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Technologies for Future Precision Strike Missile Systems - Missile Design Technology

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Abstract/Executive Summary

This paper provides an assessment of the state-of-the-art and design considerations of missile design technology for future precision strike missile systems. Benefits of missile design technology include advanced missile concepts, identification of driving parameters, balanced subsystems, incorporation of new technologies, light weight/low cost missiles, and launch platform compatibility. The paper discusses the missile design process, presents examples of simulation and spreadsheet conceptual design computer programs, provides missile configuration design criteria, and lists references that are applicable to missile design technology.

Missile Design Process

Figure 1 shows the relationship of missile design to the development process of research, technology, and acquisition. Conceptual design is most appropriate during the exploratory development phase of missile development. A primary objective of exploratory development is to investigate and evaluate technology alternatives. The advanced technology development phase of missile development is intended to mature the enabling technologies of key subsystems. Although conceptual design methods are also used during advanced development, preliminary design methods are usually more appropriate. Preliminary design methods continue to be used during the advanced

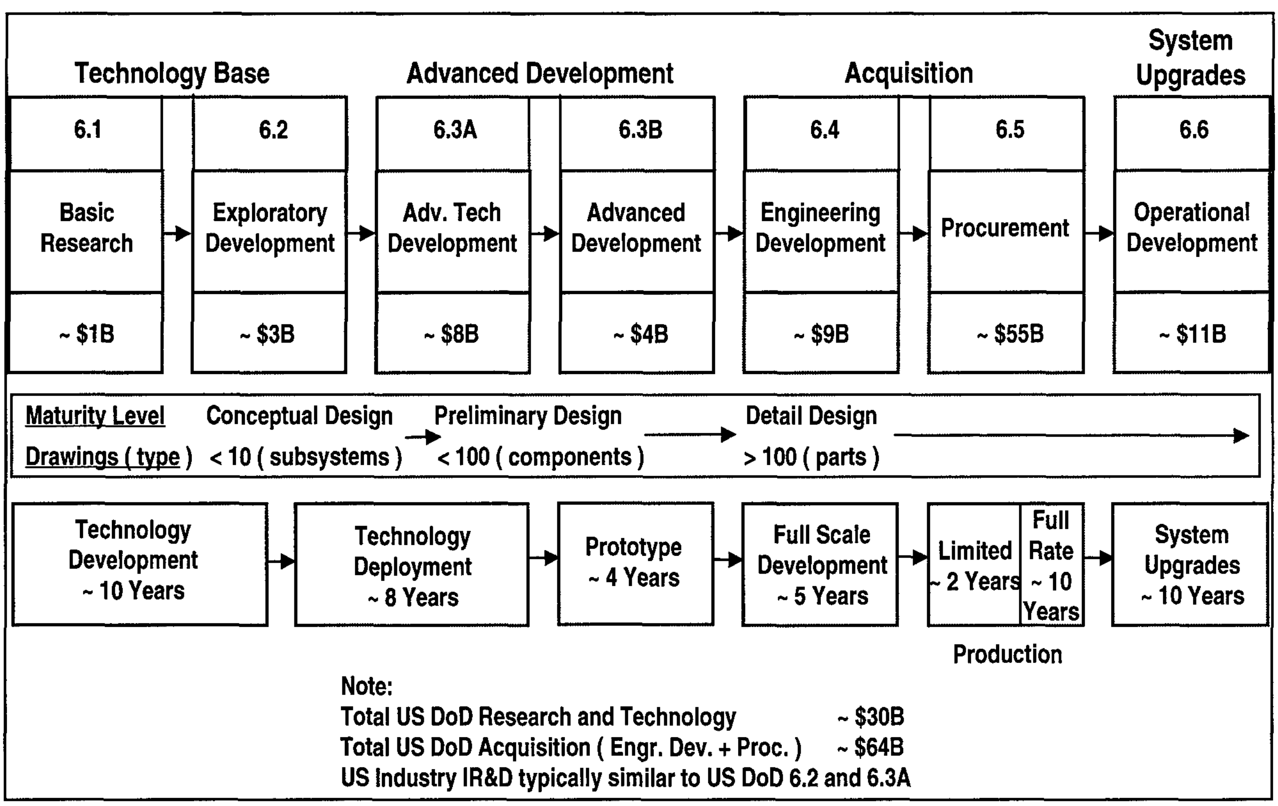

Figure 1. Relationship of Level of Design to the Research, Technology, and Acquisition Process.

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development demonstration of the prototype missile. Following successful demonstration of a prototype, the missile program moves into engineering and manufacturing development (EMD). At this point more detail design methods are required.

An indicator of design maturity is the number of drawings that are required to describe the design. Conceptual design may be characterized by fewer than ten drawings, describing fewer than ten subsystems. Conceptual design drawings include the missile overall dimensions, major subsystems layout, and may also list the major subsystems mass properties. Preliminary design drawings of a prototype missile are usually characterized by up to 100 drawings, with greater detail and showing up to 100 components. Preliminary design drawings have fully dimensioned subsystems, inboard layouts showing subsystems, individual subsystem and component drawings, and dimension tolerances. Detail design for EMD usually requires more than 100 drawings and often has more than 1,000 drawings. EMD drawings also have greater detail, including drawings of each part, detailed work assembly instructions and descriptions of the manufacturing processes.

Conceptual design and sensitivity studies should be conducted early in the exploratory development process, and continued into advanced development. Many of the cost performance drivers are locked in during the conceptual design phase. It is therefore important to quickly evaluate a large number of alternatives that cover the feasible design solution space.

Figure 2 shows a typical missile conceptual design process. Conceptual design is an iterative process, requiring a balance of emphasis from diverse inputs and outputs. The major tasks of conceptual design are 1) mission/scenario definition; 2) weapon requirements, trade studies and sensitivity analysis; 3) physical integration of the missile with the launch platform; 4) weapon concept design synthesis; and 5) technology assessment and technology development roadmap. The initial design process begins with a general definition of the mission/scenario. Mission/scenario definition can have one or more updates during the design process. The initial input is a "requirements pull" desired capability from the military customer. It is evaluated against the "technology push" potential technology availability, provided by the technical community. The weapon requirements, trade studies, and sensitivity analysis task provides high level requirements on the missile such as range, speed, and other measures of merit. This task is oriented towards an operations analysis of a system-of-systems. The high level requirements may be derived from system-of-system models such as campaign, raid, or engagement models. The system-of-systems modeling could include a campaign model with many different types of systems interacting over a simulated time interval from days to weeks. It could also include a raid model of multiple platforms engaging multiple targets. Finally, the system of systems model could include a one-on-one engagement model of a launch platform and missile engaging a target or threat. The third task, physical integration of the missile with the launch platform, provides constraints such as length, span, and weight. This task is oriented towards systems integration. The fourth task, weapon concept design synthesis, is the most iterative and arguably the most creative. As the design matures and becomes more defined through iteration, the number of alternative solutions is reduced from a broad range of possibilities to a smaller set of preferred candidates. More in-depth information is provided for the design subsystems. Finally, a technology assessment task further defines the subsystems and selects the best technology from candidate approaches. The technology trades lead to a set of enabling technologies. A technology roadmap documents the development plan for maturing the enabling technologies.

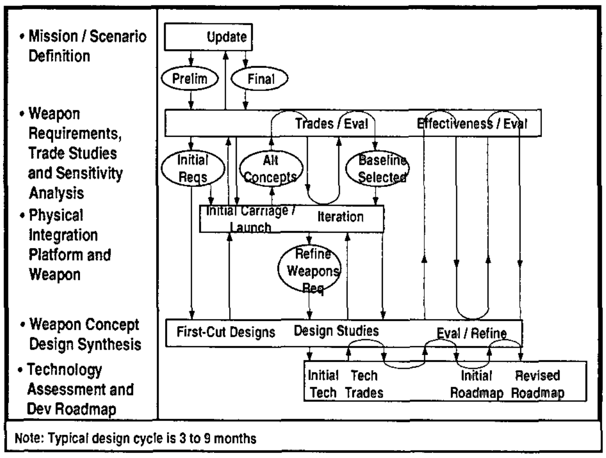

Figure 2. Conceptual Design of Precision Strike Missiles Requires Iteration.

A typical duration for conceptual design is three to nine months. The products of the missile design activity include refined mission/scenario definitions, system-of-systems definition of the missile requirements, launch platform compatibility, advanced missile concepts, identification of the enabling technologies, and a technology roadmap.

Conceptual design is an opportunity to harmonize diverse inputs early in the development process. The military customer has the lead in providing the "requirements pull" initial input for the mission/scenario definition task. The mission/scenario definition may be modified later as a result of the "technology push" of available capability. The system-of-systems weapon requirements, trade studies, and sensitivity analysis is usually conducted by operations analysis personnel. System integration engineers usually lead the task to integrate the missile with the launch platform. Missile design engineers lead the task to synthesize missile concepts. Finally, technical specialists provide the lead input for the "technology push" of potentially available technical capability and the technology development roadmap.

Figure 3 shows current missiles that address the precision strike mission/scenario task shown in the previous figure. The possible solution space for mission/scenario definition of a precision strike missile covers a broad range of alternatives. Precision strike missile targets include fixed targets, radar sites, ships, armor, and buried targets.

In the case of fixed targets (which usually are of large size and relatively soft), a blast fragmentation or dispensed submunition warhead is usually used. These missiles are relatively large, with wings for efficient subsonic flight. Current missiles in this category include AGM-154 JSOW, Apache, KEPD-350, BGM-109 Tomahawk, and AGM-142 Have Nap.

The second target category is radar sites. These are also relatively soft, and a blast fragmentation warhead is usually used. Anti-radar missiles have an anti-radiation homing (ARH) seeker and generally fly at high supersonic Mach number. High speed is desirable for launch aircraft survivability in a SAM engagement and to minimize the probability of shut down by the threat radar before missile impact. Current anti-radar site missiles include AGM-88 HARM, AS-11 Kilter/Kh-58, ARMAT, AS-12 Kegler/ Kh-27, and ALARM.

A third category is ship targets. Ships are relatively hard targets and usually require a kinetic energy penetrating warhead, followed by blast fragmentation after penetration of the hull. Anti-ship missiles are generally large size and have a large warhead. Anti-ship missiles are designed to survive ship defenses, relying on either speed or flying at low altitude in clutter to survive. Current anti-ship missiles include MM40 Exocet, AS-34 Kormoran, AS-17 Krypton/Kh-34, Sea Eagle, and SS-N-22 Sunburn/3M80.

A fourth category is armor targets. This includes tanks, armored personnel carriers, and other armored combat vehicles. Armor targets are small size, mobile, and very hard. Typical anti-armor warheads include shaped charge, explosively formed penetrator (EFP), and kinetic energy penetrator. Most anti-armor missiles are small size, have hit-to-kill accuracy, and are low cost. The examples shown in Figure 3 are Hellfire/Brimstone, LOCAAS, MGM-140 ATACMS, AGM-65 Maverick, and TRIGAT.

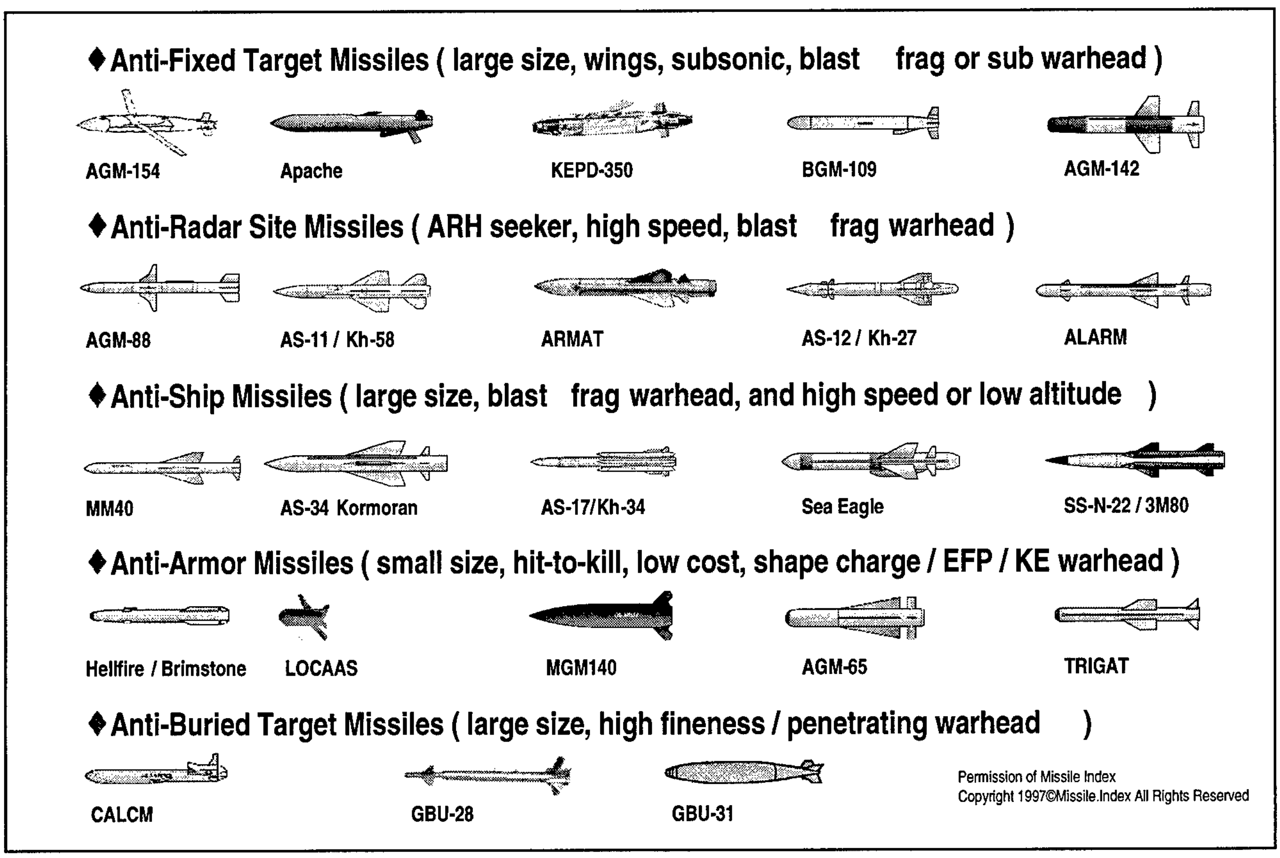

Figure 3. Current Missiles for Precision Strike Mission/Scenario Generally Have Similar Characteristics.

A final category is buried targets, such as underground command posts and bunkers. Buried targets require a high fineness kinetic energy penetration warhead, followed by blast fragmentation. These missiles are large and heavy. Examples of missiles in this category are CALCM, GBU-28, and GBU-31 JDAM.

New precision strike missiles have capability against more than one type of target. An example is a combined capability to engage and defeat hardened, buried targets and mobile surface targets. Benefits of producing a multipurpose missile that is effective against a broader range of targets include reduced unit production cost and reduced logistic cost. A multipurpose precision strike missile requires that the system-of-systems weapon requirements, trade studies, and sensitivity analysis task explore a broad operations analysis space during conceptual design. An example of the broad analysis space for the weapon requirements of future precision strike missiles is shown in Figure 4. One approach is based on a standoff launch platform, with an aircraft or ship standing off outside the threat country border. Hypersonic long-range precision strike missiles provide broad coverage, holding a large portion of the threat country at risk. This approach is attractive in the small number of launch platforms required and the effectiveness against time critical targets. The cost of future hypersonic missiles is expected to be comparable to that of the current cruise missiles, such as the BGM-109 Tomahawk.

Another alternative approach is to use overhead loitering unmanned combat air vehicles (UCAVs) with hypersonic precision guided missiles. The number of UCAVs required is dependent upon the speed and range of their on-board precision strike missiles. This approach would probably provide the fastest response time against time critical targets, because of the shorter required missile flight range for an overhead loitering system.

A third approach is overhead, loitering UCAVs with subsonic precision guided munitions. This approach would have the lowest cost per shot, but would require a relatively large number of UCAVs.

Figure 5 shows a typical process for conceptual design synthesis. Based on mission requirements, an initial baseline from an existing missile with similar propulsion is established. It is used as a starting point to expedite design convergence. Advantages of a baseline missile include balanced system engineering for the subsystems and an accurate benchmark of test data (e.g., wind tunnel data). Changes in the baseline missile aerodynamics, propulsion, weight, and flight trajectory are then evaluated against the new missile flight performance requirements (e.g., range, time to

Alternatives for Precision Strike	Cost per Shot	Number of Launch Platforms Required	TCT Effectiveness
Future Systems			
◆ Standoff platforms / hypersonic missiles	○	●	◒
◆ Overhead loitering UCAVs / hypersonic missiles	◒	◒	●
◆ Overhead loitering UCAVs / subsonic PGMs	●	○	◒
Current Systems			
◆ Penetrating aircraft / subsonic PGMs	●	–	–
◆ Standoff platforms / subsonic missiles	○	●	–

Note: ● Superior ◒ Good ○ Average – Poor

Note: C4ISR targeting state-of-the-art for year 2010 projected to provide 2 minutes target – shooter connectivity and target location error (TLE) less than 1 meter.

Figure 4. Weapon Trade Studies of Future Precision Strike Missiles Must Address A Broad Analysis Space.

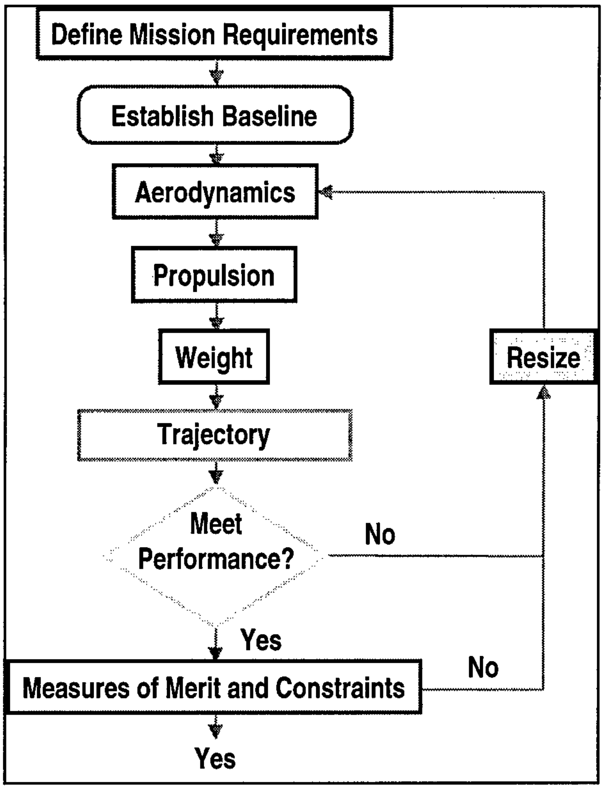

Figure 5. Missile Concept Synthesis Requires Iteration.

target, maneuver footprint). The aerodynamics portion of the conceptual design process is an investigation of alternatives in configuration geometry. The output of the aerodynamics calculation is an input to propulsion system sizing. Propulsion sizing includes providing sufficient propellant or fuel to meet the range and time-to-target requirements. The next step is to estimate the weight of the new missile with its modified aerodynamics and propulsion. Much of this activity is focussed on structural design, which is sensitive to changes in flight performance. Following the weight sizing, flight trajectories are computed and the range, terminal velocity, maneuverability, miss distance, and other parameters are computed and compared with the mission flight performance requirements. If the missile does not meet the flight performance requirements, it is resized and reiterated. After completing a sufficient number of iterations to meet the flight performance requirements, the next step is evaluating the new missile against the measures of merit and constraint requirements. If the missile does not meet the requirements, the design is changed and resized for further evaluation.

Figure 6 is an example of baseline data that is used in conceptual design sizing. The example is based on a chin inlet, integral rocket ramjet. Other examples could be based on the current precision strike missiles

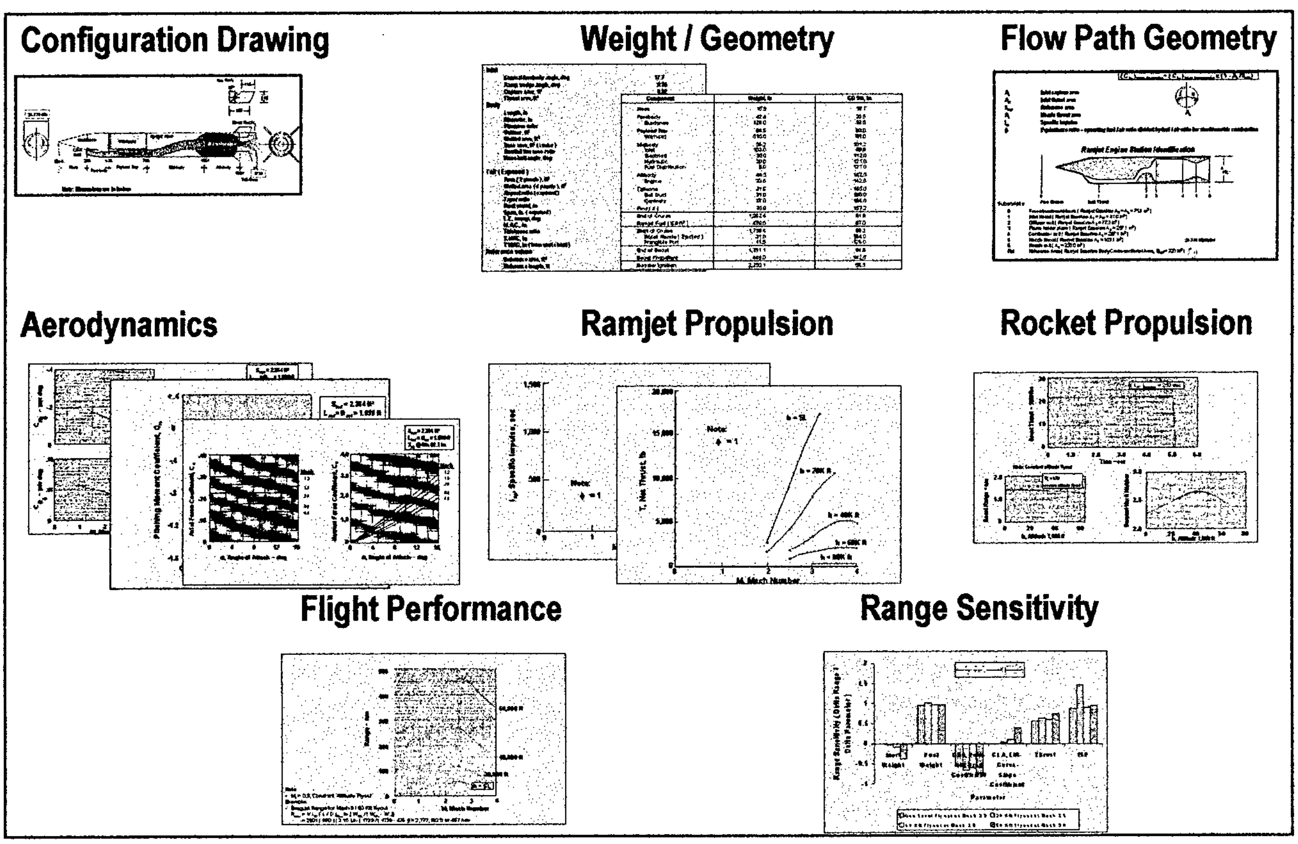

Figure 6. Example of Precision Strike Missile Baseline Data.

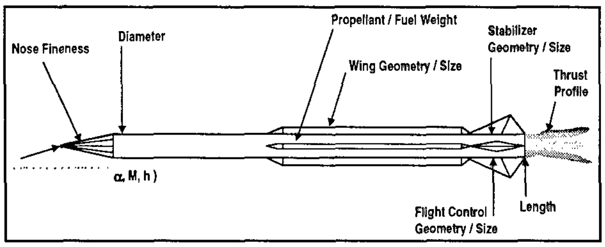

Figure 7. Aerodynamic Configuration Sizing Parameters.

shown in Figure 3. In the upper left of Figure 6 is an illustration of a configuration drawing of the baseline missile. The configuration drawing is a dimensioned layout, with an inboard profile showing the major subsystems (guidance, warhead, fuel, booster/engine, and flight control surfaces). In the upper center of the figure are examples of tables for a missile weight statement and geometry data. Missile weight and center-of-gravity location are provided for launch, booster burnout, and engine burnout flight conditions. Weight and geometry data are also provided for the major subsystems. The upper right corner of the figure is an illustration of a description of ramjet internal flow path geometry. The internal flow path geometry data includes the inlet design capture area and the internal areas of the inlet throat, diffuser exit, flame holder plane, combustor exit, nozzle throat, and nozzle exit. Examples of aerodynamic data plots are illustrated in the left center section of the figure. Aerodynamic data for the ramjet baseline covers angles of attack up to 16 degrees and Mach numbers up to 4.0. Aerodynamic coefficients and derivatives include zero-lift drag coefficient (C_{D_0}), normal force coefficient (C_N), pitching moment coefficient (C_m), pitching moment coefficient control effectiveness (C_{m_δ}), and normal force coefficient control effectiveness (C_{N_δ}). Examples of ramjet propulsion thrust (T) and the ramjet specific impulse (I_{SP}) are shown in the center of the figure. Thrust and specific impulse are functions of Mach number and fuel-to-air ratio. Rocket booster propulsion thrust, boost range and burnout Mach number are illustrated in the right center of the figure as a function of launch Mach number and altitude. The left bottom section of the figure shows the maximum flight range of the ramjet baseline. Maximum flight range is a function of launch Mach number and altitude. Finally, the right bottom section of the figure is an example of the sensitivity of design parameters on maximum flight range. Sensitivity parameters include inert weight, fuel weight, zero-lift drag coefficient, lift-curve-slope coefficient (C_{L_α}), ramjet thrust, and ramjet specific impulse. The sensitivity study in the example was conducted for cruise flight conditions ranging from Mach 2.4/sea level to Mach 3.0/60,000 feet.

Figure 7 is a summary of the aerodynamic configuration sizing parameters for precision strike missiles. Flight condition parameters that are most important are angle of attack, Mach number, and attitude. The missile diameter and length have a first order effect on missile drag, subsystem packaging available volume, launch platform integration, seeker and warhead effectiveness, and body bending. Nose fineness is an important contributor to missile drag, especially for supersonic missiles. Also, nose fineness affects seeker performance, available propellant length, and missile observables. Missile propellant/fuel is directly related to the flight performance range and velocity. Wing geometry and size are often set by maneuverability requirements. Stabilizer geometry and size are often established by static margin requirements. In the flight control area, the geometry and size of the flight control surfaces determine the maximum achievable angle of attack and the resulting maneuverability. Finally, the thrust profile determines the missile velocity time history.

The aerodynamic configuration sizing parameters shown in the previous figure have a strong impact on the weapon requirements for precision strike missiles. Figure 8 is an assessment of the relative impact of aerodynamic configuration sizing parameters on their measures of merit (e.g., weight, range, maneuver footprint, time to target). Also shown is the impact of aerodynamic configuration sizing parameters on other measures of merit (e.g., robustness, lethality, miss distance, observables, survivability, cost), as well as their impact on constraints (e.g., launch platform integration weight, length, and span constraints).

The flight trajectory evaluation activity under missile concept synthesis, discussed previously in Figure 5, requires consideration of the degrees of freedom to be simulated. Figure 9 compares the simulation modeling degrees of freedom that are usually used in conceptual design with the degrees of freedom that are appropriate for preliminary design. As discussed previously, conceptual design requires rapid evaluation of a large range of alternatives, requiring that the design methods be fast, easy to use, and have a broad range of applicability. The simplest model, often acceptable for the conceptual design of high-speed missiles, is one degree of freedom. One degree of freedom modeling requires only the zero-lift drag coefficient, thrust, and weight. Analytical equations can be used to model a one degree of freedom simulation. Other models used for conceptual design are two degrees of freedom, three degrees of freedom point mass modeling, and three degrees of freedom pitch modeling. Finally, missile simulation modeling during preliminary design is usually modeled in six degrees of freedom (6DOF). The 6DOF simulation includes three forces (normal, axial, side), three moments (pitch, roll, yaw), thrust, and weight.

Aero Configuration Sizing Parameter	Impact on Weapon Requirement									
	Aero Measures of Merit			Other Measures of Merit						Constraint
	Weight	Range / Maneuver	Time to Target	Robust-ness	Lethality	Miss Distance	Observ-ables	Survivability	Cost	Launch Platform
Nose Fineness	●	●	●	●	●	●	●	●	◒	○
Diameter	●	●	●	●	●	◒	●	●	●	●
Length	●	●	◒	●	◒	◒	●	●	●	●
Wing Geometry / Size	●	●	◒	●	●	●	●	●	●	●
Stabilizer Geometry / Size	●	●	○	●	●	●	●	●	◒	●
Flight Control Geometry / Size	●	●	○	●	●	●	●	●	◒	●
Propellant / Fuel	●	●	●	●	◒	◒	◒	●	●	◒
Thrust Profile	●	●	●	●	◒	◒	◒	●	●	–
Flight Conditions (α, M, h)	●	●	●	●	●	●	◒	●	●	○

● Very Strong ◒ Strong ○ Moderate – Relatively Low

Figure 8. Aerodynamic Configuration Sizing Parameters Have High Impact on Precision Strike Missile Measures of Merit and Constraints.

It is instructive to examine the equations of motion for missile design drivers. Figure 10 shows the equations of motion for three degrees of freedom with pitch modeling. The figure shows the missile angular acceleration ($\ddot{\theta}$), rate of change in the flight path angle ($\dot{\gamma}$), and the rate of change in the velocity ($\dot{V}$). The configuration sizing implication from examining the angular acceleration equation shows the importance of control effectiveness. High control effectiveness is provided by high pitching moment control effectiveness ($C_{m\delta}$), low static stability ($C_{m\alpha}$), and small moment of inertia (I_Y). A small moment of inertia is a characteristic of a light weight missile. The second equation shows the design drivers for missile maneuverability. High maneuverability is the capability to make large and rapid changes in the flight path angle. This occurs for large normal force coefficient (C_N), light weight (W), and low velocity (V). Implications of the third equation are missile speed and range. High-speed and long-range flight is provided by large total impulse, or the integral of thrust for the burn time duration ($\int T dt$). There is payoff for flight range in using high density propellant/fuel. High density propellant/fuel increases the total impulse of a volume limited propulsion system. The third equation also shows that low axial force coefficient (C_A) provides longer range. Axial force coefficient is approximately equal to zero-lift drag coefficient (C_{D_0}).

Referring back to Figure 2, the physical integration of the conceptual missile with the launch platform uses first-cut missile designs for an initial check on carriage

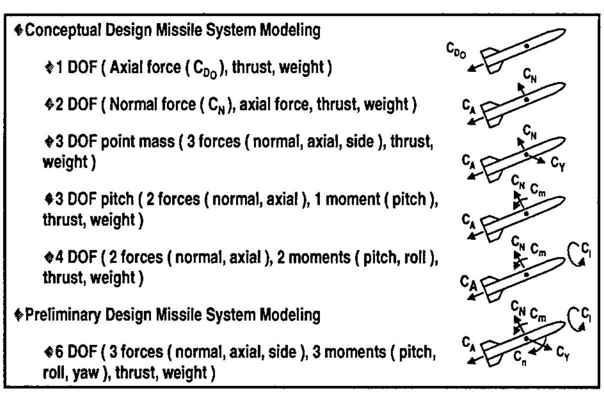

Figure 9. Conceptual Design Uses Simple Modeling of the Missile System.

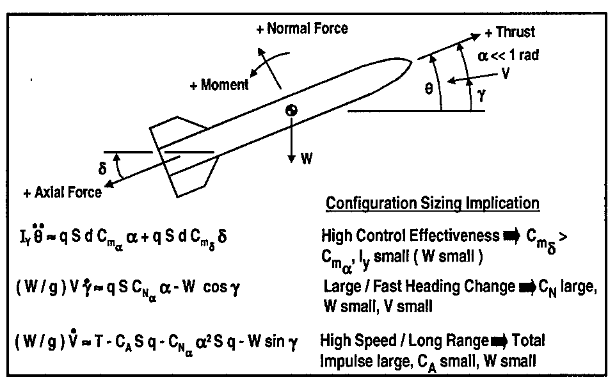

Figure 10. 3DOF Simplified Equations of Motion Show Drivers for Missile Configuration Sizing.

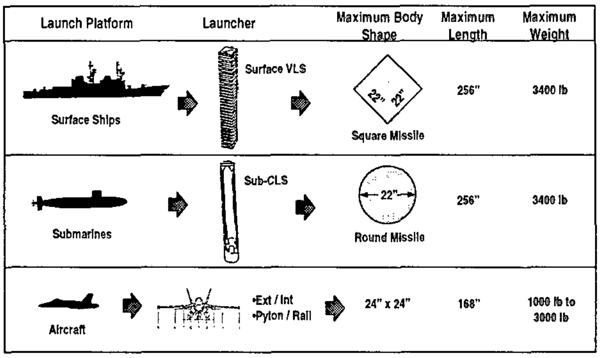

Figure 11. Missile Shape, Size, and Weight Are Driven By Launch Platform Compatibility.

and launch compatibility. Additional checks in launch platform compatibility are made during the design iteration process. Examples of launch platform carriage constraints for missiles on surface ships, submarines, and aircraft are shown in Figure 11. In the United States, the Vertical Launch System (VLS) is a standard carriage and launch system for missiles on surface ships. The VLS geometry constraints are 22 in x 22 in x 256 in. The maximum weight constraint is 3400 lb. United States submarines have a similar standard launcher that is circular in cross section. The submarine Canister Launch System (CLS) has a diameter constraint of 22 inches and a length constraint of 256 inches. Maximum missile weight for the CLS is the same as VLS, 3400 lb. Finally, aircraft launch platforms for precision strike missiles include tactical fighters, bombers, and helicopters. Shown in the figure is an example of a fighter aircraft, the F-18C. The F-18C carries weapons externally on pylons and rails. Other aircraft, such as the F-22, have an additional capability of internal carriage. Missile span constraint for aircraft is about 24 in x 24 in. Length constraint is about 168 in, and maximum missile weight varies from about 1,000 to 3,000 lb, depending upon the aircraft. There is a strong desire for light weight precision strike missiles, in order to maximize the firepower of small aircraft, such as the F-18C.

Finally, referring back a final time to Figure 2, note that the last activity in conceptual design is technology assessment and a technology development roadmap. Technology road maps identify the technology drivers, key decision points, critical paths, and resource needs. The purpose of a technology roadmap is to establish time phase relationships for the missile technology development activity. This includes 1) development of plans for technology development and validation, 2) identification of technology options, 3) setting time-phased technology goals, and 4) development of a plan for technology transition. The technology plan shows a proposed approach in maturing the missile through the missile development phases previously discussed in Figure 1. As a result of technology development, the missile level of maturity will move from that of exploratory development, to advanced technology development, to a prototype demonstration. For most new missiles, a technology development, risk reduction, and maturity demonstration activity is required prior to entering EMD.

Examples of Missile Conceptual Design Simulation Programs

A fundamental requirement for conceptual design is short turnaround time. Fast turnaround time is necessary to search a broad solution space with a sufficient number of iterations for design convergence. The computer program used in conceptual design should be fast and easy to use. A good design code connects the missile physical parameters directly to a trajectory code that calculates flight performance.

More detailed computational methods are used later, in preliminary design, when the number of alternative geometric, subsystem, and flight parameters has been reduced to a smaller set of alternatives. As an example, it is inappropriate to use computational fluid dynamics (CFD) in conceptual design. The mathematical considerations of CFD (e.g., mesh size, time interval, numerical stability, turbulence modeling, smoothing) are impediments to the fast response required for conceptual design. Similarly, a 6DOF trajectory simulation is inappropriate for convenient evaluation of missile guided flight. The development of the required autopilot for 6DOF guided flight is time consuming, diverting emphasis from other more appropriate considerations. Similarly, missile optimization codes are generally inappropriate for conceptual design. Optimization in conceptual design is best left to the creativity and the intuition of the designer. Also, optimization codes work best when there is a continuous smooth variation in parameters, which is usually not the case in conceptual design. For example, optimization codes do not work well in comparing ramjet propulsion versus rocket propulsion. The CFD, 6DOF guided flight trajectory simulations, and optimization codes have seductive "precision." However more often than not their accuracy in conceptual design is worse than simpler methods. Simpler aerodynamic and simulation methods, combined with a well defined baseline missile, and the designer's creativity and intuition are a preferable approach for alternatives selection, sizing, and optimization. They are invariably more accurate and robust. References 1 through 4 are examples of conceptual design methods that are fast, robust, and have sufficient accuracy for the relative screening of missile concept alternatives.

A synthesized missile will differ from the starting point baseline in several respects. For example, the wing area may be resized to meet the maneuverability requirement. The tail area may be resized to meet static margin and maximum trim angle of attack requirements. The rocket motor or the ramjet engine may be modified to improve its efficiency at the selected design altitude. Additionally, the length of the propulsion system may be changed in order to accommodate additional propellant/fuel necessary to satisfy flight range requirements. The design changes are reflected in revisions to the mass properties, configuration geometry, thrust profile, and flight trajectory for the missile. Typically, three to ten design iterations are required before a synthesized missile converges to meet the flight performance requirements.

Advanced Design of Aerodynamic Missiles (ADAM). The following discussion of the ADAM missile simulation program (Reference 4) is provided as an example of a computer program that meets the conceptual design criteria of speed, ease of use, and applicable to a broad range of configurations and flight conditions. ADAM is a DOS code that runs on a PC. The aerodynamics predictions are based on the slender body and linear wing theory of Reference 5. Except at Mach 1, the aerodynamic methods are valid from subsonic through hypersonic Mach numbers. The ADAM aerodynamics module calculates static stability derivatives, dynamic stability derivatives, trim conditions, and control effectiveness. Modeling of the equations of motion can be in three, four, five, or even six degrees of freedom. The three degrees of freedom flight trajectory model requires approximately one second of run time on a PC. The 6DOF flight trajectory simulation is used to analyze the nutation/precession modes of missiles during their unguided portion of flight, unguided bombs, and unguided projectiles. It requires approximately three seconds of run time on a PC. For homing missiles, proportional guidance is used, as well as other guidance laws. The input to the flight trajectory module is provided automatically by the aerodynamics module, simplifying the user input. The benchmark missiles used in the aerodynamics module have corrected coefficients and derivatives based on wind tunnel data. Greater than fifty input parameters are available. The input default is the baseline missile parameters, simplifying the input data preparation.

The baseline missiles in ADAM include air-to-air, surface-to-air, air-to-surface, and surface-to-surface missiles. The aerodynamic modeling of the body includes the diameter, nose configuration (geometry, fineness, bluntness), body bulge, boattail, and length. Up to three surfaces (stabilizers, wings, and controls) can be specified. The geometric modeling of each surface includes: the location, leading edge root and tip station, span, trailing edge root and tip station, thickness, control surface deflection limit, and the number of surfaces. The program models the missile center of gravity variation from launch to burnout. For propulsion, the thrust is modeled as a two value thrust profile, of a given time duration. The propellant weight of each thrust-time phase can also be specified. The target can be fixed or moving. Down range and cross range of the target is specified, as well as target altitude and velocity. Launch conditions for the missile are specified, including altitude, velocity, launch angle, and the guidance law. The output of a three degrees of freedom pitch simulation modeling includes a drawing of the missile geometry with dimensions, aerodynamic coefficients and derivatives, flight performance parameters (velocity, trim angle of attack, acceleration, range, trim control surface deflection) versus time, and missile miss distance.

Tactical Missile Design (TMD) Spreadsheet. Another computer technique suitable for conceptual design is spreadsheet analysis. Figure 12 (following page) shows the design parameters of the TMD Spreadsheet (Reference 1). The TMD Spreadsheet runs in Windows on a PC. It has six modules that follow the conceptual missile design tasks outlined in Figure 5. Based on external mission requirements (e.g., maximum range, minimum range, average velocity, measures of merit, and constraints), a baseline design is selected from the baseline missile spreadsheet module. Currently there are two possible baselines: a rocket powered missile, similar to the Sparrow AIM-7 missile, and a ramjet missile. The configuration, subsystem, and flight performance characteristics of the ramjet missile baseline are illustrated in Figure 6. The rocket missile baseline has a similar level of detail in its configuration, subsystem, and flight performance data.

Following the definition of mission requirements and the selection of a baseline configuration in the baseline spreadsheet module, the aerodynamics spreadsheet module is exercised. The aerodynamics spreadsheet module calculates zero-lift drag coefficient, normal force coefficient, aerodynamic center location, pitching moment control effectiveness, lift-to-drag ratio, and the required tail stabilizer surface area. The output data from the aerodynamics spreadsheet module, along with other default data from the baseline missile, are input into a propulsion spreadsheet module. The methodology used to calculate the aerodynamics of a supersonic missile body are based on slender body theory (Reference 5) for the linear low angle of attack contribution and blended with cross flow theory (Reference 6) at high angles of attack. It is applicable for all angles of attack, from zero to 180 degrees. The method used in calculating aerodynamics of supersonic missile fixed surfaces (e.g., wings, strakes, stabilizers) and movable surfaces (e.g., canards, tails) is based on linear wing theory (Reference 5) at low angle of attack and blended with Newtonian impact theory (Reference 6) at high angles of attack. The methods are valid for Mach numbers greater than about 1.5.

The propulsion spreadsheet module provides an estimate of range, velocity, thrust, and specific impulse. For a ramjet, the output also includes total pressure recovery in the inlet (Reference 7). Rocket motor thrust and specific impulse are based on the isentropic flow equations, adjusted for the change in specific heat ratio with temperature. Incremental velocity and range are based on the one-degree of

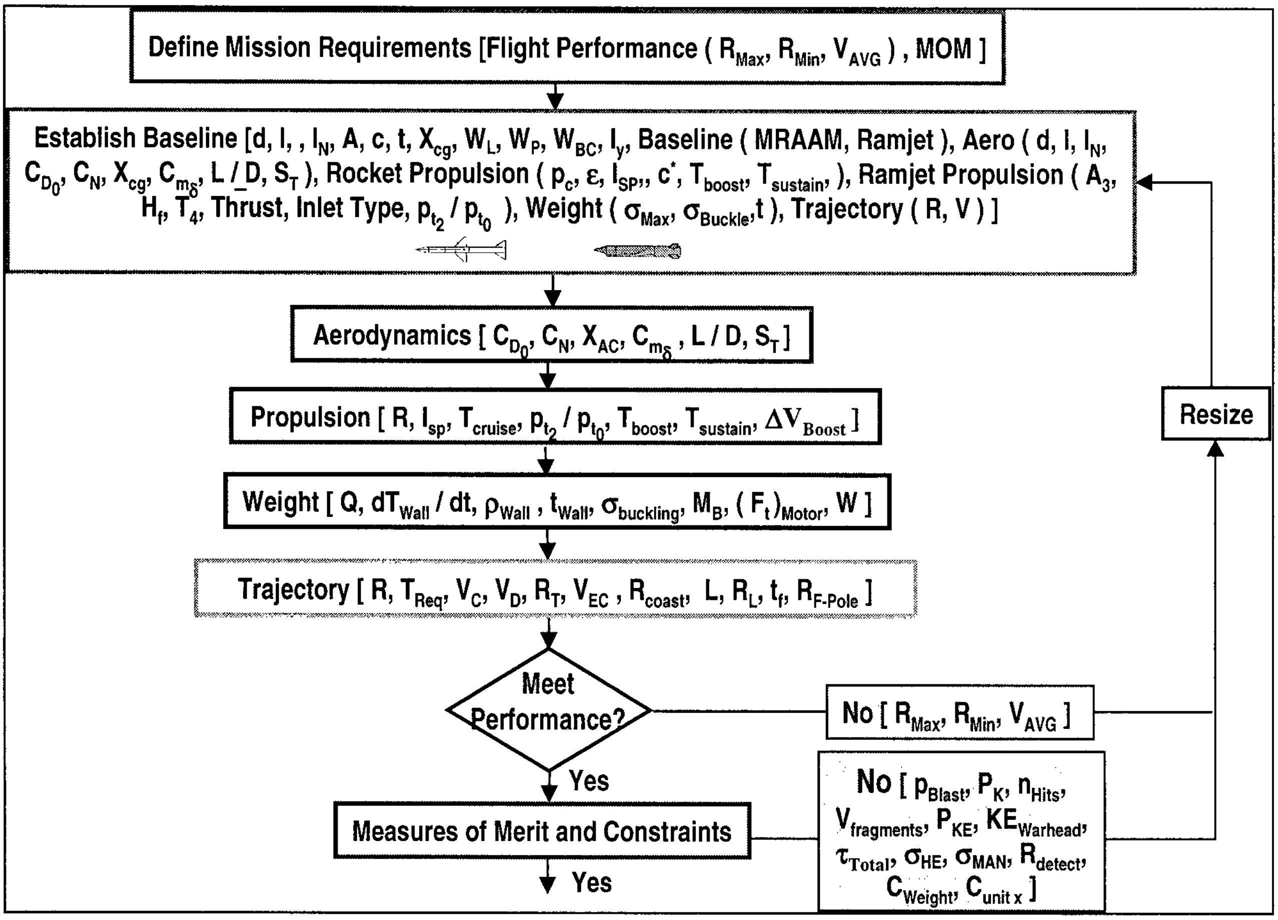

Figure 12. Tactical Missile Design (TMD) Spreadsheet Parameters.

freedom equation of motion. The ramjet thrust and specific impulse predictions include the forebody and cowl oblique shocks and the inlet normal shock losses in total pressure.

After redesigning the aerodynamic configuration and propulsion system, a weight spreadsheet is used to revise the missile weight. The weight spreadsheet module includes an estimate of aerodynamic heating, surface temperature versus time, required airframe and motor case thickness, buckling stress, bending moment, motor case stress, and the density/weight of subsystems. Missile system weight scaling is provided by the density relationship with diameter described in Reference 8. Scaling of the weights of subsystems is provided by the density relationships in Reference 1. Material data (e.g., density, stress-strain versus temperature) are also from Reference 1. Predictions of aerodynamic heating and surface temperature rate are given by the method described in Reference 9. Finally, missile body buckling stresses due to bending moment and axial loads, motor case stress, and required motor case thickness are from Reference 1.

The flight trajectory spreadsheet module has analytical expressions for one degree and two degrees of freedom trajectories. The output includes flight range, thrust required for steady flight, steady climb velocity, steady dive velocity, turn radius, velocity at the end of coast, range at the end of coast, seeker lead angle for proportional homing guidance, required launch range, missile time of flight, and F-pole range. Flight trajectory methods are based on closed-form analytical methods. Cruise range prediction is based on the Breguet range equation described in Reference 1. Thrust required for steady cruise, steady climb, and steady dive is based on Reference 10. Turn radius, coast velocity, coast range, missile homing lead angle, launch range, and F-pole range (relative range between the launch platform and the target when the missile impacts the target) are based on Reference 1.

Finally, the designer compares the output of the flight trajectory spreadsheet module against mission flight performance requirements. If the missile design does not meet the flight performance requirements, the process is repeated until the requirements are satisfied. The modularity of the spreadsheet and the default baseline missile data allows the designer to easily modify the input for the next iteration.

Once flight performance requirements are met, the measures of merit and constraints are then evaluated. The measures of merit spreadsheet module calculates parameters for warhead lethality, miss distance, survivability, and cost. Output parameters for the warhead lethality measure of merit include warhead blast pressure, kill probability, number of warhead fragments impacting the target, warhead fragment velocity, kinetic energy warhead penetration, and missile kinetic energy impacting the target for hit-to-kill missiles. Warhead blast pressure is based on Reference 11. Fragment velocity, kill probability, number of warhead fragments impacting the target, kinetic energy warhead penetration, and penetrator kinetic energy are based on Reference 1. Kinetic energy penetration depth is based on Reference 12. Output parameters for the missile miss distance measure of merit include missile time constant, missile miss distance due to heading error, and missile miss distance due to a maneuvering target. Miss distance is based on References 1 and 13. Output parameters for the missile survivability measure of merit include detection range, based on Reference 1. Finally, the output parameters for missile cost measure of merit include missile production cost due to weight and missile production cost due to the learning curve. Cost prediction is based on Reference 1, using data from Reference 14.

Again, the missile design is iterated until the measures of merit and constraints (such as launch platform integration) are satisfied.

Configuration Conceptual Design Sizing Criteria

An examination of configuration characteristics of the current precision strike missiles, missile sizing method parameters, and missile design activities suggests configuration design criteria. Table 1 has eleven configuration design criteria related to flight performance and guidance & control.

Configuration design criteria related to flight performance include missile body fineness ratio, nose fineness ratio, boattail ratio, cruise dynamic pressure, ramjet combustor temperature, and inlet integration. A design criterion for the missile body fineness ratio (length-to-diameter ratio) is that it should be between 5 and 25, to harmonize tradeoffs of drag, subsystem packaging available volume, launch platform integration, seeker and warhead effectiveness, and body bending. The nose fineness (nose length-to-diameter ratio) for supersonic missiles should be greater 1 to avoid high drag at high speed. Boattail ratio (boattail diameter-to-maximum missile diameter ratio) should be greater than 0.6 for supersonic missiles to avoid increased drag at high speed. A design criterion for efficient cruise flight is that the dynamic pressure be less than 1,000 lb/ft^2. Ramjet combustor temperature should be greater than 3,500 degrees Fahrenheit for high specific impulse and thrust at Mach number greater than 3.5. Efficient inlet integration for supersonic missiles requires at least one oblique shock prior to the inlet normal shock, for good inlet total pressure recovery at Mach numbers greater than 3.0. For Mach numbers greater than 3.5, at least two oblique shocks prior to the inlet normal shock are desirable for inlet total pressure recovery.

Configuration Sizing Parameter	Design Criteria
◆ Flight Performance Related	
♦ Body fineness ratio	$5 < l / d < 25$
♦ Nose fineness ratio	$l_N / d > 1$ if $M > 1$
♦ Boattail ratio	$0.6 < d_B / d_{Ref} < 1.0$
♦ Cruise dynamic pressure	$q < 1{,}000$ psf
♦ Ramjet combustor temperature	> 3,500 Degrees Fahrenheit
♦ Ramjet inlet integration	> 1 oblique shock if $M > 3.0$, > 2 oblique shocks if $M > 3.5$
◆ Guidance & Control Related	
♦ Body bending frequency	$\omega_{BB} > 2\omega_{ACT}$
♦ Trim control power	$\alpha / \delta > 1$
♦ Stability & control cross coupling	< 30%
♦ Airframe time constant	$\tau < 0.2$ sec
♦ Proportional guidance ratio	$3 < N' < 5$

Table 1. Precision Strike Missile Configuration Design Criteria.

Configuration design criteria related to guidance & control include the flight control actuator frequency, trim control power, stability & control derivatives cross coupling, airframe time constant, and proportional guidance ratio. Body bending frequency in the first mode of aeroelasticity should be greater than 2X the flight control actuator frequency if possible, to avoid the complication and risk of notch filters. Trim control power (trim angle of attack-to-control surface deflection ratio) should be greater than 1 for maneuverability. Stability & control derivatives cross coupling should be less than 30% for efficient dynamics. The missile airframe time constant should be less than 0.2 seconds for precision accuracy (3 meters). Contributors to a low value of the airframe time constant include high maneuverability capability, neutral static margin, high rate control surface actuators, low dome error slope, and a low noise seeker. Proportional guidance ratio should be between 3 and 5 to minimize miss distance. Values less than 3 result in excessive time to correct heading error, while values greater than 5 make the missile overly sensitive to noise input from the seeker.

Summary/Conclusions

Missile design is a creative and iterative process that includes system considerations, missile sizing, and flight trajectory evaluation. Because many of the cost and performance drivers are "locked in" early during the design process, the emphasis of this paper has been on conceptual design.

Conceptual design is an opportunity to harmonize diverse inputs early in the missile development process. The military customer, operations analysts, system integration engineers, conceptual design engineers, technical specialists, and others work together in harmonizing the mission/scenario definition, system-of-system requirements, launch platform integration, missile concept synthesis, and technology assessment/roadmaps.

Missile conceptual design is a highly integrated process requiring synergistic compromise and tradeoffs of many parameters. The synthesis of an effective compromise requires balanced emphasis in subsystems, unbiased tradeoffs, and evaluation of many alternatives. It is important to keep track of assumptions to maintain traceable results. Starting with a well-defined baseline which has similar performance and propulsion expedites design convergence and provides a more accurate design.

Conceptual design is an open-ended problem and has no single right answer. The available starting point information is never sufficient to provide only one solution. The design engineer makes assumptions in coming up with candidate concepts, subsystems, and technologies to satisfy mission requirements and cover the solution space. Weighting of the most important measures of merit is required in coming up with a cost-effective solution. Trade studies are conducted to investigate the impact of design parameters. Sensitivity analyses are also conducted to evaluate the effects of uncertainty in the design and the benefit of new technology. The missile is designed for robustness to handle risk and uncertainty of both a deterministic and a stochastic nature.

A good conceptual design code connects the missile geometric, physical, and subsystem performance parameters directly into a flight trajectory evaluation. Good conceptual design codes do not automatically change the design or resize automatically. It is best that the missile designer make the creative decisions.

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