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Technologies for Future Precision Strike Missile Systems - Missile/Aircraft Integration

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Abstract/Executive Summary

This paper provides an assessment of the state-of-the-art and design considerations of missile/aircraft integration for future precision strike missile systems. Benefits of missile/aircraft integration include compatibility with a broader range of aircraft carriage platforms, unrestricted carriage envelope, safe and accurate store separation, and enhanced survivability for the aircraft platform. Technologies and design considerations are grouped into the following discussion areas:

- **Missile factor of safety compatibility**. Assessments in this area include structural design factor of safety, carriage flight loads, and design specification of the carriage flight environment.
- **Missile carriage and launch compatibility**. Assessments in this area include launch platform compatibility constraints, firepower, launcher alternatives, compressed carriage, and standard suspension requirements.
- **Survivability (missile observables/insensitive munitions) compatibility.** Assessments in this area include internal carriage, reduced observable plumes, and insensitive munitions.

Introduction

Missile/aircraft integration is an important part of the missile design process, as illustrated in Figure 1. Launch platform integration sets constraints on the missile that must be considered early in the development process. Moreover, the design process requires iteration to harmonize the outputs from the diverse areas of mission/scenario definitions, missile requirements, aircraft integration, missile concepts, and technologies. In a few cases it may be possible to modify a launch platform to accommodate a new missile, but in most cases this is not an option. Generally the launch platform is a constraint that drives the missile design. For example, AMRAAM was modified to a compressed carriage configuration (clipped wings and tails) to better accommodate internal carriage in the F-22 center weapons bay. Precision strike missiles are driven as much by launch platform compatibility as other measures of merit.

Figure 2 shows an example of the design validation/technology development process. Launch platform integration is considered from the start of subsystem development activities, continuing as they evolve into a missile system. In the propulsion area, static firings and insensitive munition tests are conducted before a missile with a live rocket motor is fired from a launch aircraft. In the airframe area, wind tunnel testing includes not only the basic aerodynamic configuration development, but also store separation wind tunnel tests. In the guidance & control area, the flight control system sensors, actuators, and electronics are analyzed to ensure safe separation as part of a missile modeling and simulation activity. Similar to the propulsion area, the warhead has insensitive munition tests prior to firing a missile with a live warhead from an aircraft.

The flight test progression is shown on the far right of Figure 2. Flight test validation is a progressive activity of increasing complexity. The objective of progressive testing is to minimize risk and enhance safety in the flight test activity. A typical progression of flight testing begins with captive carry and ends with live warhead launches. Intermediate tests are store jettison tests, safe separation tests, unpowered guided flights with an inert warhead, powered guided flights with an inert warhead, and finally, all-up powered guided flights with a live warhead.

A summary of the subsystem technologies for precision strike missiles that relate to missile/aircraft integration is given in Figure 3. In addition to subsystem technologies, considerations such as structure design, carriage environment, geometry/weight constraints of the aircraft, aircraft launcher requirements, and aircraft survivability also drive missile/aircraft integration. Many of the technologies in the figure are covered in this paper, however there is not sufficient time to address them all. A summary of other technologies is presented in the Introduction/Overview paper of this lecture series.

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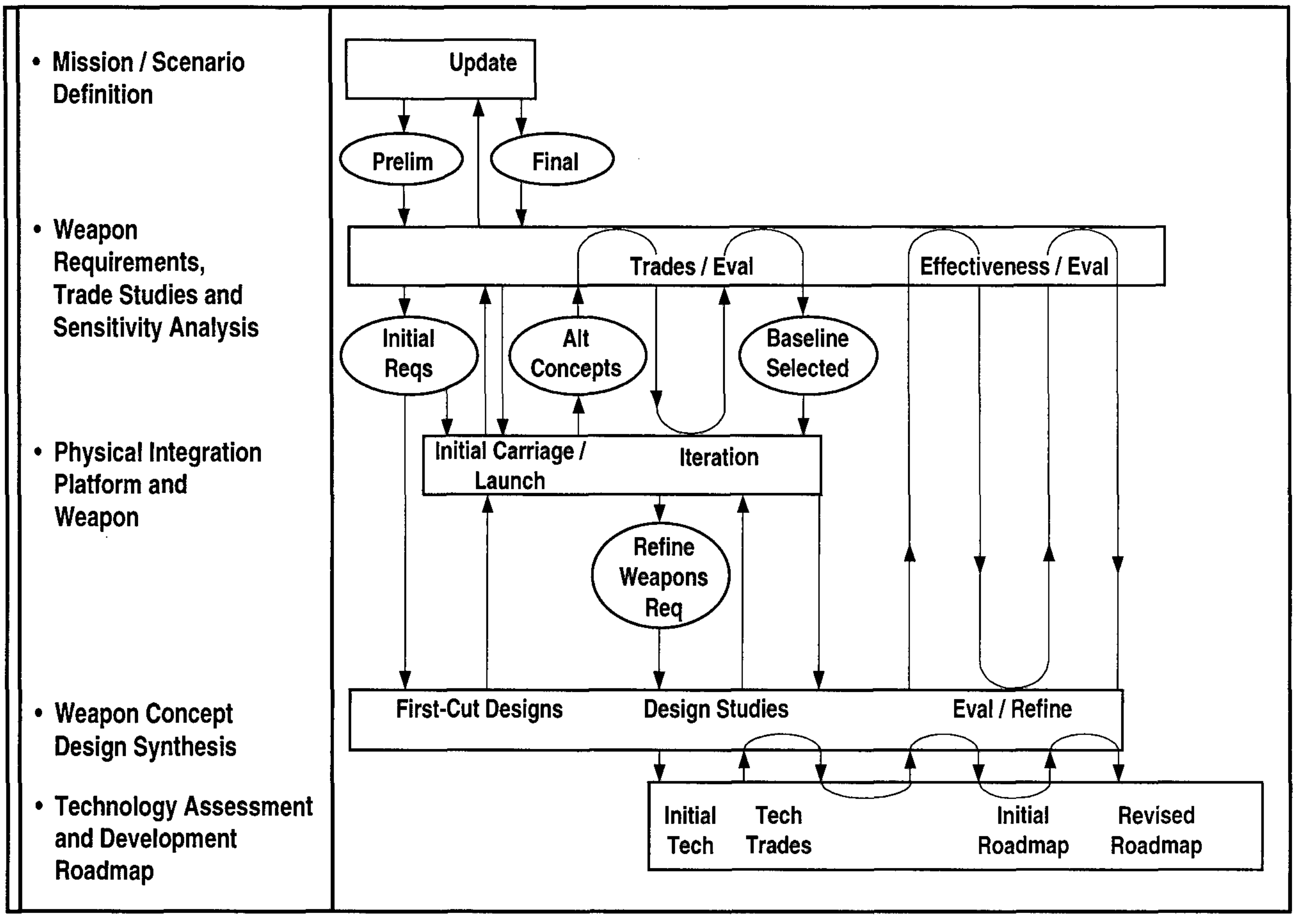


Figure 1. Launch Platform Integration Provides Constraints in Missile Design.

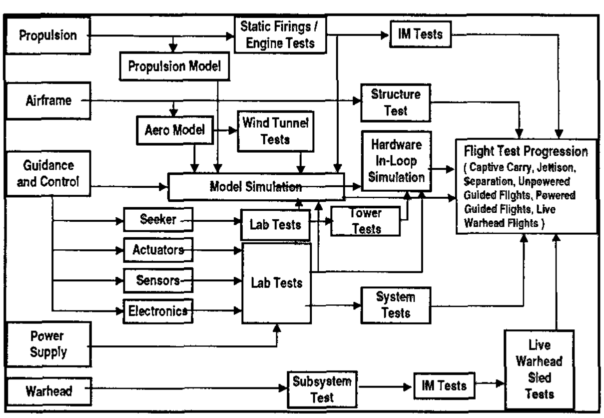


Figure 2. Air Launched Precision Strike Missile Development Leads to Aircraft Flight Test Validation

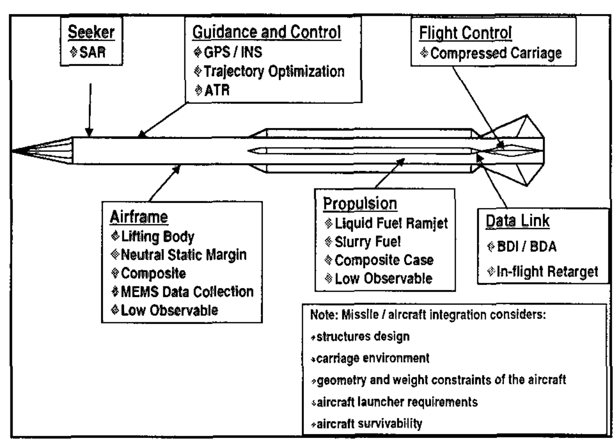


Figure 3. New Precision Strike Missile Technologies That Impact Aircraft Integration.

Missile Factor of Safety Compatibility

This assessment of missile factor of safety compatibility addresses the design considerations of structural design factor of safety, process for defining the missile structure design for compatibility with carriage flight loads, and design specification of the carriage flight environment.

Structural design factor of safety. Missile structure/aircraft integration includes the factor of safety considerations for manned operation. Typical factors of safety for tactical missiles are shown in Figure 4. The factor of safety tends to be high where there is human danger involved. As an example, pressure bottle ultimate and yield factors as safety are typically 2.5 and 1.5 respectively. Missile gas bottles can be pressurized up to 10,000 psi. Because gas bottles require periodic logistics maintenance and inspection by ground personnel, the factor of safety is high. Another area where the factor safety is high is in the area of ground handling loads, such as cross-country transportation. Factors of safety for ground handling loads are 1.5 ultimate loads and 1.15 in yield loads. Other examples of high factor of safety are captive carriage and separation. During carriage or during aircraft separation, missile factors of safety are required to be about 1.5 ultimate and 1.15 yield. The motor case is designed not only for conditions of environmental extremes, such as a hot day, but also for consideration of pilot safety. The ultimate and yield factors of safety for motor maximum effective operating pressure are about 1.4 and 1.1 respectively. The required factors of safety are lower for flight conditions where the missile is safely away from the launch aircraft. For example, missile free flight loads factors of safety are about 1.25 and 1.1 respectively and the thermal loads, which occur near the end of flight, are just design considerations with a factor of safety of 1.0. A distinguishing characteristic of precision strike missiles is lower factor of safety compared to manned aircraft or even unmanned air vehicles (UAVs). Since missiles are a throw-away, the factor of safety can be reduced if there is no human danger involved, resulting in lighter weight compared to an aircraft or a UAV. It is noted that an additional factor of safety is required for structural areas where there is relatively large uncertainty. An example is castings, which can have hidden voids, requiring an incremental factor of safety of about 1.25 in addition to the normal design factors of safety. Fittings also require an additional factor of safety of about 1.15 because of the uncertainty in the analysis for attachment integrity. The applicable military standards in the U.S. that are considered in factors of safety include environmental military standards such as MIL-STD-210 and 810, strength and rigidity standards such as MIL-STD-8856, and the carriage requirements of MIL-STD-8591.

Because high performance missiles such as ramjets are severely weight and volume limited, there is high leverage in improving performance if the required factor of safety could be reduced. Technology in improved analysis and development tools will provide reductions in missile weight and cost by reducing the design uncertainty and the required factor of safety. An example is Micro-machined Electro-Mechanical Systems (MEMS) technology. MEMS devices are fabricated from a single piece of silicon by semiconductor manufacturing processes, resulting in a small, low-cost package. For example, between 2,000 and 5,000 MEMS sensor devices are produced from a single five-inch silicon wafer. Future precision strike missiles will have low cost/small size MEMS sensors for data collection during missile development and for health monitoring after production. Localized stress/strain, vibration, acoustics, temperature, pressure, and other environmental conditions can be monitored through many sensors scattered around the airframe.

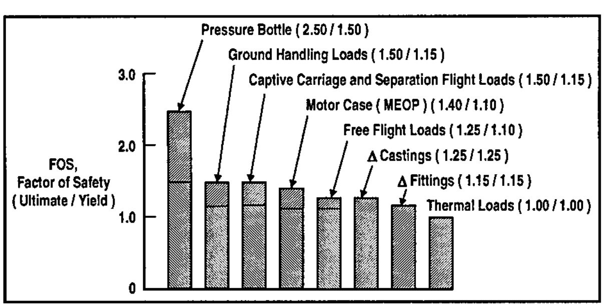


Figure 4. Missile Structural Design Is Driven by Safety.

Carriage flight loads. Figure 5 shows the considerations of flight carriage on missile design. A comparison is shown of a representative distribution of missile free flight maneuver loads versus carriage loads. The figure shows a typical weight load distribution on each bulkhead, air loads, and carriage loads. As shown in the figure, carriage loads are taken out through a suspension system. It is usually possible to get a fairly accurate prediction of the missile free flight loads. Also, wind tunnel tests are usually conducted to determine free flight air loads. Unfortunately, this is usually not the case for carriage flight loads, as it is difficult to accurately predict the two-body problem of a store in the flow field of the launch aircraft. In addition, it is difficult to get accurate wind tunnel data, due to the small size of the missile model for aircraft carriage wind tunnel tests. As a result, the current process for estimating carriage loads is usually based on the conservative process of MIL-STD-8591. As missile loads estimation becomes more accurate in the future, there is a potential for structure weight savings, based on improving the estimation accuracy for captive carriage loads.

Design specification of the carriage flight environment. Air launched precision strike missiles

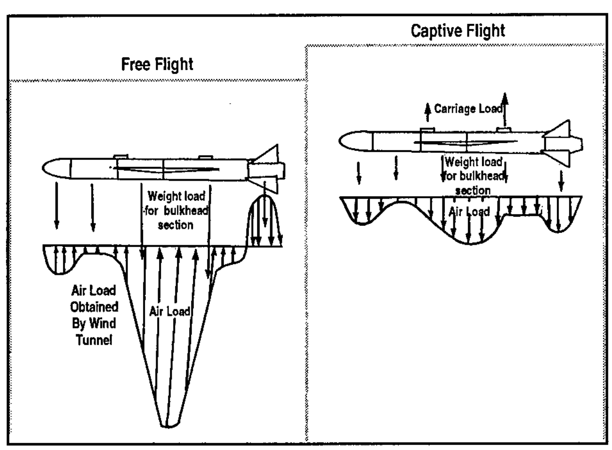


Figure 5. Process for Captive and Free Flight Loads Calculation.

Environmental Parameter	Example of Environmental Requirement
Temperature	-50°F to 160°F
Humidity	5% to 100%
Rain	4.0 mm / hr to 120 mm / hr
Snow	Crystal size 0.05 to 20.0 mm 21mm / hr snow rate
Wind	54 m / s gusts
Salt fog	3 grams / mm² per year
Vibration	MIL STD 810, MIL STD 648
Shock	Drop height 0.5 m
	MIL STD 810
	100 g's 10 ms, half sine wave Drop height 0.5mMIL 810
Acoustic	160 dB

Table 1. Robustness Is Required to Satisfy Aircraft Carriage Environmental Requirements.

must have sufficient robustness in their design to accommodate a broad flight environment during carriage. Table 1 has examples of environmental requirements for aircraft carriage temperature, humidity, rain, snow, wind, salt fog, vibration, shock, and acoustics. An example of concern at the temperature extremes is propulsion and warhead safety, reliability, and performance. Another example is high rain rate. Rain is a particular concern for dome erosion at high carriage velocity. A third example is corrosion from salt fog, particularly for naval operation. An advantage of internal bay carriage over external carriage is that many of the carriage environment concerns are alleviated. However, some carriage environment concerns could be greater for internal carriage than that of external carriage. Examples include high vibration and acoustic loads when the carriage bay doors are open.

Missile Carriage/Launch Compatibility

This assessment of missile carriage and launch compatibility addresses the design considerations of launch platform compatibility constraints, firepower, launcher alternatives, compressed carriage, and standard suspension requirements.

Launch platform compatibility constraints. Carriage constraints for missiles on surface ships, submarines, and aircraft are shown in Figure 6. Cross-platform compatibility is desirable for a missile system. A larger total buy of missiles for cross-platform application has benefits of lower unit production cost and lower logistics cost. Referring to the figure, in the case of the US standard Vertical Launch System (VLS) for surface ships, the physical constraints are 22 in x 22 in x 256 in. Maximum weight is 3400 lb. US 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 include tactical fighters, bombers, and helicopters. Shown in the figure is an example of a small fighter aircraft, the F-18C. The F-18C carries weapons externally on pylons and rails. Other aircraft may also have an additional capability of internal carriage. For an aircraft using external carriage, the missile span constraint 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. Small aircraft can have severe maximum weight constraints.

Aircraft store compatibility wind tunnel tests are conducted to determine store carriage loads and store separation forces, moments, and trajectories. Figure 7 shows wind tunnel installations of aircraft and store models. Note that a typical store loadout has closely spaced stores. The local air flow around a store is difficult to predict. There is a complex flow field interaction of a store with the aircraft and also with the adjacent stores.

Firepower. Figure 8 shows how day/night operation, firepower objectives, and weapons loadout affect the maximum allowable weight of a precision strike missile. Shown are examples of the F-18C and F-18E aircraft. Note that the F-18C aircraft has less capability than the F-18E in all loadout configurations. Figure 8 shows a large difference in maximum allowable missile weight for day versus night operation. The difference is due to the additional fuel that must be reserved for night operation off an aircraft carrier. The maximum weapon weight shown in the curves must also be reduced to account for limits in asymmetric carriage (2,500 lb for inboard carriage and 1,500 lb for outboard carriage). Finally, note the reduction in maximum allowable missile weight as the loadout configuration is changed from a clean aircraft with precision strike missile(s) to other configurations. Five other loadout configurations are the precision strike missile(s) plus 1) a centerline fuel tank, 2) two inboard fuel tanks, 3) centerline fuel tank plus two Sidewinder air-to-air missiles, 4) centerline fuel tank plus two anti-radiation missiles (ARM), and 5) two inboard fuel tanks plus two Sidewinders. The maximum allowable weight of a single precision strike missile on the F-18E is about 4,800 lb under ideal conditions. For an F-18C operating at night with two inboard fuel tanks and two Sidewinders, the maximum allowable weight of a precision strike missile is much lower, about 1,800 lb. In the case of carriage of two precision strike missiles, the F-18E under ideal conditions can carry a missile weighing up to 2,400 lb. At the other extreme for an F-18C loadout of two precision strike missiles, operating at night with the addition of two inboard fuel tanks and two Sidewinders requires that the precision strike missile weigh less than 900 lb. A precision strike missile weight of about 1,400 lb is probably a good compromise for the example of F-18C/E aircraft

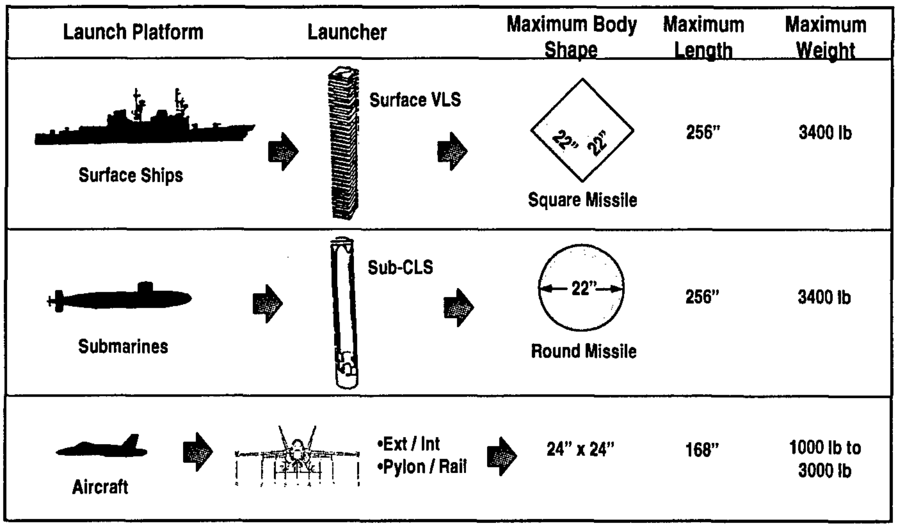


Figure 6. Missile Shape, Size, and Weight Are Driven by Launch Platform Compatibility.

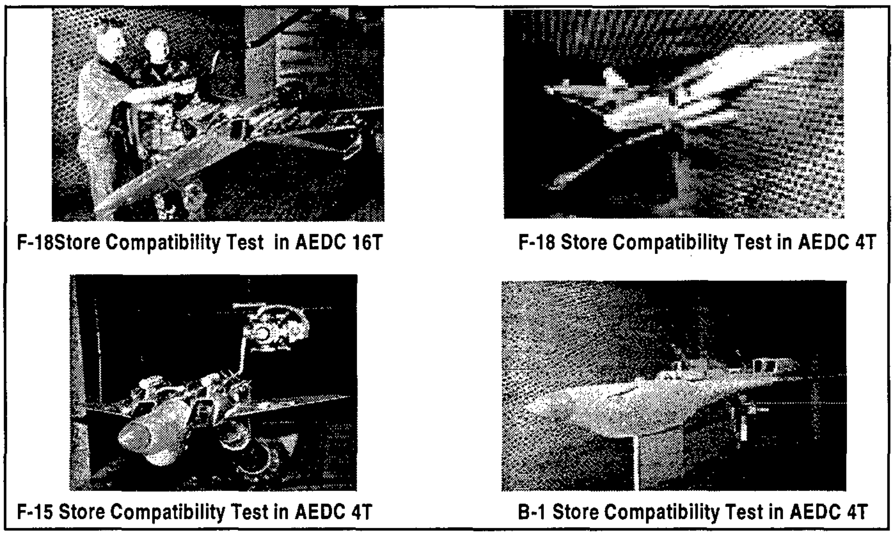


Figure 7. Store Separation Wind Tunnel Tests Are Required for Missile/Aircraft Compatibility.

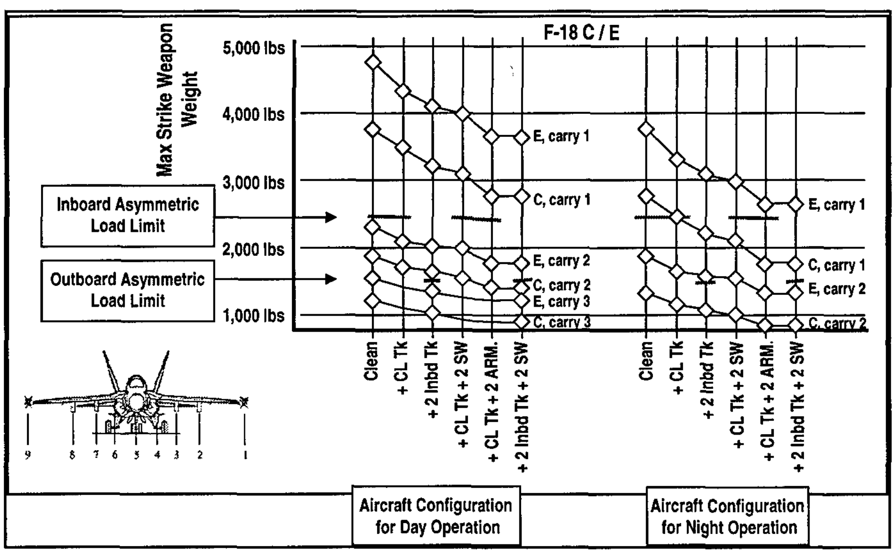


Figure 8. Light Missiles Enhance Firepower

integration. It allows two weapons on the F-18C for unrestricted day operation, two weapons on the F-18E for near unrestricted night operation, and three weapons on the F-18E for day operation with two inboard fuel tanks.

Launcher alternatives. Figure 9 shows examples of missile carriage on US standard rail and ejection launchers. In the upper left is an AGM-114 Hellfire II missile on a helicopter rail launcher. Rail launchers are particularly suited to light weight, high thrust missiles such as Hellfire. Hellfire weighs 100 lb, with a launch thrust-to-weight of about 30:1. Hellfire has a laser seeker with +/- 30 degrees field of regard. A launch platform integration consideration is that the missile must be mounted sufficiently far forward on the aircraft such that the seeker line-of-sight to the target is not obscured by the launch platform. Another concern for rail launch is the effect of tip off error. A rail-launched missile has roll, pitch and yaw rate excursions as it moves down the rail, due to missile/rail clearances and the aeroelasticity of the launcher. Tip off error at launch has an effect on the missile miss distance at its minimum effective range. Another contributor to missile miss distance at the minimum effective range is the effect of helicopter downwash on the missile angle of attack at launch. In the upper right corner of Figure 9 is an AGM-88 HARM missile. Most precision strike missiles, including HARM, use ejection launch. HARM has an anti-radiation homing seeker. The installation pylon must also be sufficiently far forward on the aircraft that the seeker line-of-sight to the target is not obscured by the launch platform. The pylon contains ejection cartridges that provide downward velocity and pitch rate to the missile at launch, aiding safe and accurate separation. Suspension of the missile is such that the missile center-of-gravity is midway between the ejectors. A concern during launch is the aircraft local angle of attack and local angle of sideslip effects on the missile flight trajectory. Finally, the bottom of Figure 9 shows an example of internal carriage. Eight AGM-69 SRAM missiles are shown on a bomber rotary launcher. The missiles are ejected from the bay at an ejection velocity of about 20 ft/sec. Concerns for internal bay carriage include bay acoustics, bay vibration, and flow field angularities near the aircraft.

Compressed carriage. Compressed carriage has reduced span missile surfaces during carriage, allowing closer spacing of adjacent missiles on the launch platform. Approaches for compressed carriage include reduced span/longer chord surfaces, folded surfaces, wraparound surfaces, and switch blade surfaces. Figure 10 illustrates the benefits of compressed carriage. A baseline AMRAAM missile in an F-22 internal bay allows two missiles per bay. However, compressed carriage AMRAAM can be packaged three missiles per bay, a 50% increase in firepower loadout.

Store Weight / Parameter	30 Inch Suspension	14 Inch Suspension
♦ Weight Up to 100 lb	Not Applicable	Yes
• Lug height (in)	↓	0.75
• Min ejector area (in x in)	↓	4.0 x 26.0
♦ Weight 101 to 1,450 lb	Yes	Yes
• Lug height (in)	1.35	1.00
• Min lug well (in)	0.515	0.515
• Min ejector area (in x in)	4. 0 x 36.0	4.0 x 26.0
♦ Weight Over 1,451 lb	Yes	Not Applicable
• Lug height (in)	1.35	↓
• Min lug well (in)	1.080	↓
• Min ejector area (in x in)	4.0 x 36.0	↓

Table 2. MIL-STD-8591 Ejection Launcher Requirements.

Standard suspension requirements. Store suspension requirements for ejection launchers, based on US MIL-STD-8591 are summarized in Table 2. Shown are store weight and parameters for light weight stores (up to 100 lb), medium weight stores (101 to 1,450 lb), and heavy weight stores (over 1,451 lb). Suspension alternatives are 30 inch and 14 inch suspension systems. For an ejected store weight up to 100 lb, only the 14 inch suspension can be used. For a light weight missile on the 14 inch suspension, the lug height and minimum ejector pad area are prescribed as 0.75 inch and 4.0 in x 26.0 in respectively. For a medium weight missile, with a weight between 101 and 1,450 lb, either the 14 inch suspension or a 30 inch suspension may be used. Medium weight ejected stores have larger required lug height and minimum ejector area. They also require lug wells. The required lug wells could have a strong impact on the missile internal structure design. For example, in some cases the rocket motor overlaps the missile center of gravity, and it may be difficult to accommodate lug wells in the rocket motor case. A strong back may be required, similar to that of the AGM-69 SRAM missile. For a heavy missile with a weight over 1,451 lb, only the 30 inch suspension can be used. MIL-STD-8591 requires that the lugs have a deeper well if the missile weighs more than 1,451 lb.

Survivability (Missile Observables and Insensitive Munitions) Compatibility

This assessment of survivability (missile observables and insensitive munitions) compatibility addresses the design considerations of internal carriage, reduced observable plumes, and insensitive munitions.

Internal carriage. Alternative approaches for missile carriage include conventional external carriage, conformal carriage, and internal carriage. Conventional external carriage has disadvantages of high radar cross section (RCS), high carriage drag, and potentially adverse aeroelastic, stability, and control interactions with the aircraft platform. Conformal carriage has an advantage of reduced RCS and drag compared to conventional carriage. However, the

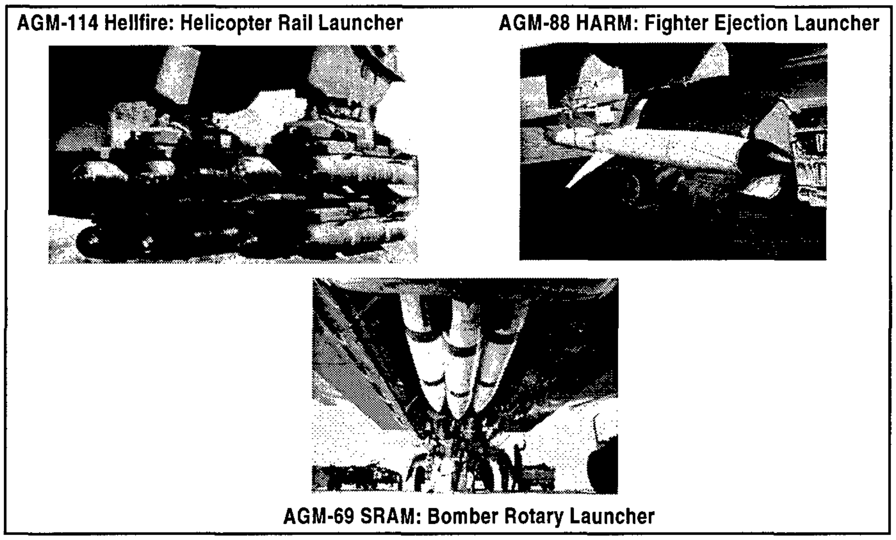


Figure 9. Precision Strike Missile/Aircraft Launch Integration Considerations.

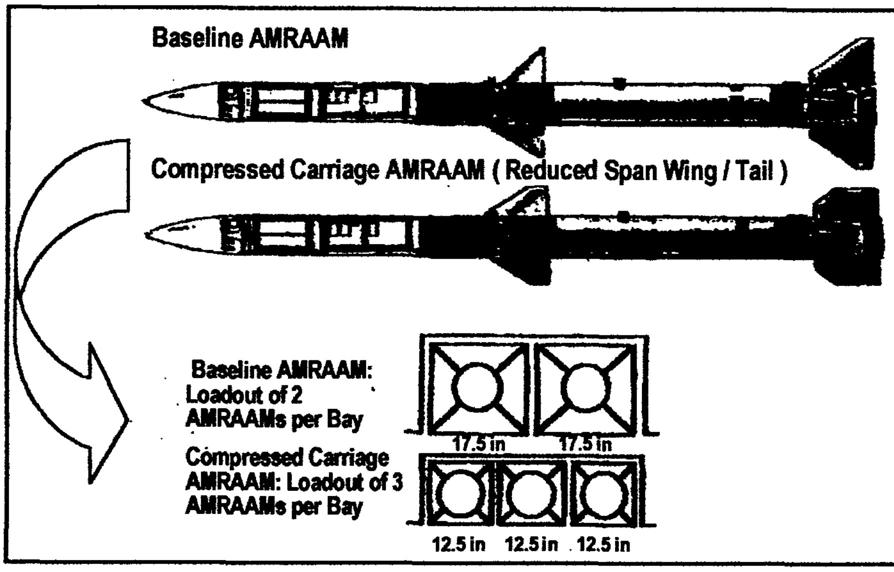


Figure 10. Compressed Carriage Missiles Provide Higher Firepower for Aircraft with Internal Weapon Bays.

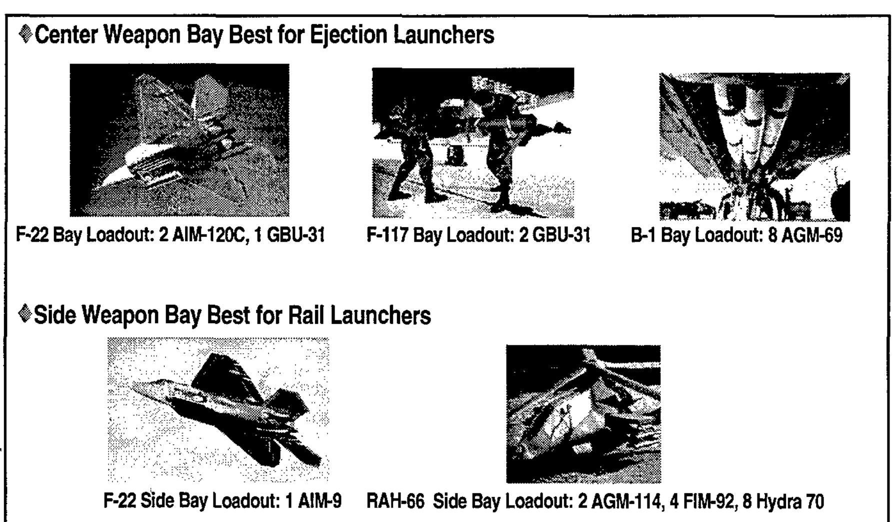


Figure 11. Internal Bay Carriage Has Low Observables.

preferred approach for the lowest carriage RCS and the lowest drag is internal carriage. Figure 11 shows examples of internal carriage and loadouts for a low observable fighter, bomber, and helicopter. In the upper left is shown the F-22 internal center bay. A typical loadout of the F-22 center bay is two AMRAAMs plus one 2,000 lb JDAM. Ejection launchers are provided for AMRAAM and JDAM. The F-117 has a similar weapons bay. A typical loadout for the F-117 is two JDAMs. The B-1 bomber has three bays. Each bay has a rotary launcher for ejection of missiles and bombs. A standard loadout is eight AGM-69s per bay. In the lower left of the figure is a photograph of an F-22 side bay. The F-22 has two side carriage days. Each bay is capable of carrying a single Sidewinder missile on a rail launcher. The RAH-66 Commanche helicopter has two side bays with rail launchers. Each bay has a typical loadout of one Hellfire missile plus two Stinger missiles and four Hydra 70 rockets.

Reduced observable plumes. Table 3 shows tradeoffs of rocket motor performance versus safety and observable concerns. The highest performance propellants unfortunately also have high observable smoke particles (e.g., Al_2O_3), due to metal fuels such as aluminum. An initial approach to reduce plume observables is reduced smoke motors. Reduced smoke motors replace the metal fuel with a binder fuel such as HTPB. The performance and insensitive munition capability of reduced smoke motors is slightly lower than that of high smoke motors. Reduced smoke propellants can still have visual observables from a hydrogen chloride contrail. The HCl contrail occurs at low atmospheric temperature. A third type of propellant is minimum smoke propellant. Minimum smoke propellants eliminate the HCl contrail by eliminating ammonium perchlorate as an oxidizer, resulting in lower visual observables. The performance and safety of current minimum smoke propellants is not as good as that of high smoke propellants. Examples of current minimum smoke propellants are cross-linked double base (XLDB) propellants such as HMX and RDX. An example of a new minimum smoke propellant is the US Navy China Lake CL-20 propellant. CL-20 is chemically related to current XLDB nitramine explosives. However, CL-20 is a cyclic polynitramine, with a unique caged structure that provides higher crystal density, heat of formation, and oxidizer-to-fuel ratio. CL-20 propellant has 10-20% higher performance than HMX and RDX. CL-20 also has reduced shock sensitivity (class 1.3 versus 1.1) and milder cookoff reaction than either HMX or RDX.

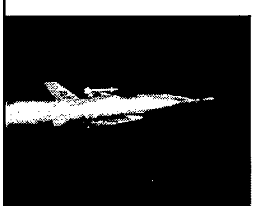
Figure 12 illustrates the plume observables of high smoke, reduced smoke, and minimum smoke propellants. The relatively old Sparrow missile rocket motor is a representative high smoke motor. The high smoke plume is shown in the upper left corner of the figure. Sparrow has high smoke Al_2O_3 particles from aluminum fuel. Also shown is an example of a reduced smoke rocket motor. AMRAAM is a more recent missile, with a reduced smoke motor. It still has a contrail of HCl from the ammonium perchlorate oxidizer. The HCl contrail occurs if the atmospheric temperature is less than -10° Fahrenheit, corresponding to altitudes greater than about 20,000 feet. Finally, the far upper right photograph is an example of a minimum smoke rocket motor. Javelin is a recent missile with a minimum smoke motor. It has almost no smoke from either the launch motor or the flight motor, enhancing the survivability of the gunner. Minimum smoke propellants can have an H_2O (ice) contrail if the atmospheric temperature is less than - 5° Fahrenheit, corresponding to altitudes greater than about 27,000 feet.

Insensitive Munitions. Insensitive munitions have high payoff in improving launch platform survivability. The critical subsystems are the rocket motor propellant/engine fuel and the warhead. In the US the design considerations for insensitive munitions are based on MIL-STD-2105B. MIL-STD-2105B includes design considerations of hardening against threat weapons, safety from fire, dropping the weapon, extremes in environmental temperature, missile vibration, and operation off an aircraft carrier. Hardening against threat weapons includes considerations of fragment impact and blast. Cookoff from a fire includes the type of fire (slow cookoff, fast cookoff) and the reaction to the fire (e.g., burning, detonation). Drop considerations include ground maintenance personnel dropping the missile during handling. The environmental temperature includes both very low temperatures that could damage the rocket motor and very high temperatures that could cause detonation of the warhead or rocket motor. Missile vibration includes the dynamic acceleration imparted by carriage on the launch platform. Finally, aircraft carrier operation includes the shock of aircraft landing sink rates as high as 18 ft/sec.

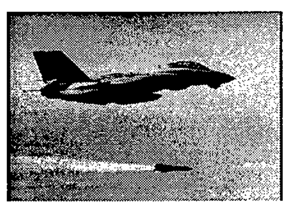
Type	I_{SP}, Specific Impulse, sec	ρ, Density, lb / in^3	Burn Rate @ 1,000 psi, in / sec	Hazard	Observables
• *Min Smoke.* No Al fuel. No AP (CL-20, ADN, or AN oxidizer). Very low contrail (H_2O).	– 220 - 250	– 0.055 - 0.062	○ 0.25 - 1.0	–	◒
• *Reduced Smoke.* No Al (binder fuel). AP oxidizer. Low contrail (HCl)	○ 250 - 260	○ 0.062	◒ 0.1 - 1.5	○	○
• *High Smoke.* Al fuel. AP oxidizer. High smoke (Al_2O_3).	◒ 260 - 265	◒ 0.065	● 0.1 - 3.0	◒	–

● Superior ◒ Above Average ○ Average – Below Average

Table 3. Minimum Smoke Propellant Has Low Observables.

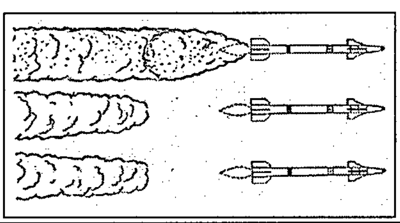


High Smoke (AIM-7)



Reduced Smoke (AIM-120)

Minimum Smoke (Javelin)



High Smoke particles (e.g., metal fuel) at all atmosphere temperature

Reduced Smoke contrail (HCl from AP oxidizer) at < -10° Fahrenheit atmos temp

Minimum Smoke contrail (H_2O) at < -35° Fahrenheit atmos temp

Figure 12. Minimum Smoke Propellant Has Low Observables (continued).