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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 considerations of missile design technology for future precision strike missile systems. Benefits of missile design technology include new 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 often conducted 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 may also be conducted during advanced development, preliminary design methods are usually more appropriate. Preliminary design continues during advanced development demonstration of the prototype missile. Following successful demonstration of a prototype, the program moves into engineering and manufacturing development (EMD). At this point more detail design methods are appropriate for the operational missile. However, the assessment of possible future block upgrades may require the reintroduction of preliminary design and conceptual design activities.

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

An indicator of design maturity is the number of drawings that are required to describe the design. Conceptual design may be characterized by approximately five drawings for each concept, describing perhaps five subsystems. A large number of alternative concepts, perhaps ten, are in evaluation during conceptual design. Conceptual design drawings include the missile overall dimensions, major subsystems layout, and may also list the major subsystems mass properties. The next step is preliminary design. 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 the subsystems, individual subsystem and component drawings, and dimension tolerances. A fewer number of alternative missile concepts, perhaps four, are under evaluation during preliminary design. Following preliminary design, the next step is detail design. Detail design for EMD usually requires more than 100 drawings and often has more than 1,000 drawings. EMD drawings have even greater detail, including drawings of each part, detailed work assembly instructions and descriptions of the manufacturing processes. During EMD there is usually only one concept by a sole source contractor.

Figure 2 shows a typical missile conceptual design process. Conceptual design is an iterative process, requiring a balance of emphasis from the 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 documentation. 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 the high level requirements on the missile such as range, time to target, and other measures of merit. This task is oriented towards an operations analysis of a system-of-systems, including targeting. The high level requirements may be derived from campaign, raid, or engagement models. In a campaign model many different types of systems are interacting over a simulated time interval from days to weeks. A raid model has multiple platforms engaging multiple targets. An engagement model may be that of a single launch platform and missile engaging a single 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. Characteristics such as the aerodynamic shape, propellant or fuel type and weight, flight trajectory range, time to intercept, maneuverability, seeker detection range, accuracy, lethality, and cost are evaluated; and the missile is resized and reconfigured in an iterative process. As the design matures and becomes better 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 as the design matures. Finally, a technology assessment task further defines the subsystems and selects the best technology from the candidate approaches. The technology trades lead to a set of preferred, enabling technologies. A technology roadmap documents the development plan for maturing the enabling technologies.

A typical duration for a conceptual design activity 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 compliance, 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.

Examples of design alternatives for lightweight, air-launched multi-purpose precision strike weapons and their system considerations are shown in Figure 3. The selected examples are relatively lightweight air-launched missiles, because of the importance of firepower. Firepower is especially important for lightweight fighter aircraft, helicopters, and UCAVs, which may have a firepower limitation due to a store weight limit. Current operational air-launched precision strike missiles that are relatively lightweight include AGM-65 Maverick, Small Smart Bomb, AGM-88 HARM, Brimstone/Longbow/Hellfire, and LOCAAS. Measures of merit shown are the effectiveness against fixed surface targets, effectiveness against moving targets, effectiveness against time critical targets, effectiveness against buried targets, effectiveness in adverse weather, and the firepower loadout on the launch aircraft. Note that no one operational missile is superior in all areas. Small Smart Bomb has good effectiveness against fixed surface targets, has good effectiveness against buried targets, is capable of operation in adverse weather, and is relatively light weight (100, 250, and 500 pounds), providing high firepower. However Small Smart Bomb is relatively ineffective against moving targets and time critical targets. A new lightweight precision strike missile that combines the attributes of a small smart

bomb with the capability to handle moving targets and time critical targets would be more robust. Examples of technologies that provide robustness to handle a broad range of targets include:

- GPS/INS precision guidance
- SAR or imaging millimeter wave seeker for adverse weather homing
- Ducted rocket propulsion for higher speed and longer range
- Low drag airframe for higher average speed and longer range
- Multi-mode kinetic energy/blast fragmentation warhead
- Light weight subsystems for a lighter weight missile

Figure 4 shows the iterative process used 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 the design convergence. Advantages of a baseline missile include the prior consideration of balanced system engineering for the subsystems and the use of an accurate benchmark based on existing test data (e.g., wind tunnel data). Changes are made in the baseline missile aerodynamics, propulsion, weight, and flight trajectory to reflect the new requirements of the new missile concept. The new conceptual design is evaluated against its flight performance requirements (e.g., range, time to 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 then inputted to the propulsion system design to size the propulsion system. 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 for the new missile. The range, terminal velocity, maneuverability, and other flight performance parameters are then 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 other measures of merit and constraint requirements. If the missile does not meet the requirements, the design is changed (alternative configuration, subsystems, technologies) and resized for the next iteration and evaluation.

A synthesized missile will differ from the starting point baseline in several respects. For example, the wing area may have been resized to meet the maneuverability requirement. The tail area may have been resized to meet static margin and maximum trim angle of attack requirements. The rocket motor or the ramjet engine may have been modified to improve its efficiency at the selected design altitude or Mach number. Additionally, the length of the propulsion system may have been changed 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 six design iterations are required before a synthesized missile converges to meet the flight performance requirements.

Figure 5 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 precision strike missiles shown in Figure 4. In the upper left of the figure 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_{D0}), normal force coefficient (C_N), pitching moment coefficient (C_m), pitching moment coefficient control effectiveness derivative ($C_{m\delta}$), and normal force coefficient control effectiveness derivative ($C_{N\delta}$). 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, launch altitude, cruise Mach number, and cruise 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 derivative ($C_{L\alpha}$), 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, 60K feet altitude.

Figure 6 is a summary of the aerodynamic configuration sizing parameters for precision strike missiles. *Flight condition* parameters that are most important in the design of tactical missiles are angle of attack (α), Mach number (M), and altitude (h). For the aerodynamic configuration, the missile *diameter* and *length* have a first order effect on characteristics such as missile drag, subsystem packaging available volume, launch platform integration, seeker and warhead effectiveness, and body bending. Another configuration driver is *nose fineness*, an important contributor to missile drag for supersonic missiles. Also, nose fineness affects seeker performance, available propellant length, and missile observables. Another example is missile *propellant/fuel* type and weight, which drive flight performance range and velocity. The aerodynamic configuration *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 flight trajectory evaluation activity under missile concept synthesis requires consideration of the degrees of freedom to be simulated. Figure 7 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 is the rapid evaluation of a large range of alternatives. It requires 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 point mass modeling, three degrees of freedom point mass modeling, three degrees of freedom pitch modeling and four degrees of freedom roll modeling. In the 4DOF roll modeling the normal force, axial force, pitching moment, rolling moment, thrust, and weight are modeled for a rolling airframe missile. Finally, missile simulation 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. Missile degrees of freedom greater than 6DOF describe the structure bending modes. Because most tactical missiles are relatively stiff, modeling at greater than 6DOF is usually not required for aerodynamic control missiles but may be required for impulse reaction jet control missiles.

It is instructive to examine the equations of motion for missile design drivers. Figure 8 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 ($C_{m\alpha}$), small moment of inertia (I_y), and large dynamic pressure (q). A small moment of inertia is a characteristic of a lightweight 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), lightweight (W), and large dynamic pressure (q). Large C_N is achievable through large values of $C_{N\alpha}$, α , $C_{N\delta}$, and δ . Implications of the third equation are missile speed and range. High-speed and long-range are provided by large total impulse, or the integral of thrust for the burn time duration ($\int T dt$). There is also payoff for flight range in using higher density propellant/fuel. Higher 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) and low dynamic pressure provide longer range. Axial force coefficient is approximately equal to the zero-lift drag coefficient (C_{D0}).

Examples of Missile Conceptual Design Simulation Programs

Two fundamental requirements for computer programs used in conceptual design are fast turnaround time and ease of use. Fast turnaround is necessary to search a broad solution space with a sufficient number of iterations for design convergence. A good design code connects the missile physical parameters directly to a trajectory code that calculates flight performance. The conceptual design methods should be simple physics-based methods, incorporating only the most important, driving parameters. Baseline missile data should be imbedded in the code, to facilitate startup. 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 turnaround time that is required for conceptual design. Similarly, a 6DOF trajectory simulation is inappropriate during conceptual design for the convenient evaluation of 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. 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.

Advanced Design of Aerodynamic Missiles (ADAM).

The following discussion of the ADAM missile simulation program is provided as an example of a computer program that generally meets the conceptual design criteria of fast turnaround, ease of use, and applicable to a broad range of configurations and flight conditions. ADAM is a DOS code that runs on a PC. ADAM may have compatibility problems with higher speed computers. It may require a compatible timing hardware emulation setting, to reduce the rate at which the computer’s timer sends timing. The ADAM aerodynamics predictions are based on slender body theory and linear wing theory. The aerodynamic methods cover subsonic to hypersonic Mach numbers and angles of attack up to 180 degrees. The ADAM aerodynamics module calculates force and moment coefficients, static and dynamic stability derivatives, trim conditions, control effectiveness, and center of pressure location. Modeling of the equations of motion can be in three, four, five, or even six degrees of freedom (unguided flight). The three degrees of freedom flight trajectory model runs faster than real time. A thirty-second time of flight requires about eight seconds of run time. The 6DOF flight trajectory simulation is used to analyze the nutation/precession modes of missiles during their unguided portion of flight, as well as unguided bombs and unguided projectiles. It requires longer run time. For homing missiles, proportional guidance is used as well as other guidance laws. The input to the ADAM 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 (e.g., Archer), surface-to-air (e.g., Patriot), air-to-surface (e.g., Hellfire), and surface-to-surface (e.g., ATACMS) missiles. The aerodynamic modeling of the body includes the diameter, nose configuration (geometry, fineness, bluntness), body bulge, boattail, and length. The body cross section may be circular or elliptical. 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 are specified, as well as the target altitude and velocity. Launch conditions for the missile are specified, including altitude, velocity, launch angle, and the guidance law. The output of the three degrees of freedom pitch simulation modeling includes a drawing of the missile geometry with dimensions, aerodynamic coefficients and derivatives, center of pressure location, 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 9 shows the design parameters of the Tactical Missile Design (TMD) Spreadsheet. The TMD Spreadsheet runs in Windows on a PC. It has modules that follow the conceptual missile design tasks outlined in the figure. 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 were illustrated previously in Figure 5. 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 missile body are based on slender body theory for the linear low angle of attack contribution and blended with cross flow theory 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 missile fixed surfaces (e.g., wings, strakes, stabilizers) and movable surfaces (e.g., canards, tails) is based on linear wing and slender wing theory at low angle of attack and blended with Newtonian impact theory at high angles of attack.

The propulsion spreadsheet module provides an estimate of powered range, velocity, thrust, and specific impulse. For a ramjet, the output also includes total pressure recovery in the inlet. 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 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, diameter, and length. Scaling of the weights of subsystems is provided by the density and volume relationships. Material data (e.g., density, stress-strain versus temperature) are also provided. Predictions are made of aerodynamic heating and surface temperature rate. Finally, missile body buckling stresses due to bending moment and axial loads, motor case stress, and required motor case thickness are calculated.

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 and range at the end of boost, velocity and 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. Thrust required is estimated for steady cruise, steady climb, and steady dive. Turn radius, boost and coast velocity, boost and 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 also calculated.

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 allow 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 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. Output parameters for the missile miss distance include missile time constant, missile miss distance due to heading error, and missile miss distance due to a maneuvering target. Output parameters for the missile survivability include detection range. Finally, the output parameters for missile cost include missile production cost due to weight and missile production cost due to the learning curve.

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

Verification of the TMD Spreadsheet was based on comparing the source code with the equations from the Tactical Missile Design textbook, comparing results with the ADAM code, and also comparing the results with the examples in the Tactical Missile Design textbook. The rocket and ramjet baselines, which are based on test data, were used in the verification of the TMD Spreadsheet.

Configuration Conceptual Design Sizing Criteria

Table 1 shows conceptual design configuration sizing criteria. The table has fourteen configuration design criteria related to the areas of 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, missile homing velocity, ramjet combustion temperature, oblique shocks prior to the inlet normal shock, and inlet spillage. 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 approximately two to avoid high drag at high speed without degrading seeker performance. Boattail diameter 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 pounds per square foot. Missile velocity should be at least 50 percent greater than the target velocity to capture the target. Ramjet combustion temperature should be greater than 4,000 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. Finally, the forebody shock wave should impact the inlet cowl lip at the highest Mach number cruise condition, to minimize the spillage drag at lower Mach number.

Configuration design criteria related to guidance & control include the flight control actuator frequency, trim control power, stability & control derivatives cross coupling, airframe time constant, missile maneuverability, and proportional guidance ratio. Body bending frequency in the first mode should be greater than twice 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 percent for efficient dynamics. The

missile airframe time constant should be less than 0.2 second 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. Missile maneuverability should be at least three times the target maneuverability, for small miss distance. Finally, the 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 and the dome error slope.

Summary/Conclusions

Missile design is a creative and iterative process that includes system-of-systems considerations, missile sizing, and flight trajectory evaluation. Because many of the cost and performance drivers may be “locked in” early during the design process, the emphasis of this text has been on conceptual design.

Missile 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-systems 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 the evaluation of many alternatives. It is important to keep track of assumptions to maintain traceable results. Starting with a well-defined baseline that has similar propulsion and performance 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. The military customer buy-in is important in achieving a consensus weighting of the most important measures of merit. 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.

Finally, a good conceptual design code is a physics-based code that 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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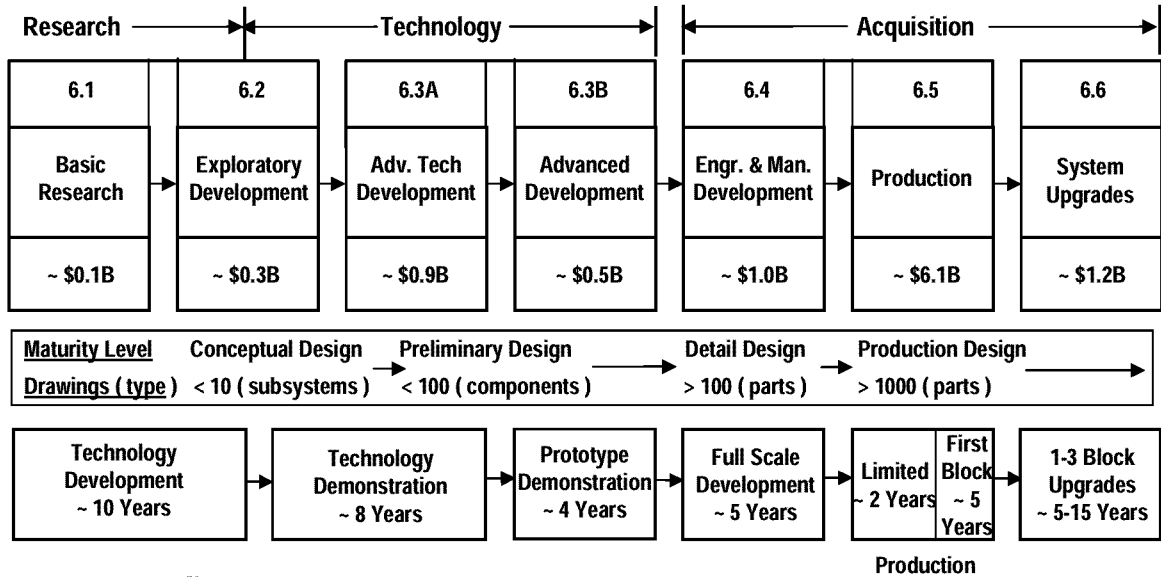
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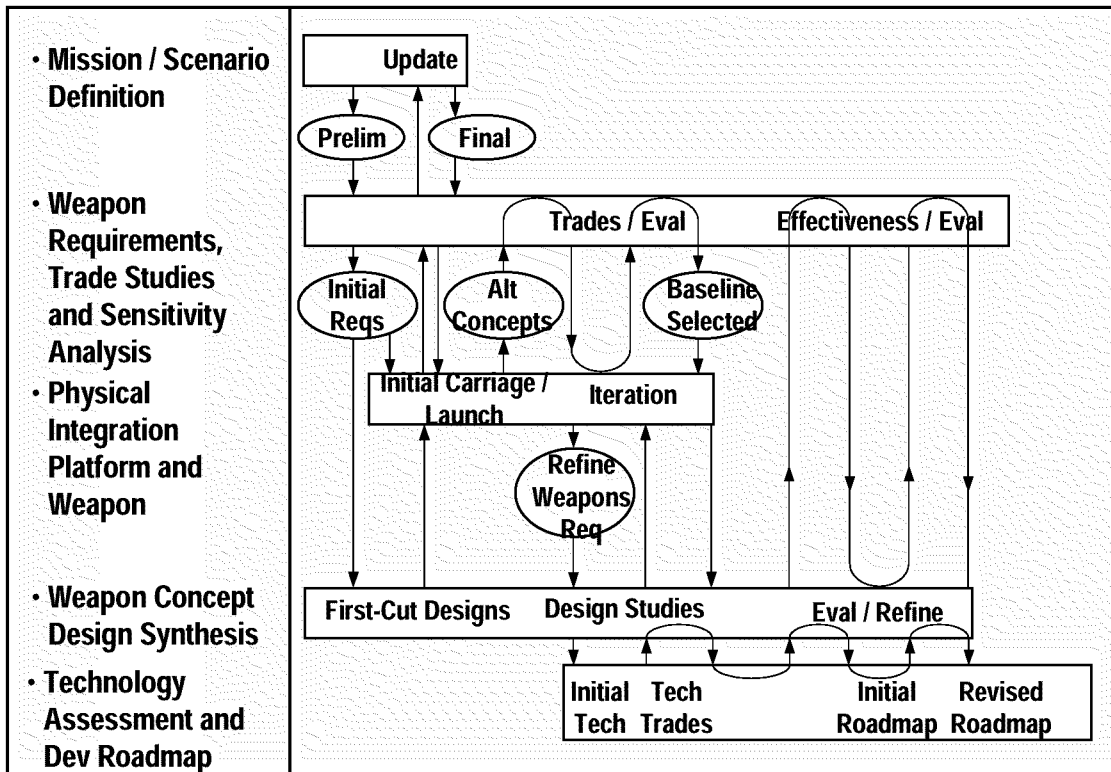
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Note:
 Total US DoD Research and Technology for Tactical Missiles ≈ \$1.8 Billion per year
 Total US DoD Acquisition (EMD + Production + Upgrades) for Tactical Missiles ≈ \$8.3 Billion per year
 Tactical Missiles ≈ 11% of U.S. DoD RT&A budget
 US Industry IR&D typically similar to US DoD 6.2 and 6.3A

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



Note: Typical design cycle for conceptual design is usually 3 to 9 months

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

<i>Weapon</i>		Fixed Surface Targets⁽¹⁾	Moving Targets⁽²⁾	Time Critical Targets⁽³⁾	Buried Targets⁽⁴⁾	Adverse Weather⁽⁵⁾	Firepower⁽⁶⁾
 Example New Missile		●	●	●	●	●	◐
 AGM-65		●	○	○	○	—	○
 Small Smart Bomb		●	—	—	●	●	●
 AGM-88		●	—	●	—	●	—
 Hellfire / Brimstone / Longbow		○	●	○	—	●	●
 LOCAAS		○	●	—	—	○	●

(1) - Large warhead desired. GPS / INS provides precision (3 meter) accuracy.

(2) - Seeker required for terminal homing.

(3) - High speed required $\Rightarrow$ High payoff of rocket or ducted rocket propulsion and low drag.

(4) - Kinetic energy penetration required $\Rightarrow$ High impact speed $\Rightarrow$ High payoff of low drag and long length.

(5) - GPS / INS, SAR seeker, and imaging mmW seeker have high payoff

(6) - Light weight required. Light weight also provides low cost

Note:

● Superior
 ◐ Good
 ○ Average
 — Poor

Figure 3. Examples of Design Alternatives for Light Weight Precision Strike Missiles.

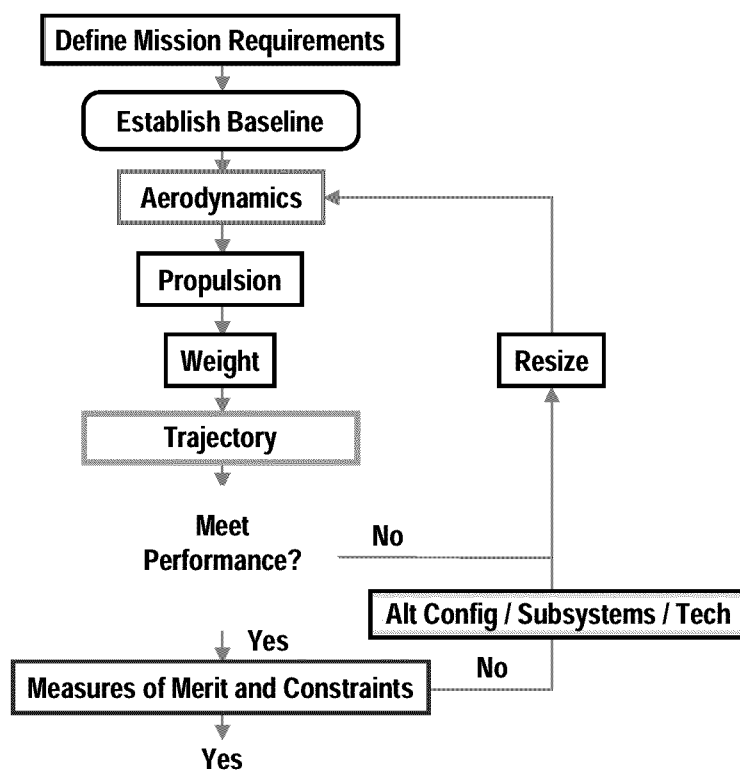
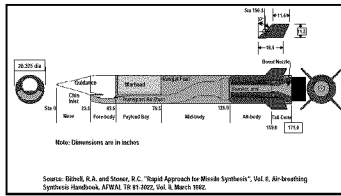


Figure 4. Missile Concept Synthesis Requires Iteration.

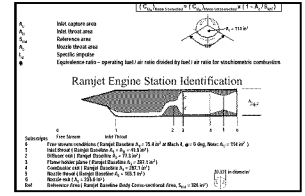
Configuration Drawing



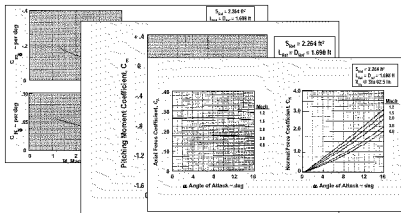
Weight / Geometry

Weight / Geometry	Weight / Geometry	Weight / Geometry
Weight	Weight	Weight
Geometry	Geometry	Geometry
...	...	...

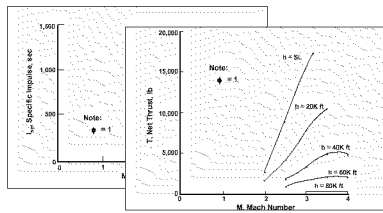
Flow Path Geometry



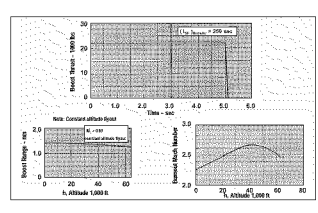
Aerodynamics



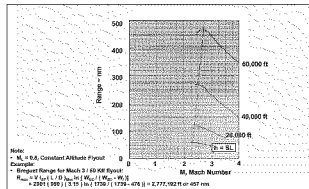
Ramjet Propulsion



Rocket Propulsion



Flight Performance



Range Sensitivity

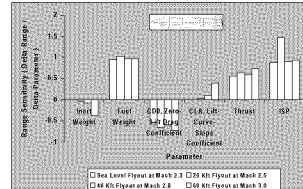


Figure 5. Example of Precision Strike Missile Baseline Data.

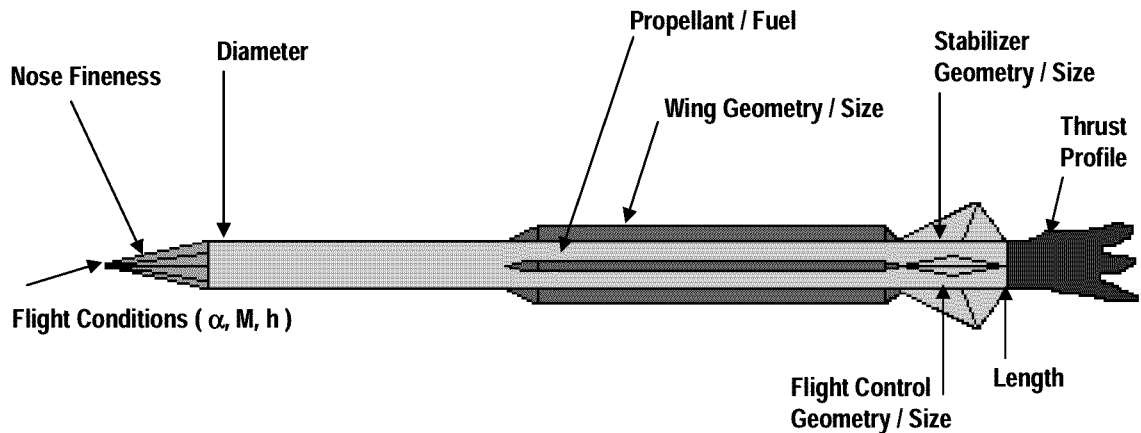


Figure 6. Aerodynamic Configuration Sizing Parameters.

◆ Conceptual Design Modeling

- ◆ 1 DOF (Axial force (C_{D0}), thrust, weight)
- ◆ 2 DOF (Normal force (C_N), axial force, thrust, weight)
- ◆ 3 DOF point mass (3 forces (normal, axial, side), thrust, weight)
- ◆ 3 DOF pitch (2 forces (normal, axial), 1 moment (pitch), thrust, weight)
- ◆ 4 DOF (2 forces (normal, axial), 2 moments (pitch, roll), thrust, weight)

◆ Preliminary Design Modeling

- ◆ 6 DOF (3 forces (normal, axial, side), 3 moments (pitch, roll, yaw), thrust, weight)

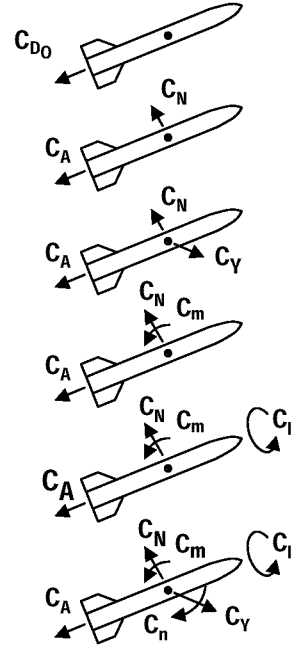
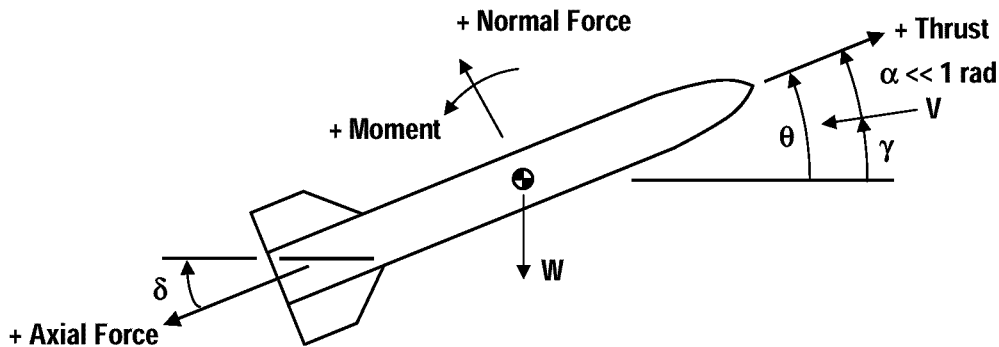


Figure 7. Conceptual Design Uses Simple Modeling of the Missile System.



$$I_y \theta'' \approx q S d C_{m_\alpha} \alpha + q S_{Ref} d C_{m_\delta} \delta$$

$$(W / g_c) V \gamma' \approx q S C_{N_\alpha} \alpha + q S C_{N_\delta} \delta - W \cos \gamma$$

$$(W / g_c) V' \approx T - C_A S q - C_{N_\alpha} \alpha^2 S q - W \sin \gamma$$

Configuration Sizing Implication

High Control Effectiveness $\Rightarrow C_{m_\delta} > C_{m_\alpha}$, I_y small
(W small), q large

Large / Fast Heading Change $\Rightarrow C_N$ large, W small, q large

High Speed / Long Range $\Rightarrow$ Total Impulse large, C_A small, q small

Figure 8. 3DOF Simplified Equations of Motion Show Drivers for Missile Configuration Sizing.

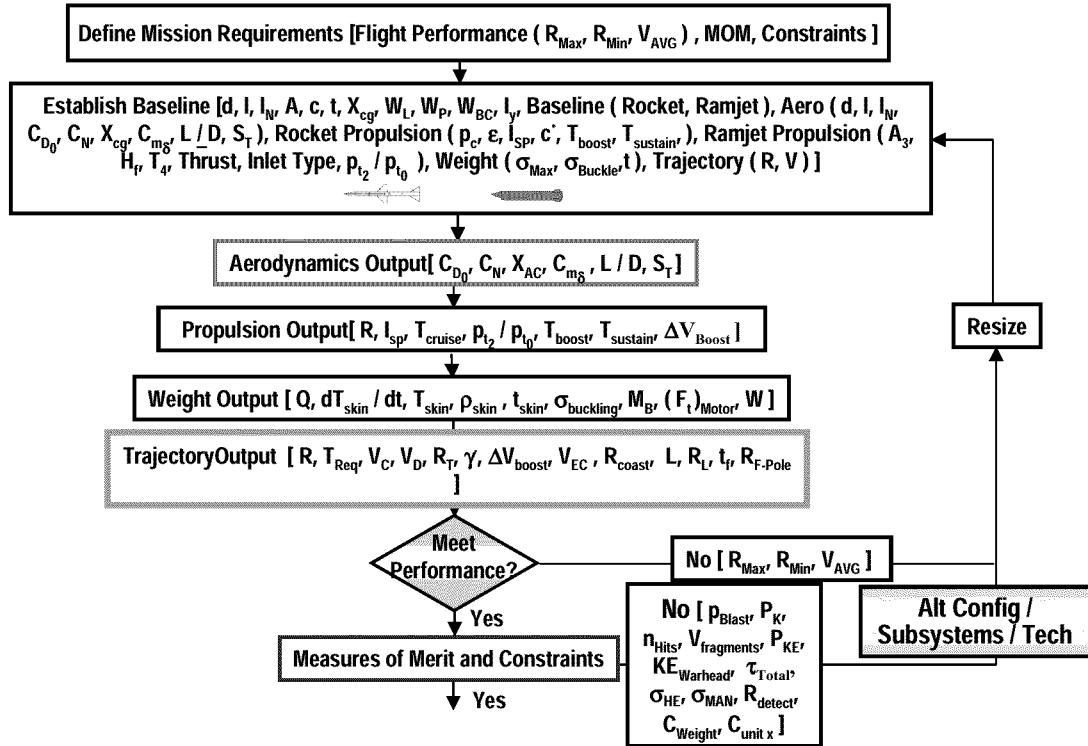


Figure 9. Tactical Missile Design (TMD) Spreadsheet Parameters.

Table 1. Precision Strike Missile Configuration Design Criteria.

Configuration Sizing Parameter	Design Criteria
◆ Flight Performance Related	
◆ Body fineness ratio	$5 < l/d < 25$
◆ Nose fineness ratio	$l_N/d \approx 2$ if $M > 1$
◆ Boattail diameter ratio	$0.6 < d_B/d_{Ref} < 1.0$
◆ Cruise dynamic pressure	$q < 1,000$ psf
◆ Missile homing velocity	$V_M/V_T > 1.5$
◆ Ramjet combustion temperature	$> 4,000$ degrees Fahrenheit
◆ Oblique shocks prior to inlet normal shock	> 1 oblique shock if $M > 3.0$, > 2 if $M > 3.5$
◆ Inlet spillage	Shock on cowl lip at M_{max} cruise
◆ 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
◆ Missile maneuverability	$n_M/n_T > 3$
◆ Proportional guidance ratio	$3 < N' < 5$

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