible by comparison with the advantages.

STANDARD MISSILE DESIGN

At a later date, when initial ship defense requirements had been met and homing system designs had been proven, a decision was made to stop production of the beamriding version of Terrier. At that time, the follow-on versions of Homing Terrier and Tartar were designated Standard Missile to emphasize the "single missile" nature of the development process.[26] The value of the program approach was further evidenced when Standard Missile versions were quickly and efficiently developed for applications other than surface-to-air defense of the fleet, for example, as air-to-surface antiradiation missiles or antisurface missiles with active guidance.[27]

SYSTEMS ENGINEERING TECHNIQUES

As previously stated, the sectionalized missile designs and the noncritical aerodynamic configuration were essential to effective implementation of the interchangeability concept for Terrier/Tartar/Standard Missile. It is important to note, however, that the programs could not have been successful without the concurrent development of requisite systems engineering approaches and techniques. Reference 28 specifically discusses systems engineering for the initial tail-control beamriding Terrier program, but the design philosophy and methodology were applied for all of the interactive programs.

It is emphasized in Ref. 28 that the process of defining performance requirements was closed-loop, involving preliminary design trade-offs to assure that the specified performance would be consistent with the goal of designing a high-performance missile capable of large-scale production on an established schedule (see Fig. 15). The general approach is outlined as follows:

1. An over-all missile design is selected that appears to provide a substantial margin of performance over the stated requirements; a combination of aerodynamic, dynamic, and structural characteristics is chosen that seems appropriate to noncritical design.

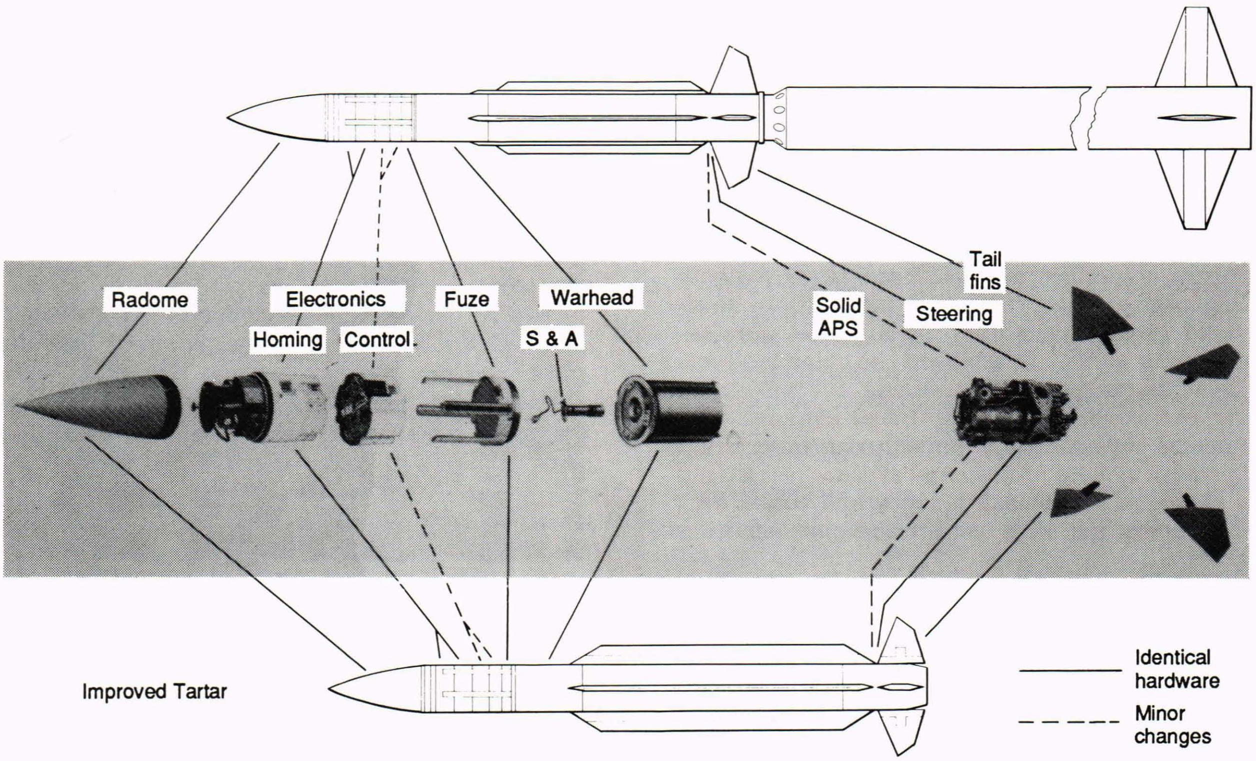

Figure 14. Terrier HT (Homing Terrier) and improved Tartar showing interchangeable hardware (APS = auxiliary power supply, S & A = safety and arming).

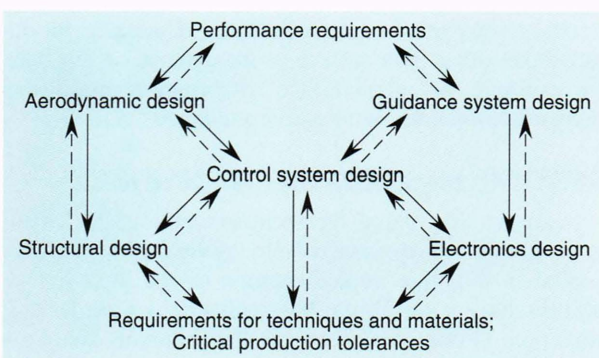

Figure 15. Terrier BT (Beamriding Tail-Control) Preliminary Design Approach.

2. The design is subdivided (sectionalized) along functional lines, to permit flexibility of design in functionally separate areas and to minimize coordination problems.
3. The design areas of greatest difficulty are determined, and all design requirements are organized to provide maximum latitude in those areas.
4. Each element of the missile is designed for required performance, rather than for maximum possible performance; simplification of design and broadening of tolerances are emphasized rather than improvement of performance beyond the given requirements.
5. Reserve design margins are provided in the preliminary design phase to "leave room" for unforeseen problems.
6. The number of engineering challenges is minimized by employing techniques well within the state-of-the-art; techniques not yet proved in production are used only where absolutely essential.[28]

In the development of production tolerances,

> Statistical (Monte Carlo) methods are employed to evaluate the effects of production tolerances on performance; the possibility of a small percentage of functional failures is allowed in order to permit general broadening of tolerances. Studies are directed toward broadening of permissible tolerances in areas of design difficulty; an attempt is made to determine the best balance of tolerances for the stated over-all performance goal.[28]

Overall, the intent was to develop and use production designs as early as possible during the flight-testing programs so that there could be a relatively smooth transition from development to production. In the latter stages of the flight demonstration/validation programs, the prototype missiles were very similar to the planned pilot production designs.

For each section of the missile, all functional design requirements were specified in APL "Performance and Compatibility Requirements" documents (see, for example, Fig. 16 for Standard Missile), and interface control among elements was maintained by using "Correlation Drawings" that defined electrical, mechanical, and spatial requirements. Formal, continuing studies were conducted under APL direction with representation by all contractors affected by a particular interface to ensure that an appropriate balance of interface requirements had been achieved.

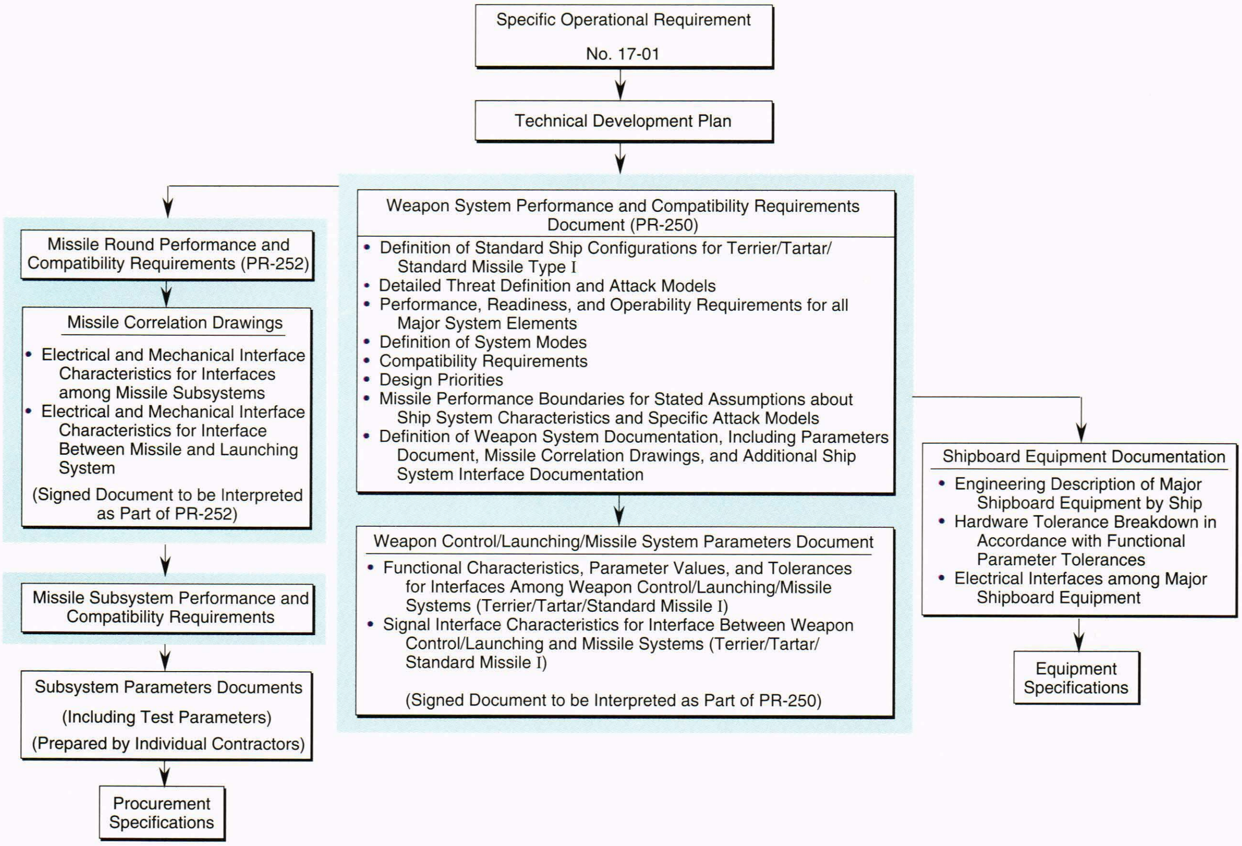

Figure 16. Hierarchy of APL Performance and Compatibility Requirements documents for the Standard Missile.

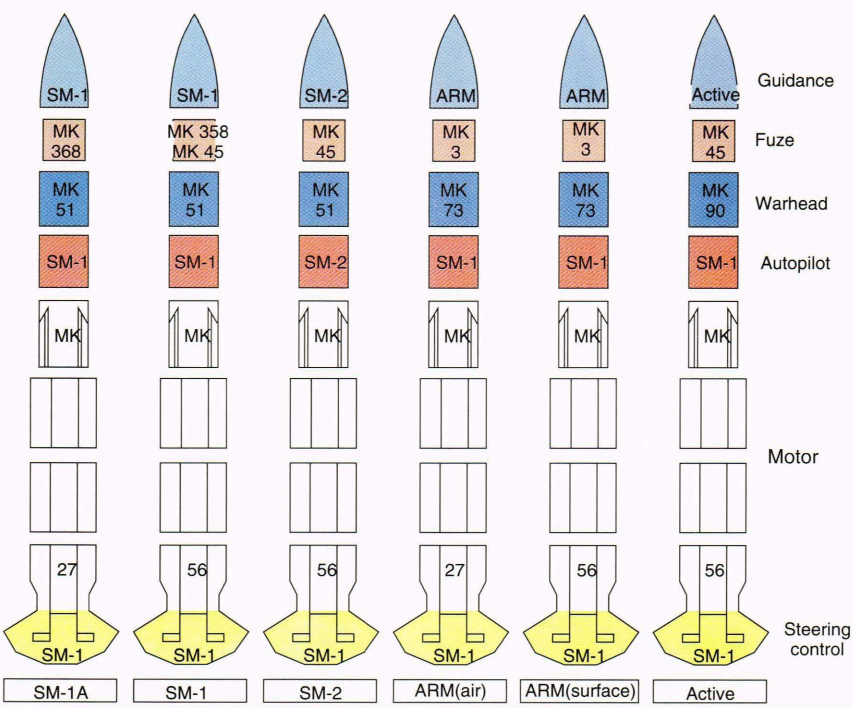

Figure 17. Medium-range Standard Missile family, including antiradiation and active-guidance missiles, derived from combination of components (ARM = antiradiation missile).

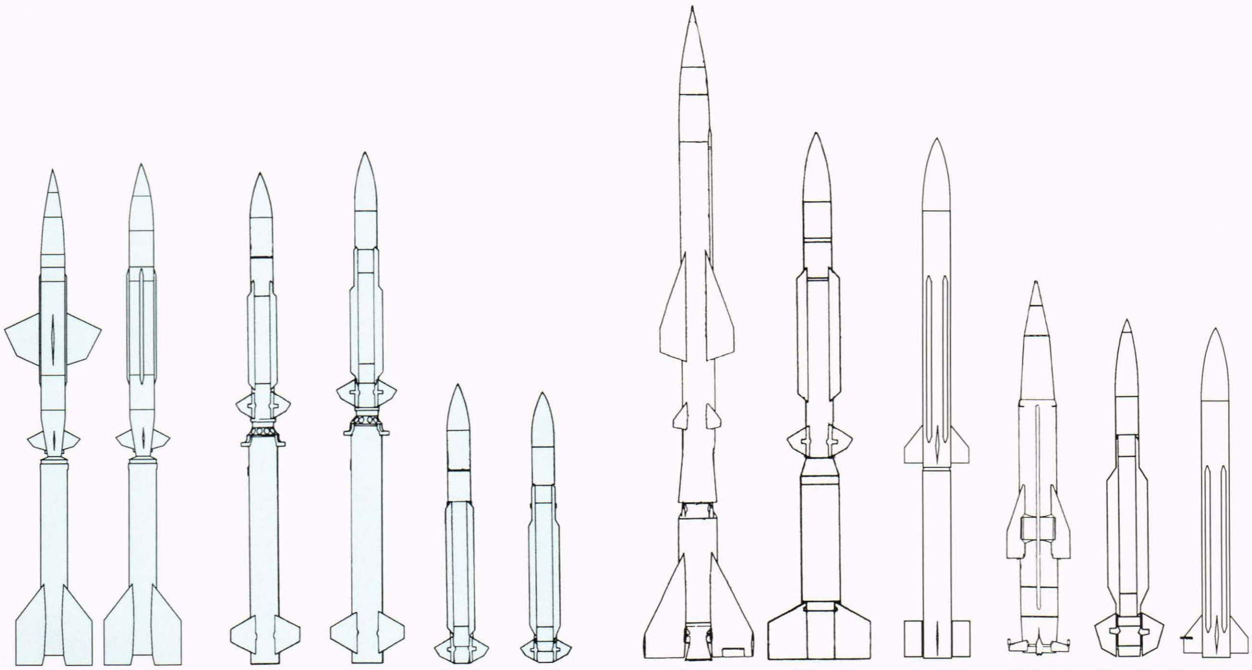

Figure 18. Missile configuration comparisons (ER = extended range, MR = medium range).

RECOGNITION OF THE STANDARD MISSILE APPROACH

It is worth noting that the value of the overall program approach was recognized and commended in a widely distributed report in 1974.[29] To quote from the reference:

> An outstanding example of the manner in which carefully-controlled interface specifications can provide a framework for evolution of variants of a mission-critical system is the Navy's Standard Missile program. The program involved the evolution of missiles to meet different threats in a field of rapidly changing technology. It invoked standard interfaces with the platform, launchers, etc., so that the new Standard Missiles could be employed on the older Terrier and Tartar ships with only minor (usually electrical) modifications required aboard ship. Intramissile interfaces were established and controlled so that new technology or new capability could be added a section at a time, and as a result new missiles representing completely new capabilities have been developed while making use of existing, available standard and proven missile sections and elements.
>
> The sketch [see Fig. 17] illustrates the several members of the Standard Missile (medium-range) family and the degree to which standardization has been achieved. Not shown is the fact that the Standard Missile-1 (SM-1) was itself developed by using many prior proved components, assemblies and sections from Terrier and Tartar.
>
> The benefits of this approach can be seen in two areas. First, the manpower in man-months and the calendar time required to achieve the first successful guided test vehicle of each successive type have been substantially smaller than what was required for the initial Standard Missile. Second, despite continuing performance improvement in successive missile types (e.g., doubling in altitude capability, quadrupling in range), missile production costs have stayed essentially constant.

WORLDWIDE AERODYNAMIC DESIGNS

With respect to the basic aerodynamic design of Terrier, Tartar, and Standard Missile, it is interesting to make comparisons with missile configurations that have evolved—some quite recently—in other countries (see Fig. 18).[30] Since fundamental aspects of aerodynamics and control technologies are involved, it is probable that many of the designs were derived independently, but the similarities are compelling. In any event, it is clear that the specific tail-control aerodynamic configurations pioneered by APL during the Bumblebee days are in widespread use and have not been outdated by subsequent developments.

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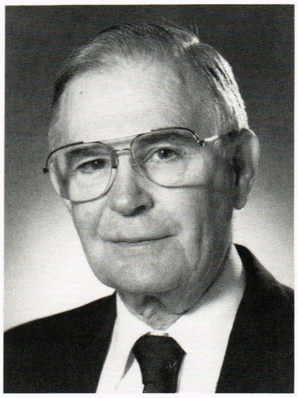

ALVIN R. EATON received his A.B. in physics from Oberlin College and his M.S. in aeronautical engineering from the California Institute of Technology. Relative to the subject of this article, he received a U.S. Navy Meritorious Public Service Citation as "personally responsible for most of the aerodynamic design of Terrier, and for the solution of many difficult problems, such as supersonic roll reversal, which threatened to halt the successful development of the missile." He was responsible for direction of the tail-control Terrier program from inception into production. After supervising other missile programs, he became Head of the Missile Systems Division in 1965, Head of the Fleet Systems Department and Assistant Director for Tactical Systems in 1973, Assistant Director in 1979, and Associate Director from 1986 to 1989. He is currently a Senior Fellow and Director of Special Programs. He has received a U.S. Navy Distinguished Public Service Medal and numerous commendations from other agencies. He is listed in *Who's Who in America* and *Who's Who in the World.*