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INTEGRATED DESIGN THEORY AND FLIGHT PERFORMANCE ANALYSIS OF A SURFACE-LAUNCHED ROCKET

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Abstract

This paper is outlined the conceptual design and general aspects of flight performance of an advanced Surface-Launched Rocket. Brief descriptions of the technologies in the rocket design, parameters driving the rocket design and performance, the rocket performance prediction and examples of maximizing flight performance are presented. The structure of the written conceptual sizing computer code for the rocket design and optimizing the baseline configuration geometry, weight, and balance is described using a flowchart. Some examples in the rocket technology state-of-art advancement including maneuverability, supersonic air breathing and enhance tactical rocket performance are given. The main parameters that drive flight performance are introduced. The conceptual design modeling vs the preliminary design modeling is briefly discussed for a rocket configuration and it follows by the configuration sizing criteria for maximizing flight performance. In this design theory, the range calculation using Breguét method is discussed in depth. Among the major outcomes of the rocket design theory and the flight performance analysis used for a reference rocket with certain specifications are wing skin friction drag is more important than shock wave drag for a thin wing of the rocket; high specific impulse provides higher thrust and reduces fuel consumption; flight trajectory shaping modifies extended range; and flight envelope should have large max range, small min range, and large off bore sight.

1) Introduction

The primary purpose of the paper is to distill the technical knowledge into an integrated approach for a step-by-step rocket design. Initially, the objective of the project was 'Hands-on-Learning' of the design and flight mechanics of a specific rocket based on Design-Build-Fly concept.

This design method generally uses simple closed-form analytical expressions that are physics-based, to provide insight into the primary drivers. Closed-form analytical expressions are used in lieu of computers - a throwback to the way rocket design was conducted over thirty years ago. The paper also provides example calculations of rocket-powered and ramjet-powered baseline rockets, typical values of rocket parameters, examples of the characteristics of current operational rockets, discussion of the enabling subsystems and technologies of tactical rockets, and the current/projected state-of-the-art of tactical rockets.

The cruise range is driven by L/D, I_{SP}, velocity and propellant or fuel weight fraction, drag, static margin, thrust, and zero-lift drag coefficient. The theory starts with the initial requirements and specifications of the rocket and the step-by-step design procedure mainly covers the design body and tails for maximum flight range, and for accurate and stable flight; calculation of aerodynamic drag coefficient; calculation of thrust and thrust duration; measurement of weight (± 1% accuracy); prediction of flight range and altitude for proscribed;

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proscribed target location, launch location, launch pressure, and launch angle; discussion reasons for performance of alternative concepts; initial sizing and flight performance analysis; aerodynamics parameters estimation; propulsion parameters estimation; flight performance parameters' estimation; and integrating flight performance envelope. Some examples of the current operational tactical rockets are:

- Loading rockets on rail and ejection launchers and rocket carriage on launch platforms
- Pilot actions prior to launching rockets
- Store separation trajectories (safe as well as unsafe)
- Flight trajectories, intercepts and detonations of warheads for air and surface targets
- Plume observable of high smoke, reduced smoke, and minimum smoke motors
- Rocket countermeasures and counter-countermeasures
- Development facilities, development testing, and manufacturing processes.

In recent years, the increased usage of tactical rocket systems has been seen for military operations. Moreover, tactical rockets are expected to have an even larger share of military operations in the future. A key contributor to the increased effectiveness is the advancement in technology. Examples of advancement in rocket system effectiveness include improved range, firepower, maneuverability, accuracy, lethality, and adverse weather capability. A historical example of the value of guided weapons is Thanh Hoa Bridge in Vietnam. For over six years, a total of 871 aircraft sorties dropped unguided bombs but failed to close the bridge. However, the first operational application of laser-guided bombs on 13 May 1972 resulted in direct hits on the supporting piers, dropping the center span and closing the bridge. It is noted that eleven aircraft were lost using unguided munitions in the 871 previous sorties. No aircraft were lost in the four sorties using precision-guided munitions.

The complexity of the design equations and the number of parameters involved make it difficult to appreciate how a change to the specification of a rocket alters the final design. The analysis in this paper gives readers an insight into the interaction between the many important parameters in the rocket design. Due to limited length for the paper, the authors have to eliminate nearly all equations and the step-by-step mathematical procedure to be able to keep the paper within the allowed number of pages.

2) Definitions

The followings are the major parameters that initially drive rocket design and its flight performance. These are the aerodynamic configuration sizing parameters emphasized in this paper.

- Flight conditions (α, M, h)
- Nose fineness
- Diameter
- Propellant/fuel type and weight
- Wing geometry/size
- Stabilizer geometry/size
- Flight control geometry/size
- Length
- Thrust profile

Flight condition parameters that are most important in the design of tactical rockets are angle of attack (α), Mach number (M), and altitude (h). For the aerodynamic configuration, the rocket diameter and length have a first order effect on characteristics such as rocket 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 rocket drag for supersonic rockets. Also, nose fineness affects seeker performance, available propellant length, and rocket observable. Another example is rocket 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 and aerodynamic efficiency. 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 rocket velocity time history.

3) Historical Design Trend

Table 1 shows a comparison of the baseline liquid fuel ramjet with the propulsion/fuel alternatives of low smoke ducted rocket, high performance ducted rocket, solid fuel ramjet, and slurry fuel ramjet propulsion. The comparison is conducted for a volume limited rocket. Note that the solid hydrocarbon ducted rocket has 75 percent of the range of the liquid fuel ramjet, due to lower specific impulse and available fuel volume. Although a solid hydrocarbon ducted rocket has less range than a liquid fuel ramjet, other attributes such as simpler logistics and higher acceleration capability may make it attractive for some missions. The high performance boron ducted rocket has 94 percent of the range of the liquid fuel ramjet.

A tradeoff could be made of the simpler logistics and higher acceleration of the ducted rocket versus the lower observable of the liquid fuel ramjet plume. The solid boron fuel ramjet has 27 percent longer range than the liquid fuel ramjet (496 nautical miles versus 390 nautical miles). Although boron fuel has much higher volumetric performance and density than liquid hydrocarbon fuel, some of the potential performance benefit is lost in the reduced fuel volume due to design integration. As shown in the figure, a grain cavity must be provided for the burn area, reducing the volumetric efficiency of the solid fuel ramjet. Disadvantages of the solid fuel ramjet are increased plume observable and the lack of a throttle capability compared to the liquid hydrocarbon fuel baseline.

Finally, the slurry fuel ramjet (40% JP-10, 60% boron carbide) has almost twice the range of the liquid fuel ramjet. The adverse characteristic of the high observable of the plume of the slurry fuel ramjet must be traded off with the outstanding range performance. Another important design consideration is the need for a higher performance fuel pump, due to the highly viscous slurry fuel.

In addition to the benefit of high density and high specific impulse fuel, this example illustrates the benefit of packaging efficiency to provide fuel volume. It is important to develop good drawings and packaging in the design process to have confidence in the resulting performance.

Table 1: Slurry fuel & efficient packaging provide extended range ramjet

Propulsion / Configuration	Fuel Type / Volumetric Performance (BTU / in3) / Density (lb / in3)	Fuel Volume (in3) / Fuel Weight (lb)	ISP (sec) / Cruise Range at Mach 3.5, 60K ft (nm)
Liquid Fuel Ramjet	RJ-5 / 581 / 0.040	11900 / 476	1120 / 390
Ducted Rocket (Low Smoke)	Solid Hydrocarbon / 1132 / 0.075	7922 / 594	677 / 294
Ducted Rocket (High Performance)	Boron / 2040 / 0.082	7922 / 649	769 / 366
Solid Fuel Ramjet	Boron / 2040 / 0.082	7056 / 579	1170 / 496
Slurry Fuel Ramjet	40% JP-10, 60% boron carbide / 1191 / 0.050	11900 / 595	1835 / 770

The cruise range is driven by L/D, I_{sp}, velocity and propellant or fuel weight fraction. As a good estimation for a conceptual design, it is calculated from the Breguét Range Equation

$$R = (L / D) I_{sp} V \ln [W_L / (W_L - W_P)] \qquad (1)$$

Based on an examination of the Breguét range equation, new technology development has payoff in the areas of higher cruise velocity, aerodynamic efficiency (lift/drag), specific impulse, lightweight structure, lightweight/low volume subsystems, and higher density fuel/propellant.

Table 2 compares four propulsion alternatives for a long-range precision strike rocket. The propulsion alternatives are subsonic cruise turbojet, supersonic cruise liquid hydrocarbon fuel ramjet, hypersonic cruise liquid hydrocarbon fuel scramjet, and supersonic cruise solid propellant rocket. All four propulsion types are held to a rocket launch weight of 2,000 pounds, a representative weight limit for carriage on a small fighter aircraft such as the F-18C.

Table 2: Typical Value for Precision Strike Rocket

Parameter	Total Rocket Weight of 2,000 lb			
	Subsonic Turbojet Rocket	Liquid Fuel Ramjet Rocket	Hydrocarbon Fuel Scramjet Rocket	Solid Rocket
L / D, Lift / Drag	10	5	3	5
Specific Impulse (I_{SP})	3,000 sec	1,300 sec	1,000 sec	250 sec
Average Velocity (V_{AVG})	1,000 ft / sec	3,500 ft / sec	6,000 ft / sec	3,000 ft / sec
Cruise Propellant or Fuel Weight / Launch Weight (W_P/W_L)	0.3	0.2	0.1	0.4
Cruise Range (R)	1,800 nm	830 nm	310 nm	250 nm

As it can be seen from the table, ramjet and scramjet rockets booster propellant for Mach 2.5 to 4 take-over speeds not included in W_P for cruise. Rockets require thrust magnitude control (e.g., pintle, pulse, or gel motor) for effective cruise. For maximum range, a rocket usually follows a semi-ballistic flight profile instead of cruise flight. It can be also noticed from the table that the subsonic cruise turbojet propulsion is the preferred approach for long-range strike against targets that are not time-critical. Subsonic cruise turbojet propulsion has 120 percent greater range than the next best alternative, a supersonic cruise liquid fuel ramjet (1800 nm vs 830 nm).

An examination of the Breguét range equation explains the difference in performance. The subsonic cruise turbojet rocket is superior to the supersonic cruise ramjet rocket in the maximum lift-to-drag ratio (L/D = 10 vs 5), specific impulse (I_{SP} = 3000 seconds vs 1300 seconds), and available fuel for a rocket launch weight limited to 2,000 pounds (600 pounds of fuel versus 400 pounds of fuel).

The ramjet rocket has less available weight for fuel because it requires a rocket to boost the rocket up to about Mach 2.5 for transition to ramjet propulsion. However, a ramjet rocket has an advantage of a shorter response time against time critical targets. It may also have an advantage in survivability due to the higher flight altitude and higher speed. If time critical targets are of utmost importance, scramjet propulsion may be preferred. As shown in the figure the scramjet rocket example is 70 percent faster than the ramjet (6000 ft/sec vs 3500 ft/sec).

However, the maximum range of a scramjet rocket that is limited to 2000 pounds launch weight is only 37 percent that of a liquid fuel ramjet (310 nm vs 830 nm). Again, it is instructive to examine the Breguét range equation. The liquid fuel ramjet rocket is superior to the scramjet in the aerodynamic efficiency (L/D = 5 vs 3), specific impulse (I_{SP} = 1300 seconds vs 1,000 seconds), and available fuel for a rocket limited to 2000 pounds launch weight (400 pounds of fuel vs 200 pounds of fuel).

The scramjet rocket has less available weight for fuel because it requires a larger rocket booster for a higher takeover Mach number (Mach 4 vs 2.5), requires a longer combustor for efficient combustion, and requires more insulation. Finally, the supersonic cruise rocket has a maximum flight range of 250 nm. The most efficient cruise condition for the long-range rocket was found to be Mach 3 cruise at high altitude. The solid propellant rocket example uses thrust magnitude control from a pintle motor, for more efficient acceleration and cruise. Although it is not shown, a semi-ballistic flight trajectory (e.g., launch, pitch-up, ballistic climb and glide) would have provided a more efficient flight trajectory for the rocket.

4) Design Sensitivity

A flight performance sensitivity study was conducted of the rocket baseline configuration to determine the most significant parameters and the required accuracy for prediction methods. General information about design sensitivity studies and the available linear incremental methods for aerospace vehicle design are given by Saeedipour & Stevenson (1998) and Stevenson & Saeedipour (1996 & 64). Based on the incremental sensitivity method, it can be concluded that the flight range is most sensitive to specific impulse, propellant weight, zero-lift drag coefficient, drag-due-to-lift, and static margin (see Figures 1 & 2).

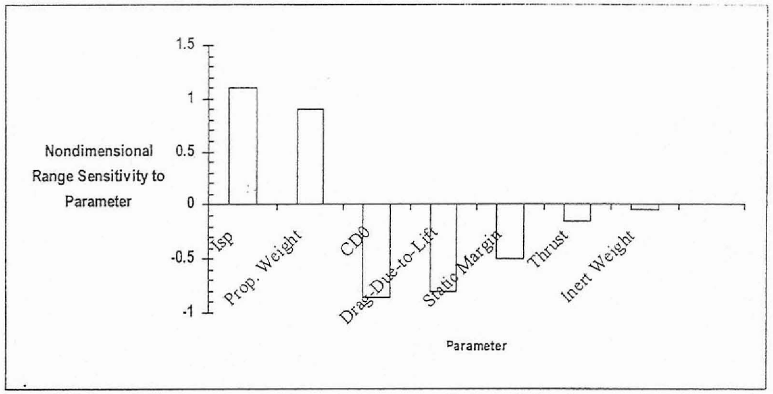

Figure 1: Rocket-baseline range driven by I_{SP}, propellant weight, drag, and static margin

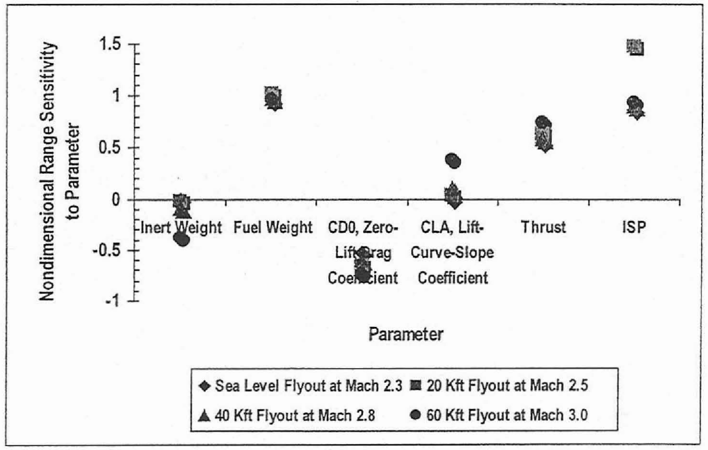

Figure 2: Ramjet-baseline range driven by I_{SP}, fuel weight, tnrust, & zero-lift drag coefficient

The prediction methods for specific impulse, zero-lift drag coefficient, and drag-due-to-lift usually have sufficient accuracy (e.g., +/- 5%, 1σ) for conceptual design. However, there is often large uncertainty in predicting the subsystem packaging volume available for the propellant weight and predicting the static margin. Inboard profile drawings and wind tunnel tests are required to reduce the design uncertainty.

A sensitivity study was conducted to define the ramjet baseline most significant parameters for flight range and the required accuracy for prediction methods. Note from the figure that flight range is most sensitive to the ramjet specific impulse, fuel weight, zero-lift drag coefficient, and the ramjet thrust. The flight range is relatively insensitive to inert weight and lift curve slope, especially for low altitude flight (high dynamic pressure).

The prediction methods for ramjet specific impulse, zero-lift drag coefficient, and ramjet thrust usually have sufficient accuracy (e.g., +/- 5%, 1 σ) for conceptual design. However, there is often large uncertainty in predicting the subsystem packaging volume available to package the fuel, providing uncertainty in the fuel weight. Inboard profile drawings are required to reduce the uncertainty.

5) Examples

The frequency of a follow-on program to a tactical rocket is about every twenty-four years for US rockets. Once a rocket is in production, it usually has a long lifetime, including block upgrades. Block upgrades are often necessary to incorporate the rapidly emerging new technologies in electronics and sensors. Block upgrades are also often necessary for launch platform integration. Eventually a capability is needed that is not easily achievable through a block upgrade, requiring a follow-on rocket development. Examples are shown in the figure of the driving requirements in the follow-on rocket programs. These are the improved maneuverability of AIM-9X, improved speed and range of AIM-120 and AGM-88, improved accuracy of PAC-3, higher gunner survivability (lower observable, launch-and-leave) and lighter weight of Javelin, reduced radar cross section of AGM-129, and the longer range and reduced observable of JASSM. It is interesting to note that in almost no case does a rocket follow-on program go to the incumbent contractor of the current rocket.

There may be opportunities for a new start for a US hypersonic air-breathing rocket in the year 2005 time frame. A hypersonic air-breathing rocket provides longer range and faster time-to-target. Opportunities include follow-on programs for the AIM-120 AMRAAM, AGM-88 HARM, BGM-109 Tomahawk, and the AGM-86 rockets.

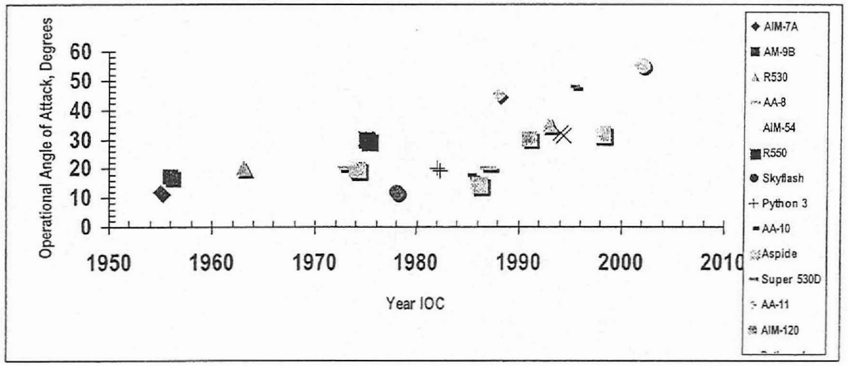

Figure 3: Example of rocket technology state-of-art advancement: rocket maneuverability

Figure 3 shows of the rocket state-of-the-art advancement in the areas of rocket maneuverability and supersonic air breathing rocket cruise Mach number. An assessment of the state-of-the-art advancement in rocket maneuverability is shown in the figure. The figure is based on the maximum angle of attack of air-to-air rockets at the date of their initial operational capability (IOC). Note that there is a trend of increased angle of attack capability, especially for short-range air-to-air rockets. Aerodynamic control rockets are limited by technology to about 35 degrees angle of attack. For very high angles of attack, unconventional flight control (i.e., thrust vector control, reaction jet/jet interaction control) is required. Examples of highly maneuverable rockets with unconventional flight control are Archer AA-11, Mica, and AIM-9X.

Ramjet propulsion has been investigated as early as the 1940s and has been used on several production rocket systems in the United States, United Kingdom, France, and Russia. The figure shows a history of the state-of-the-art advancement for supersonic/hypersonic air breathing rockets over the last fifty years. A number of liquid fuel ramjet demonstrations have been conducted.

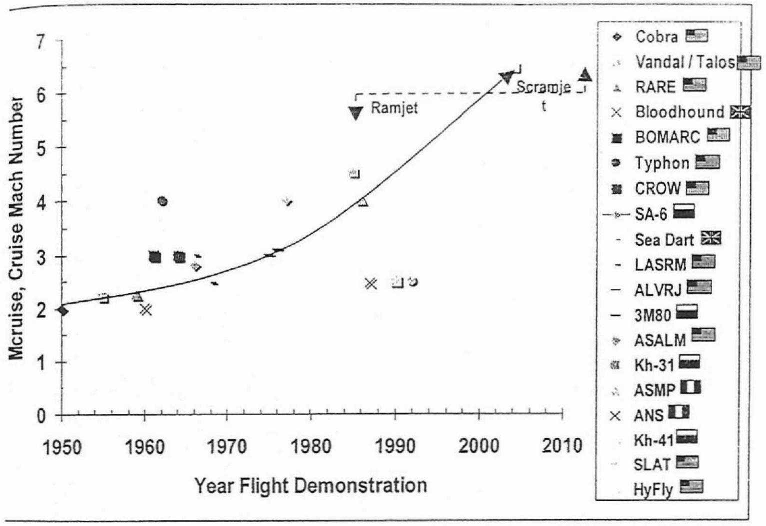

Figure 4: Historical trend of rocket technology advancement in supersonic air breathing rockets

As shown in Figure 4, the cruise Mach number demonstrations have provided higher confidence in the capability for efficient hypersonic cruise. Ramjets have demonstrated supersonic and hypersonic cruise up to Mach 4.5. A future flight demonstration of a scramjet engine may demonstrate Mach 6.5 cruise in the year 2004 time frame. Because France and Russia have maintained a steady commitment to ramjet propulsion technology and have ramjet rocket systems that are currently deployed, France and Russia are arguably the world leaders in ramjet rockets.

6) New Technologies for Tactical Rockets

The assessment and characteristics of new technologies applied to tactical rockets are (see Figure 5):

Dome: Faceted/window and multi-lens domes have reduced dome error slope, resulting in improved guidance accuracy, low observable, and low drag at supersonic speed. Multi-spectral domes will be developed.

Seeker: Multi-spectral/multi-mode imaging seekers enhance performance for ATR in countermeasures and clutter. SAR seekers have good effectiveness in adverse weather and ground clutter. Strap-down and uncooled IR seekers reduce parts count/cost. High gimbal seekers enhance off bore sight capability.

G&C: GPS/INS will permit a low cost seeker-less rocket to be used against fixed targets. Using in-flight digital trajectory flight prediction and derived flight conditions from the GPS/INS, rockets will continuously optimize the flight trajectory to maximize performance parameters. Advancements in ATR technology will provide new capabilities of near real-time ATR and lower false alarm rate.

Electronics: Processing capability is ceasing to be a limitation for the application of commercial off-the-shelf (COTS) processors to sensor data fusion and near real-time trajectory optimization to rockets.

Airframe: Lifting body airframes provide enhanced maneuverability and efficiency. Enhancements also provided by neutral static margin. Split canard control and free-to-roll tails also enhance maneuverability. Lattice fins have advantages of smaller hinge moment and higher control effectiveness. Low drag and higher-pressure recovery inlets are in development for hypersonic rockets. Increased usage will be made of castings, vacuum assisted resin transfer molding, pultrusion, extrusion, and filament winding to reduce parts count/cost. Composite and titanium materials will be used in hypersonic rockets. Low cost/small size MEMS sensors will be used in data collection and health monitoring. Airframe shaping and materials technology will provide reduced observable.

Power: A micro turbine generator is 5% of the weight of a conventional battery for the same power output.

Insulation: Higher density insulation will be developed for hypersonic rockets.

Warhead: Higher explosive warheads such as the US Navy China Lake CL-20 will be developed. Modular warheads will be developed. Kinetic energy warheads will be developed for penetrating hard and deeply buried targets. Submunition dispensers and autonomous submunitions will counter mobile, time-critical targets.

Propulsion: Ramjet, ducted rocket, and scramjet propulsion will be developed for hypersonic rockets. High temperature combustors will be developed. Higher density fuels and propellants will provide high volumetric performance. Endothermic fuels will provide higher specific impulse, shorter combustor length, and cooling for scramjets. Composites will reduce weight. Thrust management technologies will be developed for pintle, pulse, and gel motors. Reduced observable propellants will continue development. Finally, kinetic kill rockets will use high thrust motors to quickly accelerate to hypersonic speed.

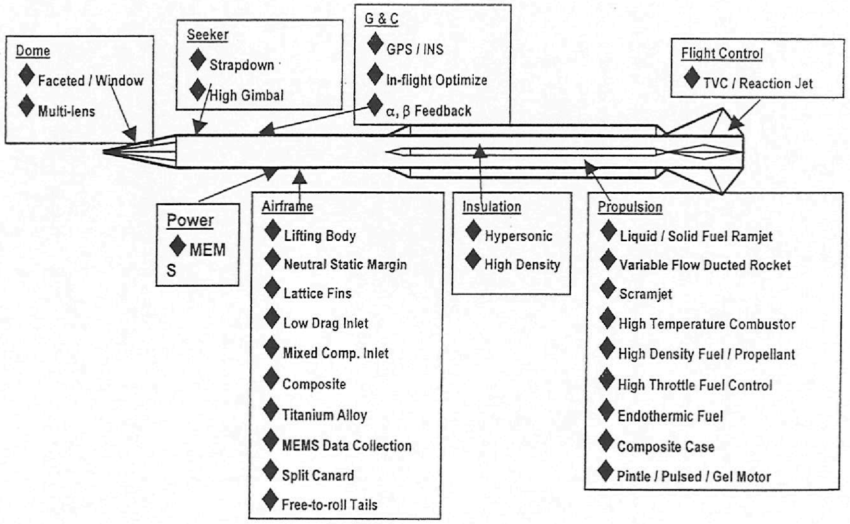

Figure 5: New technologies affecting the tactical rocket performance

Data Link: BDI/BDA will be provided by data link of target imagery. Phased array antennas will be developed for high data rate and mission flexibility. In-flight targeting will be developed for mobile targets.

Flight Control: Compressed carriage aerodynamic surfaces will be developed for internal carriage. TVC and reaction jet control will be developed for highly maneuverable and hit-to-kill rockets.

7) Alternative Propulsion Systems

For the propulsion alternatives assessment, the efficiency of tactical rocket propulsion alternatives across the Mach number range is shown in Figure 6 and it includes a typical specific impulse envelope for turbofan/turbojet, ramjet, ducted rocket, scramjet, and solid rocket propulsion. It can be seen from the figure that high specific impulse provides higher thrust and reduces fuel consumption.

Turbojet/turbofan propulsion is a relatively mature technology. It is most suited for subsonic cruise rockets, providing high efficiency against non-time-critical targets. Beyond Mach 2, increasingly complex inlet systems are required to match the inlet airflow to the compressor, and expensive cooling is required to avoid exceeding the material temperature limit at the turbine inlet.

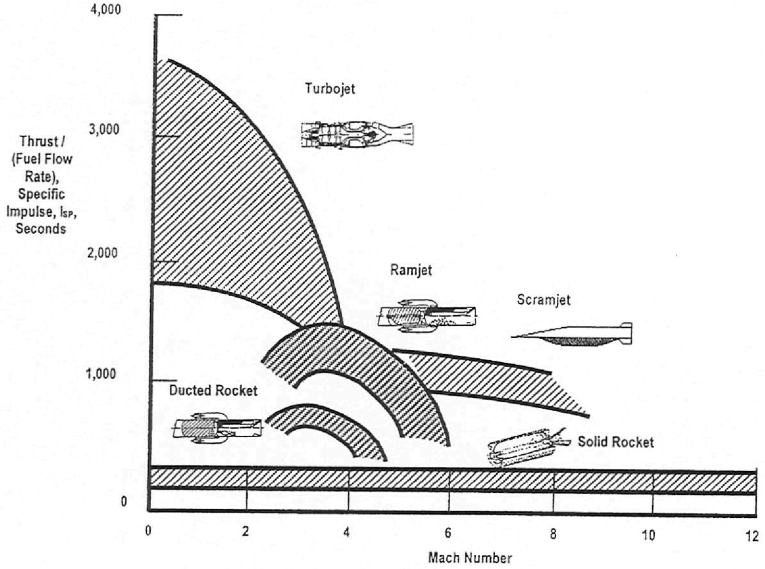

Figure 6: Alternative Propulsion Systems

A ramjet is efficient from Mach 2.5 to 5. Above Mach 5, the combustor maximum material temperature limits the achievable exit velocity and thrust. Also, deceleration of the inlet airflow to subsonic velocity results in chemical dissociation of the air, which absorbs heat and negates the energy input of the combustor. For a subsonic launch platform, a rocket boosts the rocket to the ramjet thrust takeover at about Mach 2.5. The maximum specific impulse of ducted rocket propulsion is about 800 seconds, intermediate that of a solid rocket and a ramjet. Ducted rockets are most efficient for a Mach number range from about 2.5 to 4.0. Ducted rockets have higher acceleration capability (higher thrust) than ramjets and generally have longer range capability (higher specific impulse) than solid propellant rockets.

Scramjet propulsion has supersonic flow through the entire flow path. Scramjet propulsion challenges include fuel mixing, efficient combustion, and airframe integration. A long combustion chamber is required, due to the mixing time for supersonic combustion.

An enabling technology to enhance supersonic combustion is endothermic fuels. These fuels decompose at high temperature into lighter weight molecular products that burn more readily, providing higher specific impulse and permitting shorter combustor length. An endothermic fuel also acts as a heat sink, cooling the adjacent structure. The scramjet is boosted to a takeover speed of about Mach 4, requiring a large booster. Efficient cruise is about Mach 6, 100K feet altitude. One contributor is scramjet inefficiency at lower Mach number is thermal choking. A larger inlet is required to avoid thermal choking for Mach numbers less than 6.

Dual-combustion ramjet-scramjet (DCR) propulsion separates the inlet airflow into two streams. The main airflow remains supersonic. The smaller airflow is decelerated to subsonic speed for fuel-rich combustion, after which it accelerates through a nozzle. Efficient flight is Mach 3 to Mach 7.

Solid rockets are capable of providing thrust across the entire Mach number range. Although the specific impulse of tactical rockets is relatively low, of the order of 250 seconds, rockets have an advantage of much higher acceleration capability than air-breathing propulsion. Also, its ability to operate at high altitude enables a boost-climb-glide trajectory to extend range by minimizing drag.

8) Flight Trajectory and Performance Envelope

Figure 7 illustrates the extended range advantage of rockets that use flight trajectory shaping. Flight trajectory shaping is particularly beneficial for high performance supersonic rockets, which have large propellant or fuel weight fraction. To take advantage of flight trajectory shaping, the rocket must rapidly pitch up and climb to an efficient cruise altitude.

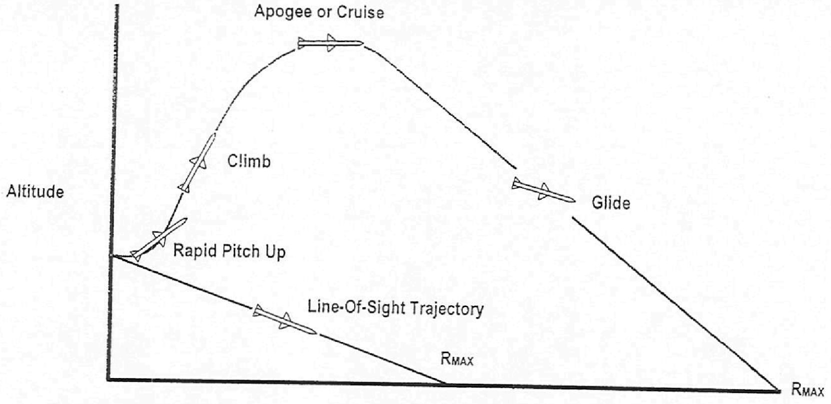

Figure 7: Flight Trajectory Shaping Provides Extended Range

During the climb, the rocket angle-of-attack should be small, to minimize drag. The rocket initial thrust-to-weight ratio should be high (≈10) for safe separation, followed by a relatively low thrust-to-weight ratio (≈2) during the climb. A thrust-to-weight ratio greater than two results in a high dynamic pressure and increasing drag. After reaching higher altitude, the rocket benefits from cruising at an improved lift-to-drag ratio, such as $(L/D)_{Max}$. Dynamic pressure for efficient cruise of a high performance supersonic rocket is of the order of 500 to 1,000 pounds per square foot. Following burnout, the rocket can have extended range through glide at a dynamic pressure of about 700 pounds per square foot, providing an aerodynamic efficiency approximately equal to $(L/D)_{Max}$.

Based on the figure, design guidelines for horizontal launch are:

- High thrust-to-weight ≈ 10 for safe separation
- Rapid pitch up minimizes time / propellant to reach efficient altitude
- Climb at a ≈ 0 deg with thrust-to-weight ≈ 2 and q ≈ 700 psf minimizes drag / propellant to reach efficient cruise altitude for $(L / D)_{MAX}$
- High altitude cruise at $(L / D)_{MAX}$ and q ≈ 700 psf maximizes range
- Glide from high altitude at $(L / D)_{Max}$ and q ≈ 700 psf provides extended range

The rocket flight envelope may be characterized by the maximum and the minimum flight ranges in forward and off bore sight flight. In the example shown in the figure, the rocket has a large off bore sight capability, up to +/- 180 degrees off bore sight. Illustrated in the figure are the maximum and minimum ranges for straight-ahead flight, beam flight, and flight to the rear of the launch aircraft. It is noted that a supersonic rocket at 1 g flight and at low altitude flies near zero angle of attack. The maximum range for a supersonic rocket in straight-ahead flight is often driven by the zero-lift drag coefficient. The maximum range may be established by the speed and maneuverability required for an intercept. It was shown previously that higher rocket speed and higher maneuverability are required against a maneuvering target. This affects the maximum effective range for low miss distance. The maximum effective range against a maneuvering target is less than the maximum range against a non-maneuvering target. Also, the maximum effective range is a function of the intercept altitude.

A boost-coast rocket has less velocity and available maneuverability in a high altitude intercept than in a low altitude intercept. Other constraints on the maximum range include the fire control system maximum range and rocket time of flight limits (e.g., battery duration). The minimum range may be established by the maneuverability required to correct an initial heading error. For a beam flight which is the side of the launch platform, the rocket must operate at high angle of attack to rapidly turn the velocity vector to 90 degrees off bore sight. The time to arm the warhead, based on establishing a safe standoff from the launch platform may also set the minimum range. Finally, the seeker gimbal limit may set the minimum range in off bore sight maneuvers. The maximum/minimum range for a beam intercept may be driven by a combination of parameters such as the seeker gimbal limit, maneuverability, stability, and the drag due to lift. For flight to the rear of the launch platform, the rocket must make a heading change of 180 degrees. The drivers for a rear intercept may be a combination of parameters such as zero-lift drag and the drag due to lift (see Figure 8).

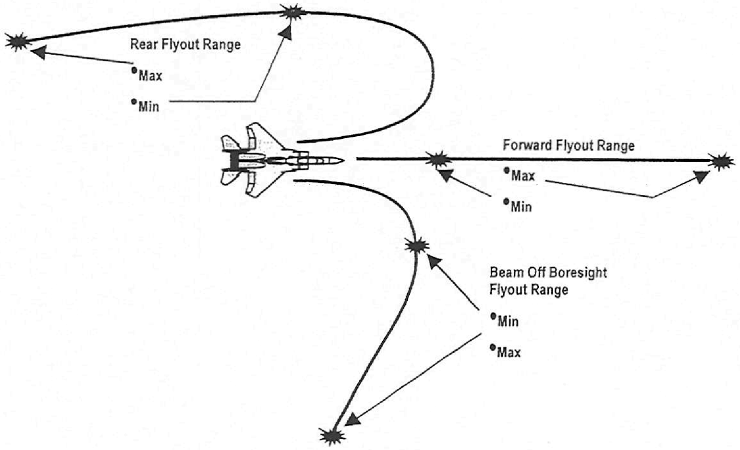

Figure 8: Flight performance envelope

9. Conclusion

The purpose of this paper has been to describe a simple method to originate the design effects in which the various rocket parameters interact. An iterative convergent rocket design program was used to validate the results of the method.

Flight performance consideration in tactical rocket design is oriented towards flight trajectory computation and comparison with the rocket flight performance requirements. Flight performance requirements include range, time-to-target, and off-bore sight capability. This paper presented equations of motion modeling, examples of flight performance drivers, typical flight performance for propulsion alternatives, steady state flight relationships, and proportional homing lead angle requirement. It also provided a method for predicting steady climb, steady glide, cruise, boost, coast, turn, and ballistic flight performance. Much of the impact of changes in the rocket aerodynamics, propulsion, and weight is in the area of flight performance. This design method that harmonizes the aerodynamics, propulsion, and weight while also satisfying the flight performance requirements is a primary activity in rocket configuration detailed design.

If practical, the rocket should have a long maximum range, a small minimum range, and a large off bore sight capability. This provides robustness for long range, short range, and off bore sight targets. It can be concluded that flight envelope should have large max range, small min range, and large off bore sight.

It is very easy to criticize the approximations made in this paper but it is hoped that it will form a basis for further discussion and development in rocket design methodologies.

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