AIGM-138 Chimera

'Tube-launched, lethal, modular'

'A modular, tube launched missile family enabling low-cost, reliable mission successes.'

US and International patents pending.

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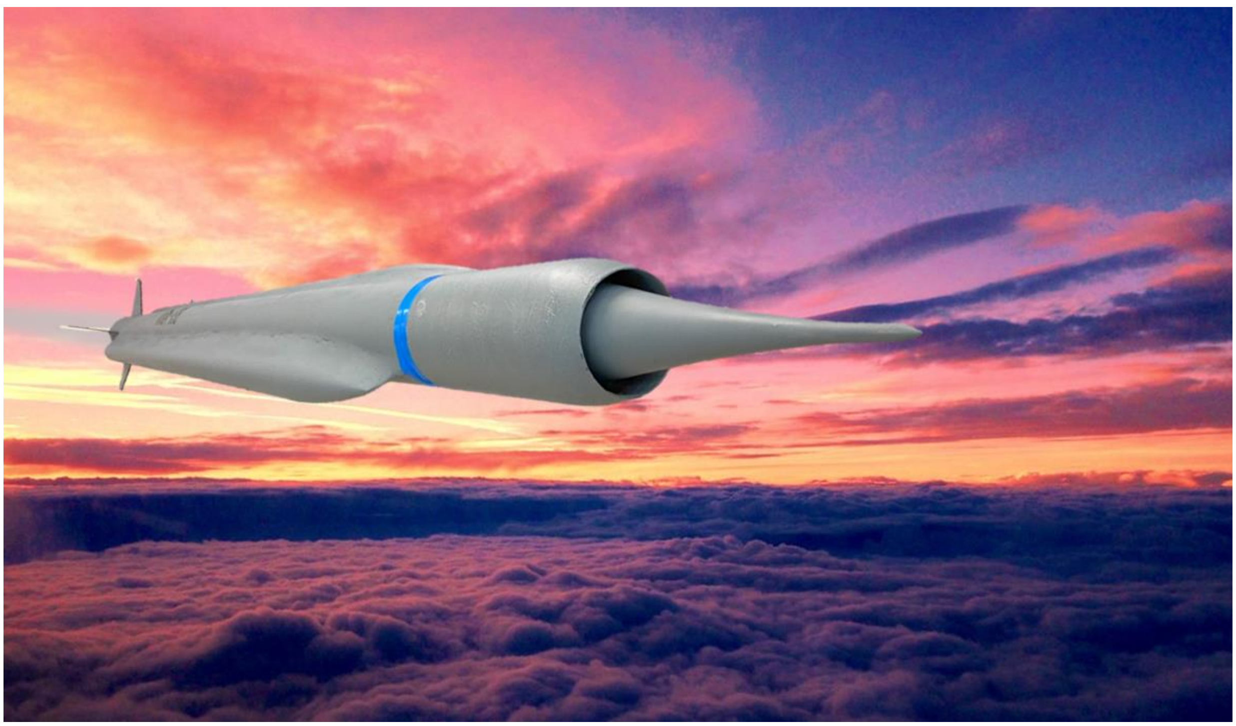

Aerospace Engineering Department

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List of Symbols

Symbol	Description	Unit
AO_i	Ancillary Objective	-
F	Force	lbf (N)
g	gravitational acceleration	32.2 ft/s^2 (9.8 m/s^2)
IA	Intercept Acceleration	ft/s^2 (m/s^2)
IV	Intercept Velocity	mph (km/h)
O_i	Objective	-
R	Range	miles (km)
R_i	Requirement	-
t	time	second
V	Velocity	mph (m/s)
W_e	Empty Weight	lbm (kg)
W_f	Fuel Weight	lbm (kg)
W_{to}	Take Off Weight	lbm (kg)

List of Acronyms

Acronym	Description
A-A	Air to Air
A-G	Air to Ground
AIAA	American Institute of Aeronautics and Astronautics
AIGM	Air Intercept Ground Missile
Anti-Rad	Anti-Radiation
BVR	Beyond Visual Range
CONOPS	Concept of Operations
RFP	Request for Proposal
VR	Visual Range

1 Introduction, General Concept of Operations, Mission Specification and Profile

This report covers the mission specification, mission profile, and the objective function of a future air launched modular missile, the AIGM-138 Chimera. The missile is designed from the requirements of the American Institute of Aeronautics and Astronautics [AIAA] Request for Proposal [RFP] for the Modular Multi-Mission Missile. The motivation for this RFP is to streamline logistics for military missiles as well as reduce the ammunition maintenance workload. [1]

1.1 Mission Specification

The designed missile has 5 missions. Air to Air [A-A] Visual Range [VR], A-A Beyond Visual Range [BVR], Air to Surface [A-G] Moving Target, A-G Anti-Radiation [Anti-Rad], A-G Ship.

The mission specifications for each mission vary in range, target, weight, carriage constraints, and post-launch support. The objective values are indicated by the value in brackets. [1] Internal carriage is defined by a box of dimensions 15 inches by 15 inches by 144 inches. External carriage is defined by a box of dimensions 22 inches by 22 inches by 168 inches. The Specification are shown below. [2]

Further tables can be found on page 3.

Table 1-1: Mission Specification Air to Air Visual Range

Mission	Air to Air Visual Range
Target	Fighters, Bombers
Range	25 miles (40.2 km)
Target Acceleration	7 G
Carriage Constraints	Internal
Max Weight	200 [150] lbm (90.7 [68.0] kg)
Post-launch Support	Fire and Forget
Assembly Time	< 1 hour
Disassembly Time	< 1 hour
Assembly Cycles	>= 20 cycles

Table 1-2: Mission Specification Air to Air Beyond Visual Range

Mission	Air to Air Beyond Visual Range
Target	Fighters, Bombers
Range	80 [100] miles (128 [161] km)
Target Acceleration	7 G
Carriage Constraints	External [Internal]
Max Weight	500 [350] lbm (227 [159] kg)
Post-launch Support	Datalink [Fire and Forget]
Assembly Time	< 1 hour
Disassembly Time	< 1 hour
Assembly Cycles	>= 20 cycles

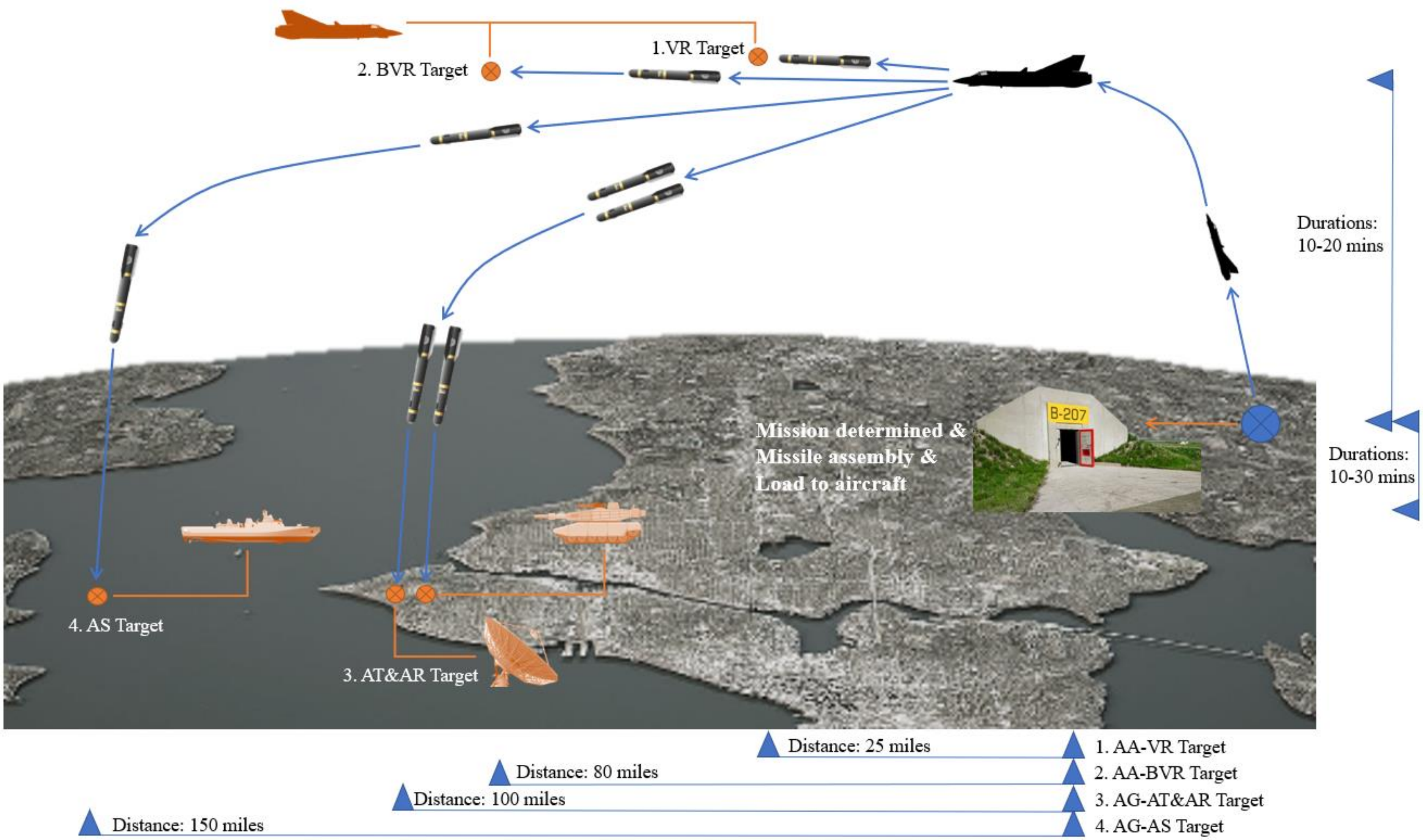


Figure 1-1: Operational Concept of the Missile in Different Target

Table 1-3: Mission Specification Air to Ground Moving Target

Mission	Air to Ground Moving Target
Target	Trucks, tanks, small boats
Range	80 [100] miles (129 [161] km)
Target Acceleration	1 G
Carriage Constraints	External [Internal]
Max Weight	1000 [500] lbm (453.59 [226.8] kg)
Post-launch Support	Datalink/Laser [Fire and Forget]
Assembly Time	< 1 hour
Disassembly Time	< 1 hour
Assembly Cycles	>= 20 cycles

Table 1-4: Mission Specification Air to Ground Anti-Radiation

Mission	Air to Ground Anti-Radiation
Target	Radar Sites
Range	80 [100] miles (129 [161] km)
Target Acceleration	0 G
Carriage Constraints	External [Internal]
Max Weight	1000 (500) lbm (454 [227] kg)
Post-launch Support	Fire and Forget
Assembly Time	< 1 hour
Disassembly Time	< 1 hour
Assembly Cycles	>= 20 cycles

Table 1-5: Mission Specification Air to Ship

Mission	Air to Ground Ship
Target	Frigates, Destroyers
Range	100 [150] miles (161 [241] kg)
Target Acceleration	0.1 G
Carriage Constraints	External [Internal]
Max Weight	2000 (1000) lbm (907 [454] kg)
Post-launch Support	Datalink [Fire and Forget]
Assembly Time	< 1 hour
Disassembly Time	< 1 hour
Assembly Cycles	>= 20 cycles

1.2 Concept of Operations

The concept of operations for the AIGM-138 is found on page 2. [1]

1.3 Mission Profile

The profile of each of these missions is similar as the missile is assembled, equipped to the aircraft, then the aircraft travels to the target and launches the missile, the differences come in guidance and targets.. [2]

The preliminary mission profile of five different missions is shown in below.

Figure 1-2: Air to Air Missile Mission Profile

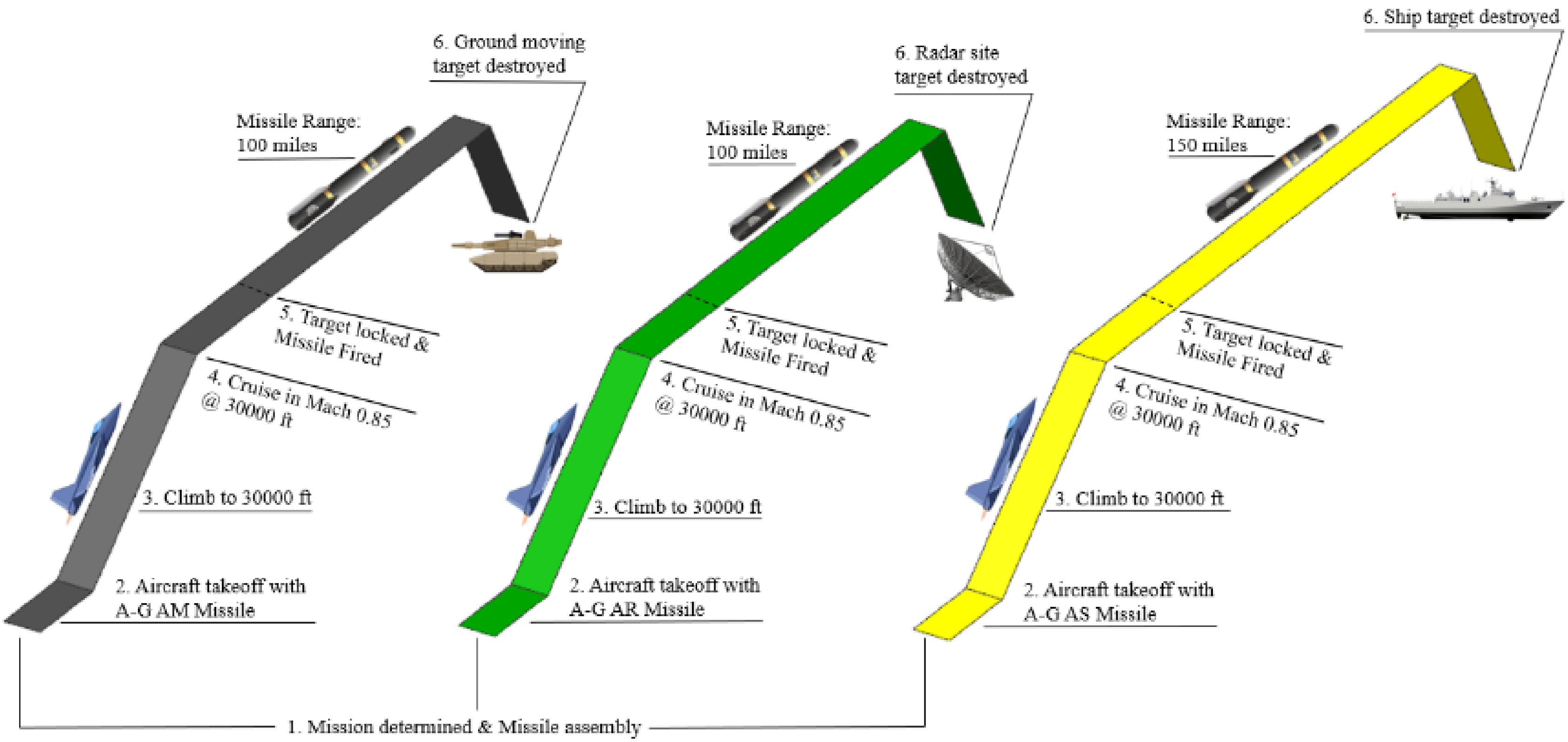


Figure 1-3: Air to Ground Missile Mission Profile

2 Historical Review, Competition in the Market

Figure 1-1: AIM-9L Sidewinder missile [28]

In order to determine what customers, view as important a historic review and market evaluation is conducted on each of the missions, A-A VR, A-A BVR, A-G Moving, A-G Anti-Rad, and A-G Anti-Ship.

2.1 Historical Review

Many missiles have been developed that satisfy one or more of the requirements laid out in the RFP. A review of these missiles is conducted below.

2.1.1 Air to Air Visual Range

Air to air missiles were first used in WW1. Those were unguided. The development of guided A-A missiles started in WW2 and continued rapidly afterwards. The AIM-4 missile was the first to be effectively used, but it was soon replaced by early AIM-9 sidewinder missiles as those could also be used against fighter jets and not only against slow bombers. [26] For the Air-to-Air missile within visual range, five currently active missiles were selected for deeper comparison. These include the western missiles AIM-9X Sidewinder (USA), IRIS-T (Germany and others) and MICA (France) as well as the Vympel R74 (Soviet Union / Russia) and the PL-8 (China). Among these, some specs are similar, but others have huge design differences. While all missiles have a length ranging between 115 and 123 in, the weight ranges between 188 and 253 lb. The range differs immensely ranging from 8 to 43 nmi. All these missiles use infrared homing, only the French MICA system is also capable of Radar homing.

Figure 2-2: IRIS-T Missile [34]

With previous versions entering service as early as 1956, the AIM-9X Sidewinder missile entered service in 2003. With a yearly production rate of over 500 units, it is heavily used across different launch platforms in the U.S. and dozens of export customers. It is the lightest out of the portraited missiles and reaches a max speed of Mach 2.7.

A big push forward in the development of missiles suitable for this mission was the discovery of the capabilities of the Soviet R73 missile, which had been severely underestimated by western militaries during the cold war. After the German reunification, western militaries tested the GDR's remaining R73 missiles and discovered great capabilities, leading to the development of AIM-9X, IRIS-T and other missile programs.

2.1.2 Air to Air Beyond Visual Range

The A-A BVR mission consists of multiple missiles in many stages of their production. These include the AIM-120 AMRAAM, AIM-7 Sparrow, AIM-54 Phoenix, R-77, V-4 R-Darter, TC-2 Sky Sword, and more.

The AIM-120D AMRAAM is the current iteration of the AIM-120 family made by Raytheon. Future upgrades are currently in development to this family of missiles. The AIM-120D entered service in 2015. [3]

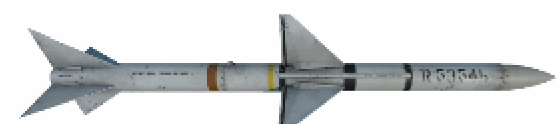


Figure 2-3: AIM-7 Sparrow [29]

The AIM-7 Sparrow, produced by Raytheon, family is no longer in production, but current stores are still in use. The AIM-7 family initial performance was extremely bad with a majority of missiles fired missing the target. This was improved in later versions. [3]

The AIM-54 Phoenix, produced by Raytheon, is no longer in production and if it is used the use is exclusively by Iran. This missile was designed for the F-14 Tomcat and entered service in 1973. [3]

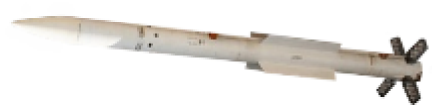


Figure 2-4: R-77 missile [30]

The R-77 Izdieliye-170, produced by JSC Tactical Missiles Corporation, is a Russian designed missile that is licensed to both Ukraine and China. This missile entered service in the 1990s. [3]

The V-4 R-Darter, produced by Denel Dynamics, is a South African missile intended as a cheaper alternative in the BVR market. This missile entered service in 2000. [3]

The TC-2 Sky Sword, produced by the National Chung-Shan Institute of Science and Technology, is a Taiwanese missile designed for local production. This missile entered service in 1999, and a newer model is in the initial stages of production. [3]

2.1.3 Air to Ground Moving Target

Air to ground missiles can be equipped on aircraft such as strategic bombers, fighter bombers, attack aircraft, fighter aircraft, armed helicopters and anti-submarine patrol aircraft etc. In this section, 6 of existing missiles from different countries were selected and the main target of those missile are moving target such tanks or armored cars.

The AGM-65 Maverick, produced by Raytheon. This development of this missile began in 1966, accepted by US Air Force in August 1972 and still in service with the militaries of more than 30 countries around the world. It is mainly used to attack ground moving targets, but there are already 8 types of AGM-65 missiles to deal with different tactical needs. [4]

The AGM-114 Hellfire, produced by Lockheed Martin. This missile, designed in 1974, is intended to primarily attack armored moving targets, it has higher accuracy and anti-interference ability compared to AGM-65 but also higher cost per unit. [5]

Figure 2-5: AGM-114 Hellfire [31]

The Kh-29 Kedge, produced by Vympel NPO, Russia. This missile design began in 1970 by Soviet Union and was accepted into service in 1980. The Kh-29 has the same purpose as the AGM-65, but the Kh-29 is 20% heavier and larger than the AGM-65 since it is loaded with a heavier warhead. [6]

Figure 2-6: Kh-29 Kedge [32]

The AGM-142 Popeye, produced by Rafael Advanced Defense System, Israel. The AGM-142 was developed by Israeli Air Force and began service in 1985. It is a heavy missile with 3000 lb of total weight that can reach the target at speeds of Mach 0.8 at range of 40 nmi. [7]

The MAM-T, produced by Roketsan, Turkey is an air to ground missile which was specially developed by Turkey for unmanned aerial vehicles (UAV) or light attack aircraft in this decade. The MAM-T is very small and lightweight, but it can reach the target precisely within the maximum effective range up to 40 nmi. [8]

The KD-63, produced by China. The KD-63 development began in 1987, and it is the largest and longest ranged missile among all selected missiles. The KD-63 can carry a 1100-pound warhead and engage targets at Mach 0.9 at a maximum range of 130 nmi. [9]

2.1.4 Air to Ground Anti-Radiation

Figure 2-7: HARM [37]

The Highspeed Anti-Radiation Missile (HARM) is the most commonly used anti-radiation missile by the United States today. It was first developed in 1985 and has seen use in the Operation Desert Storm, the Persian Gulf War and other conflicts involving suppression of enemy air defenses to today. Today the AGM-88G is the most advanced variant.

The Air Launched Anti-Radiation Missile (ALARM) was a British developed missile designed to attack enemy radar installations to disrupt their monitoring of a combat zone's airspace. While it has been retired from service by the British armed forces it was sold to Saudi Arabia while it was still being produced. Saudi Arabia continues to use the ALARM to the present day.

The Shrike was a modification made to the AIM-7 sparrow in the 1960's. It was one of the very first antiradiation missiles developed by the United States and only saw discontinuation by the United States in 1992. It saw continued use by Israel's armed forces until it was later retired at an unknown date. The Shrike was first used against Soviet made surface to air missile (SAM) sites in the Vietnam war. The Shrike remained popular for an unexpectedly long time even after the arrival of more advanced anti-radiation missiles because it was cheaper and therefore easier to obtain on the front.

Figure 2-8: AGM-78 [36]

The Standard Anti-Radiation Missile (ARM) was also used in the Vietnam war by the United States and was considerably larger than its predecessors. What makes it unique from the other missiles on this list is that it was developed from an existing surface to air missile frame, the RIM-66. It was intended to replace the Shrike which often had an insufficient warhead. The Standard ARM increased the size of the warhead significantly such that it would be able to destroy the surrounding infrastructure used to support a radar station.

The sidearm was developed in 1986 from the AIM-9C after it become obsolete. It was only used for a short period of time before stores were depleted. At one time, there were plans to resume production of the missile, but the program was ultimately canceled in favor of other anti-radiation missiles that came to the market.

The RUDRAM is a family of missiles currently under development by the Defense Research Development Organization of India. It is intended to be the first wholly indigenous missile platform developed by India. The RUDRAM II specifically is outfitted for anti-radiation missions. The RUDRAM is the newest missile being evaluated for the anti-radiation role and far surpasses the top speeds of the other market competitors as it passes into the hypersonic regime at Mach 5.5.

2.1.5 Air to Ship

The A-G anti-ship six missiles are chosen to represent this category from western and Asian nations. They are AGM-158, AGM-84, ExocetAM-39, Sea Eagle (BAE), RBS-15, and YJ-12. A common feature of the anti-ship missile classification is their sea-skimming flight path, where they fly low and close to the water surface during the terminal phase to avoid defense weapons.

The North American-produced missiles are developed by Lockheed Martin and Boeing, AGM-158 and AGM-84(Harpoon). The AGM-158 is called the joint air-to-surface standoff cruise missile (JASSM), the development of this program started in 1995 as an air-launched weapon from a standoff weapons range. The missile is designed to be carried by a wide range of aircraft like the; F-15, F-16, F-35, B-1, B-2, & B-52. To effectively reach its long-range targets the missile uses an advanced turbojet engine and folding wing configuration for maximum range.

Figure 2-9: AGM-158 missile [33]

AGM-84 designated Harpoon is an advanced ground/surface attack missile platform developed by Boeing and McDonnell Douglass, capable of hitting targets at a range of 155nmi. The Harpoon can be remotely controlled while in flight and also reassigned to a different target after launch.

The Chinese defense industry developed the YJ-12 Eagle strike as a counter to American warships and is the only supersonic entry for this category. Ramjet engines allow for flight phases to accelerate up to Mach 3, with an extended range of up to 300nmi that could be increased by mounting on larger bomber aircraft.

Figure 2-10: Sea Eagle [35]

The Sea Eagle was developed by BAE systems, now MBDA had a development program starting in 1979. It is designed to target a wide range of surface targets and is in service with British partner nations, with new upgrades planned.

RBS-15 developed by SAAB is currently an optimized anti-ship missile, air-launched and powered by a turbojet engine. It has a long-range and powerful warhead to disable most targets and can have the flight path programmed along multiple waypoints to reach a target.

Exocet AM-39 is developed by the French contractor MBDA, it is the most popular export system after the Harpoon. The missile has a shorter range than other entries but comes from a well-developed family of systems, and still has upgrades planned for future models.

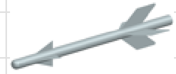
2.2 Relevant Missile Markets and Missions

To determine the importance of each mission type, a review of the market is conducted.

2.2.1 Air to Air Visual Range

The Air-to-Air visual range missile market has a diverse set of manufacturers from various countries. All A-A VR missiles currently used are powered by a solid rocket motor. Modern 5th generation A-A VR missiles feature 360° defense capability, meaning pilots can fire at targets in front and behind the aircraft. Visual range missiles are designed to target aircraft less than 16 km (10 mi) away and mostly use infrared guidance. The market review in Table 2-1 only covers a selection of the available models. [16,17]

Table 2-1: Market review of Air to Air Visual Range missiles [16]

					
Missile Name	**Sidewinder**	**Vympel**			
Designation	**AIM-9X**	**R74**	**IRIS-T**	**MICA**	**PL-8**
Manufacturer	Raytheon	Vympel	Diehl Defence, Avio spa, Litton Italia, Leonardo	MBDA	Xi'an Eastern Machinery Factory and CATIC
Number Produced	5000 (as of 2013)			1000 (as of 2010)	
Cost per unit (USD)	$ 320,000.00		$ 430,000.00	$ 70,000.00	$ 60,000.00
Country of Origin	USA	Soviet Union	Sweden, Greece, Norway, Spain	France	China
Total Sales Volume per year	560		660	70	
General Outlook in Future	latest version			latest version	
Date of Entry	2003 (based on further (	1984	2005	1996	1997
lenth (in)	119	115	115.2	122.4	118
diameter (in)	5	6.69	5	6.3	6.3
wingspan (in)	25.25	20	17.6	12.6	32
Wlaunch (lbm)	188	233	193	247	253
Wwarhead (lbm)	20.8	17	25	26.4	22
Wpropellant (lbm)	94	60	133	138	
Max Thrust (lbf)	2068	1284	7720	2717	2783
Guidance type	infrared homing	Infrared homing	infrared homing (fire and forget)	Radar and infrared homing	Infrared Homing
Max Mach #	2.7	2.5	3	4	3.5
Max Effective Range (nmi)	22	21.6	13.5	43	8.1
Operational Envelope	> 60,000 ft	0 to 65,616 ft	0 to 66,000 ft		

From this, five commonly used missiles were chosen for further analysis. These represent some of the most important systems in use today and can be seen in the table and the CAD figure.

Figure 2-11: Missile Comparison Air to Air Visual Range

The German IRIS-T missile was developed in cooperation with Italy, Sweden, Greece, Canada, and Norway by Diehl Defence. Due to the German reunification in 1990, western air forces obtained Soviet R-73 missiles which were found superior to contemporary western missile technology. This led to the development of a visual range missile to replace older AIM-9 versions. IRIS-T is capable of fire-and-forget and can be used across a variety of aircraft including the Eurofighter, the F-16, and F-18. It uses digital image processing to differentiate between targets and flares and is resistant to dazzlers. Selling points are the low cost and high capabilities. [16,18] IRIS-T is combat proven in the Russian-Ukraine war with Ukraine claiming a 100% success rate for use in air defense [19].

MICA is a French missile system developed by MBDA. It is available with active radar homing as well as infrared homing and can filter counter-measures. The radar guided version is a fire-and-forget missile, the infrared guided version is lock-after-launch. The Mach-4 missile entered service in 1996 and can be launched from the surface or several French fighter jets. [20]

The Russian R74 missiles is based on the Soviet era R73 missile entering service in 1984. It has very similar proven technology but features a newly developed infrared seeker and an increased rocket motor burn time. The new seeker increased the off-boresight capabilities from 40° to 75° from the centerline. Many specs are unknown, but the missile is very common for both export and Russian military. Production rates in the 1990s were as high as 6,000 units per year. [21,22]

The American answer to the unexpected high capabilities of the R74 discovered after the end of the cold war was the AIM-9X missile. It was developed by Raytheon based on a missile family dating back to 1956. Entering service in 2003, it features launch-and-leave capability and in newer versions also has lock-on-after-launch capability. Compared to older versions, the fin size of the AIM-9X was decreased in favor of better thrust vectoring. It is infrared guided by proportional pursuit. [23,24]

The history of China's PL-8 missiles started when Israel provided a Python 3 missile for licensed production using domestic components. Its features include a dual-thrust rocket motor, helmet-mounted sight aiming and compatibility with both western and Chinese radars. It is the first Chinese missile to feature all-aspect infrared seeking, allowing it to attack aircraft from the front. [25]

2.2.2 Air to Air Beyond Visual Range

The A-A BVR market appears to be largely dominated by two manufacturers, United States based Raytheon and Russian Federation based JSC Tactical Missiles Corporation. Raytheon has made multiple BVR missiles with the only one remaining in production being the AIM-120. JSC Tactical Missiles Corporation makes multiple BVR missiles and has licensed some of these missiles to manufacturers based in other countries. The Raytheon AIM-120D and the JSC Tactical R-77 both costs around $1 million per missile, this includes lifecycle costs such as maintenance. Other manufacturers are attempting to tap into this market such as National Chung-Shan Institute of Science and Technology developing the TC-2 Sky Sword. This missile also costs around $1 million per missile. The most likely reason for the development of this missile is that Taiwan gained domestic BVR missile production. The South American Denel Dynamics V-4 R-Darter is a cheaper alternative and only costs $50296, this likely excludes other life cycle costs. This drop in price also comes with a steep drop in performance with the maximum range being less than half the maximum range of the AIM-120D. Further information is found in Table 2-2. [3] This table is incomplete, and more information will be added in the future.

Table 2-2: Air to Air beyond visual range market analysis

Missile Name	AMRAAM	Sparrow	Phoenix	Izdieliye-170	R-Darter	Skysword 2
Designation	AIM-120D	AIM-7P	AIM-54A	R-77 (RVV-AE)	V-4	TC-2
Manufacturer	Raytheon	Raytheon	Raytheon	JSC Tactical Missiles Corporation	Denel Dynamics	National Chung-Shan Institute of Science and Technology
Number Produced	17500 total Amraams	>70000 total sparrows	>5000			
Combat Record	0.59 Pk	54.5% Kill rate	US: 3 shot 0 kills,	0.6-0.7 Pk		
Cost per unit (USD)	1.095 mil	125000	477131	~1 mil	50296	1.07 mil
Country of Origin	United States	United States	United States	Russia	South Africa	Taiwan
Total Sales Volume per year		0	0			150
General Outlook in Future	Upgraded variants in development	Replaced by AMRAAM	No longer used	Still in production, upgrades likely	All consumers opting for different missiles	Production capable, but new model began production in 2021
Date of Entry	2015	1987	1973	1990s	2000	1999
Storage Dimensions (ft)	12 x 1.6	12 x 3.28	13 x 2	12 x 1.5	11.9 x 2.1	11.9 x 2.7
Internal Carriage Dimensions	12 x 1.6	12 x 3.28	13 x 3	12 x 1.5	11.9 x 2.1	11.9 x 2.7
External Carriage Dimensions	12 x 1.6	12 x 3.28	13 x 4	12 x 1.5	11.9 x 2.1	11.9 x 2.7
Wlaunch (lbm)	358	510	976.5	386	264.5	397
Wwarhead (lbm)	44	89.5	134	50		66
Wpropellant (lbm)						
Max Thrust (lbf)						
Guidance type	Active Radar	Semi-active radar	Active/Semi-active radar	Active Radar	Active Radar	Active Radar
Max Mach #	4		5	4		
Max Effective Range (nmi)	86		73	43	34	43

Models of these missiles are shown in Figure 2-12.

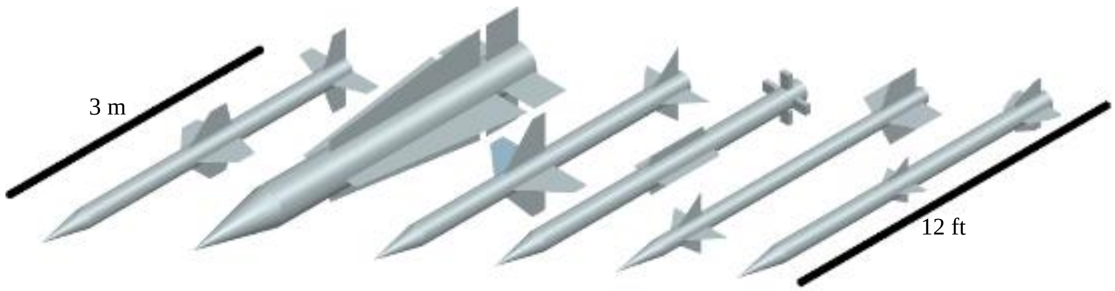
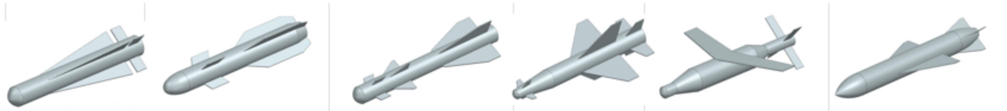


Figure 2-12: Missile Comparison Air to Air Beyond Visual Range

2.2.3 Air to Ground Moving Target

The following table is the summary of available data on six Air to Ground missiles from different countries. Figure 2-13 shows the outlook of each missile.

Table 2-3: Market Survey of Anti-Moving Target Air to Ground Missiles



Missile Name	Maverick	Hellfire	Kedge	Popeye	MAM-T	KD-63
Designation	AGM-65 A/B	AGM-114	Kh-29	AGM-142	None	None
Manufacturer	Raytheon	Lockheed Martin	Vympel NPO	Rafael Advanced Defense System	Roketsan	National Defense Ministry
Number Produced	70000+	100000+	Unknown	1300	Unknown	Unknown
Combat Record						
Cost per unit (USD)	$17000 to $110000	$150,000	$40,000	$1.02 million		
Country of Origin	US	US	Russian	Israel	Turkey	China
Total Sales Volume per year	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
General Outlook in Future	In service	In service	In service	In service	In service	In service
Date of Entry	1972	1984	1980	1992	2018	2002
Storage Dimensions	8.2"x2.5"	5.5"x1.2"	12.8"x3.6"	15.8"x6.5"	3.4"x0.6"	23"x7.9"
Internal Carriage Dimensions	8.2"x2.5"	5.5"x1.2"	12.8"x3.6"	15.8"x6.5"	3.4"x0.6"	23"x7.9"
External Carriage Dimensions	8.2"x2.5"	5.5"x1.2"	12.8"x3.6"	15.8"x6.5"	3.4"x0.6"	23"x7.9"
Wlaunch (lbm)	462	108	1520	3000	94	4400
Wwarhead (lbm)	125	19.8	705	750	20	1102
Wpropellant (lbm)						
Max Thrust (lbf)		4406				
Guidance type	Electro optical	Semi-active laser homing	Semi-active laser homing	Television and imaging infrared	Semi-active laser homing	Inertial navigation Radio command Terminal TV guidance
Max Mach #	0.94	1.3	1.8	0.7		0.9
Max Effective Range (nmi)	12	5.9	6.5	40	4.3	130
Operational Envelope						

Based on the record, every powered military country in the world has its own development Air to Ground missile. But the market of Anti moving target A-G missile appears to be leaded by Raytheon and Lockheed Martin, the AGM-65 series and AGM-114 series they designed have the largest production quantity and are widely used all over the world more than 30 countries.

Since these two missiles have multiple models and failed to know the specific production quantity of each model. Moreover, the military will use the latest equipment as much as possible to ensure combat effectiveness. Therefore, the production cost of each missile is 80% of the highest production unit price which are $88,000 per AGM-65 and $120,000 per AGM-114.

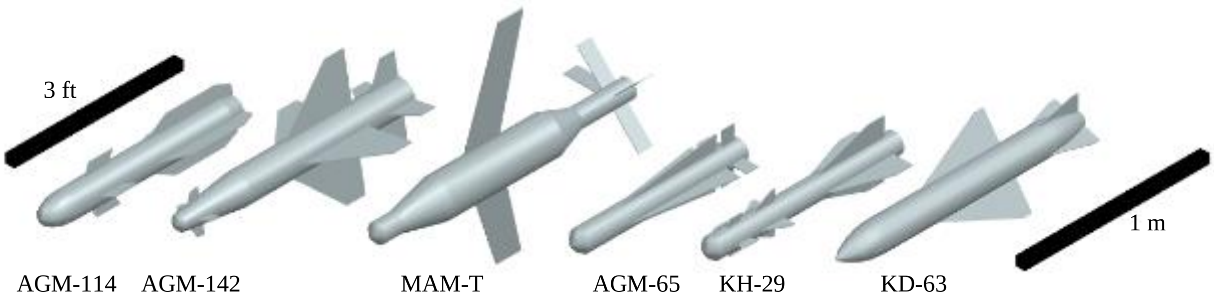
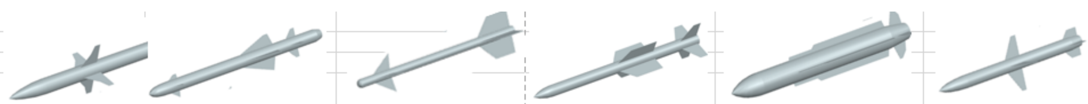


Figure 2-13: Missile Comparison Air to Ground Moving Target Missiles

2.2.4 <u>Air to Ground Anti-Radiation</u>

The following table is a summary of available data on several variations of anti-radiation missiles developed in the past.

Table 2-4: Market Survey of Anti-Radiation Air-Surface Missiles



Missile Name	HARM	ALARM	Shrike	Standard ARM	Sidearm	Rudram 2
Designation	AGM-88G		AGM-45	AGM-78	AGM-122	
Manufacturer	Raytheon	British Aerospace Dynamics	Naval Wepons Center at China Lake	General Dynamics	Naval Wepons Center at China Lake/Motorola	Development Organization of India
Number Produced	20,000 +	750 +	Unknown	3,000 +	Unknown	None
Combat Record	Unknown	Unknown	Unknown	Unknown	Unknown	None
Cost per unit (USD)	$ 870,000.00	Undisclosed	$ 7,000.00	$ 200,000.00	< $200,000	Unknown
Country of Origin	United States	Britan	United States	United States	United States	India
Total Sales Volume per						
General Outlook in Future	Serving with US and being upgraded	Retired in UK, used by Saudi Arabia	Phased out by both US and Israel	Replaced by HARM in 1980s	Production stopped, stores depleted in 1990s	Still partially under development
Date of Entry	2012	1990	1965	1968	1986	2022
Storage Dimensions	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
Internal Carriage	na	na	na	na	na	na
External Carriage	44"x44"	29"x29"	36"x36"	42.5"x42.5"	24.8"x24.8"	TBD
Wlaunch (lbm)	796	591	390	1370	195	1300
Wwarhead (lbm)	150		149	215	25	342
Wpropellant (lbm)					same as aim 9	
Max Thrust (lbf)					same as aim 9	
Guidance type	Passive Radar Homing	Pre-programmed/passive	Passive Radar Homing	Passive Radar Homing	Narrow Band Passive Radar	INS + SatNav / IIR
Max Mach #	2.9	1525 mph	1.5	1.8	2.3	5.5
Max Effective Range	80	58	22	56	9	190
Operational Envelope		43,000 ft				131000 ft
	10" diameter, 44"	9" diameter, 13' 11" long	8" diameter, 10' long,	13.5" diameter, 15' length	5" diameter, 9' 5" length	18'

The following figures are mockups of the anti-radiation missiles inspected for this market survey preceded by a brief overview of their development and current use.

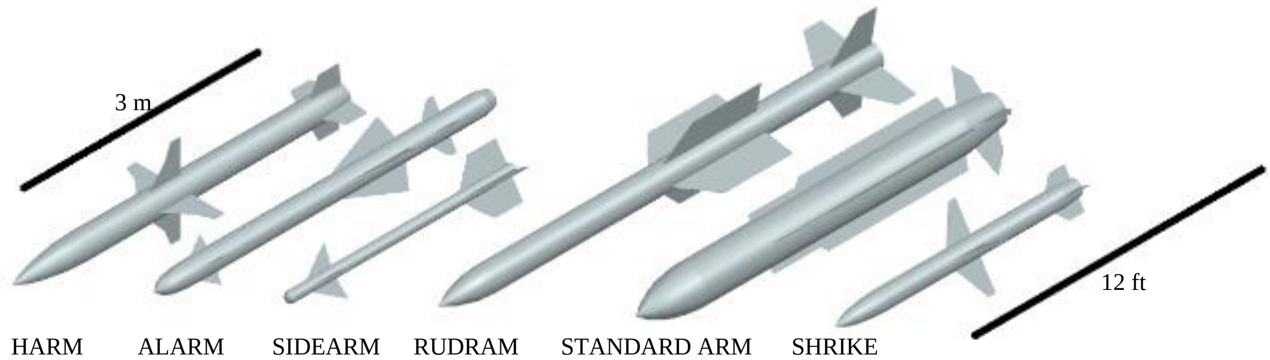


Figure 2-14: Anti-Radiation Missiles CAD models

The AGM-88 is the most commonly used anti-radiation missile by the United States today. It replaced previous anti-radiation missiles such as the AGM-45 Shrike and is still in service with the United States and allies. A mock-up of the HARM is shown in the figure below.

The British developed ALARM anti-radiation missile saw use in the Falklands War but has since been retired by the UK as well as by Saudi Arabia. A model of the ALARM is shown in the figure below.

The AGM-45 shrike was one of the very first effective anti-radiation missiles. While initially somewhat dissatisfactory, use of the Shrike continued for some time because it was much less expensive and more widely available in combat theaters than the newer missiles which were developed to replace it. A model of the shrike can be seen in the figure below.

The Standard ARM was developed to replace the shrike and was designed to not only disable radar equipment, but also the surrounding infrastructure needed to operate an air defense post. Its adoption was slow and delayed due to the much more economical AGM-45. A model of the Standard ARM can be seen below.

The Sidearm was developed by modifying the proven AIM-9 missile platform to fulfill anti-radiation roles. Its production life was short lived as only a limited number of missiles were commissioned and newer more effective missiles such as the AGM-88 superseded it. A model of the Sidearm can be seen in the figure below.

The RUDRAM is a missile currently under development in India meant to be the country's first wholly indigenous anti-radiation missile. It is currently the only missile being evaluated that is capable of what would be considered hypersonic flight with a top speed of Mach 5.5. Several variants are being tested at the moment with the RUDRAM II being the anti-radiation variant.

2.2.5 Air to Ship

The figure below lists the most common anti-ship missile systems currently in-service by NATO and other military forces.

Figure 2-15: Market Survey of Air-to-Ground Anti-Ship Missiles

Missile Name	Harpoon	LRASM	Eagle Strike 12	Sea Egale	Gungnir	Exocet
Designation	AGM-84	AGM-158	YJ-12	PT3	RBS-15	AM-39
Manufacturer	Boeing	LockHeed Martin	China	BAE	SAAB	MBDA
Number Produced	7000	4900	>100	>2000		1,100
Combat Record	TBD	TBD	TBD	TBD	TBD	TBD
Cost per unit (USD)	1,500,000	$1,266,000	1,800,000	700,000	800,000	867,000
Country of Origin	USA	USA	China	U.K	Sweden	France
Total Sales Volume per year	n/a	>1000	n/a	n/a	n/a	n/a
General Outlook in Future	in service	in service	in service	in service	in service	in-production
Date of Entry	1977	2009	2010	1985	1984	1970
Storage Dimensions	15"x13.5'	14"x8'	23"x2"	13"x4"	14"x5"	16"x4"
Internal Carriage Dimensions	15"x13.5'	16"x10"	n/a	n/a	n/a	n/a
External Carriage Dimensions	15"x13.5'	14"x8'	n/a	13"x4"	14"x5"	16"x5"
Wlaunch (lbm)	1135lb	1020lbs	5000	1278	1433	1477lb
Wwarhead (lbm)	493	992	450	507	440	364lb
Wpropellant (lbm)	TBD	TBD	TBD	TBD	TBD	TBD
Max Thrust (lbf)	600lbs	944				
Guidance type	semi-active, inertial	GPS Aided Inertial,terminal infrared	Active Radar Homing and Inertial Guidance	Active Radar Homing J-Band Radar	Active Radar homing, INS	Active RF homing
Max Mach #	0.85	0.9	3	0.85	0.9	0.9
Max Effective Range (nmi)	150	300	270	60	160	50nmi
Operational Envelope						

AGM-84 Harpoon is the most used service missile it was developed by McDonnell Douglas, currently Boeing. Designed for all weather conditions and costing $1million for each unit including lifecycle costs it has been in service since 1977 and has seen operations use in every main conflict since then.

AGM-158 is developed by Lockheed Martin, starting development in 2009, the system was designed to be a long rang cruise missile. The design features a low observable configuration cost $1.2 million per unit.

The Chinese YJ-12 Eagle strike is modern counter to Naval vessels, top speed between Mach 3-4, making it a serious threat as a first strike weapon to ships. The fast attack speed

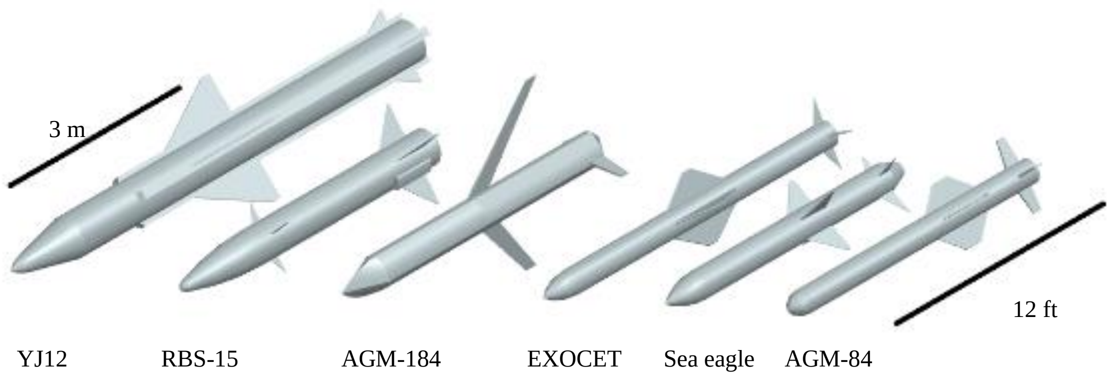


Figure 2-16: Anti Ship missiles CAD models

means much less time to intercept and would require more modern close defense weapons to counter. The system is relatively new and most estimates show the individual unit cost over $1.8million.

BAE Sea Eagle has been in service since 1985, and employed in-service primarily by the United Kingdom military. It is in service with U.K allied nations.

RBS-15 developed by SAAB in 1980’s for the Swedish Navy and modernized to be used from aerial platforms.

Exocet AM-39 is the air launched version of French made sea-skimming missile, it is the second most widely adopted missile developed in 1977 and still planned for upgrades. The system is highly effective and especially designed to defeat CIWS defenses, using a monte-carlo generator so it is random in a range and mechanically destabilizes the gun.

3 Objectives, Requirements, and Design Optimization Function

To properly consider design considerations an optimization function is made utilizing the objectives, requirements, as well as ancillary objectives that are believed to add value to the design.

The requirements are set in the RFP and are multiplicatively weighted so if a requirement is not met then the design is considered a failure. The primary requirements are range [R], target velocity [IV], target acceleration [IA], tracking method, and external carriage which is defined by a box of dimensions 22 inches by 22 inches by 168 inches. [1]

The objectives are set in the RFP as well, but these are weighted additionally and scale linearly to the defined value. The primary objectives are increases to the required values as well as fire and forget capable and internal carriage which is defined by a box of dimensions 15 inches by 15 inches by 144 inches.

The ancillary objectives are decided by the team and are additionally weighted, but the weight of the ancillary objectives is less than the objectives.

3.1 Air to Air Visual Range Mission

The A-A VR mission is similar to the mission of the Air Intercept Missile 9 missile.

3.1.1 Requirements

The requirements of the A-A VR mission are found below in Table 3-1.

Table 3-1: Air to Air Visual Range Requirements

Requirement Number	Requirement	Values
R_1	A-A VR ≥ 25-mile range (40.2 km)	R1={1 if R ≥ 25 miles, 0 if R < 25 miles
R_2	A-A VR ≥ 700 mph target (1127 km/h)	R2={1 if IV ≥ 700 mph, 0 if IV < 700 mph
R_3	A-A VR ≥ 7 G target	R3={1 if IA ≥ 7 G , 0 if IA < 7 G
R_4	A-A VR Internal Carriage	R4={1 if Internal Carriage capable, 0 if not
R_5	A-A VR ≤ 200 lbm Max Weight (90.7 kg)	R5={1 if m ≤ 200 lbm, 0 if m > 200 lbm
R_6	A-A VR Fire and Forget	R6={1 if Fire and Forget capable, 0 if not
R_7	Assembly Time < 1 hour	R7={1 if Assembly Time < 1 h, 0 if not
R_8	Assembly Cycles ≥ 20	R8={1 if Assembly Cycles ≥ 20, 0 if not

3.1.2 Objectives

The objectives of the A-A VR mission are found below in Table 3-2.

Table 3-2: Air to Air Visual Range Objectives

Objective Number	Objective	Values
O_1	A-A VR ≤ 150 lbm Max Weight (68.04 kg)	O1=$\frac{200-m}{50}$ if m ≥ 150 lbm , 1 if m < 150 lbm

3.1.3 Air to Air Visual Range Objective Function

Below is the objective function for the A-A VR mission.

$$OF_{A-A\,VR} = \prod_{n=1}^{8} R_i \cdot \left(\sum_{n=1}^{1} O_i {}_1 + \sum_{n=1}^{6} AO_i \right)$$

The function is adapted with different numbers to fit all missions.

3.2 Air to Air Beyond Visual Range Mission

The A-A BVR mission is similar to the mission of the Air Intercept Missile 120.

3.2.1 Requirements

The requirements of the A-A BVR mission are found below in Table 3-3.

Table 3-3: Air to Air Beyond Visual Range Requirements

Requirement Number	Requirement	Values
R_1	A-A BVR ≥ 80-mile range (128.75 km)	R1={1 if R ≥ 80 miles , 0 if R < 80 miles
R_2	A-A BVR ≥ 700 mph target (1126.54 kmh)	R2={1 if IV ≥ 700 mph, 0 if IV < 700 mph
R_3	A-A BVR ≥ 7 G target	R3={ 1 if IA ≥ 7 G, 0 if IA < 7 G
R_4	A-A BVR External Carriage	R4={1 if External Carriage capable, 0 if not
R_5	A-A BVR ≤ 500 lbm Max Weight (226.8 kg)	R5={1 if m ≤ 500 lbm, 0 if m > 500 lbm
R_6	A-A BVR Datalink	R6={1 if Datalink capable, 0 if Datalink incapable
R_7	Assembly Time < 1 hour	R7={1 if Assembly Time < 1 hour, 0 if not
R_8	Assembly Cycles ≥ 20	R8={1 if Assembly Cycles ≥ 20, 0 if not

3.2.2 Objectives

The objectives of the A-A BVR mission are found below in Table 3-4.

Table 3-4: Air to Air Beyond Visual Range Objectives

Objective Number	Objective	Values
O_1	A-A BVR ≥ 100-mile range (160.93 km)	O1={$\frac{R-80}{20}$ if R ≤ 100 miles, 1 if R > 100 miles
O_2	A-A BVR Internal Carriage	O2={1 if Internal Carriage capable, 0 if not
O_3	A-A BVR ≤ 350 lbm Max Weight (158.76 kg)	O3={$\frac{500-m}{150}$ if m ≥ 350 lbm, 1 if m < 350 lbm
O_4	A-A BVR Fire and Forget	O4={1 if Fire and Forget capable, 0 if not

3.3 Air to Surface Moving Target Mission

The A-G moving target mission is similar to the mission of the Air to Ground Missile 65.

3.3.1 Requirements

The requirements of the A-G moving target is found below in Table 3-5.

Table 3-5: Air to Ground Moving Target Requirements

Requirement Number	Requirement	Values
R_1	A-G Moving ≥ 80-mile range (129 km)	R1={1 if R ≥ 80 miles , 0 if R < 80 miles
R_2	A-G Moving ≥ 80 mph target (128.75 kmh)	R2={1 if IV ≥ 80 mph, 0 if IV < 80 mph
R_3	A-G Moving ≥ 1 G target	R3={ 1 if IA ≥ 1 G, 0 if IA < 1 G
R_4	A-G Moving External Carriage	R4={1 if External Carriage capable, 0 if not
R_5	A-G Moving ≤ 1000 lbm Max Weight (454 kg)	R5={1 if m ≤ 1000 lbm, 0 if m > 1000 lbm
R_6	A-G Moving Laser/Datalink	R6={1 if Laser / Datalink capable, 0 if not
R_7	Assembly Time < 1 hour	R7={1 if Assembly Time < 1 hour, 0 if not
R_8	Assembly Cycles ≥ 20	R8={1 if Assembly Cycles ≥ 20, 0 if not

3.3.2 Objectives

The objectives of the A-G moving target is found below in Table 3-6.

Table 3-6: Air to Ground Moving Target Objectives

Objective Number	Objective	Values
O_1	A-G Moving ≥ 100-mile range (160.93 km)	O1={$\frac{R-80}{20}$ if R ≤ 100 miles, 1 if R > 100 miles
O_2	A-G Moving Internal Carriage	O2={1 if Internal Carriage capable, 0 if not
O_3	A-G Moving ≤ 500 lbm Max Weight (226.8 kg)	O3={ $\frac{1000-m}{500}$ if m ≥ 500 lbm; 1 if m < 500 lbm
O_4	A-G Moving Fire and Forget	O4={1 if Fire and Forget capable, 0 if not

3.4 Air to Surface Anti-Radiation Mission

The A-G Anti-Rad mission is similar to the mission of the Air to Ground Missile 88.

3.4.1 Requirements

The A-G Anti-Rad requirements are found below in Table 3-7.

Table 3-7: Anti-Radiation Requirements

Requirement Number	Requirement	Values
R_1	A-G Anti-Rad ≥ 80-mile range (128.75 km)	R1={1 if R ≥ 80 miles , 0 if R < 80 miles
R_2	A-G Anti-Rad External Carriage	R4={1 if External Carriage capable, 0 if not
R_3	A-G Anti-Rad ≤ 1000 lbm Max Weight (453.59 kg)	R5={1 if m ≤ 1000 lbm, 0 if m > 1000 lbm
R_4	A-G Anti-Rad Fire and Forget	R6={1 if Fire and Forget capable, 0 if not
R_5	Assembly Time < 1 hour	R7={1 if Assembly Time < 1 hour, 0 if not
R_6	Assembly Cycles ≥ 20	R8={1 if Assembly Cycles ≥ 20, 0 if not

3.4.2 Objectives

The A-G Anti-Rad objectives are found below in Table 3-8.

Table 3-8: Air to Surface Anti-Radiation Objectives

Objective Number	Objective	Values
O_1	A-G Anti-Rad ≥ 100-mile range (160.93 km)	$O1=\{\frac{R-80}{20}$ if $R \leq 100$ miles, 1 if $R > 100$ miles
O_2	A-G Anti-Rad Internal Carriage	O2={ 1 if Internal Carriage capable 0 if Internal Carriage incapable
O_3	A-G Anti-Rad ≤ 500 lbm Max Weight (226.8 kg)	$O3=\{\frac{1000-m}{500}$ if $m \geq 500$ lbm, 1 if $m < 500$ lbm

3.5 Air to Ship Mission

The A-G Ship mission is similar to the mission of the Air to Ground Missile 84.

3.5.1 Requirements

The A-G Ship requirements are found below in Table 3-9.

Table 3-9: Air to Ground Anti-Ship Requirements

Requirement Number	Requirement	Values
R_1	A-G Ship ≥ 100-mile range (160.93 km)	R1={ 1 if $R \geq 1000$ miles, 0 if $R < 1000$ miles
R_2	A-G Ship ≥ 35 mph target (56.33 km/h)	R2={1 if $IV \geq 35$ mph, 0 if $IV < 35$ mph
R_3	A-G Ship ≥ 0.1 G target	R3={1 if $IA \geq 0.1$ G, 0 if $IA < 0.1$ G
R_4	A-G Ship External Carriage	R4={1 if External Carriage capable, 0 if not
R_5	A-G Ship ≤ 2000 lbm Max Weight (907.18 kg)	R5={1 if $m \leq 2000$ lbm, 0 if $m > 2000$ lbm
R_6	A-G Ship Datalink	R6={1 if Datalink capable, 0 if not Datalink capable
R_7	Assembly Time < 1 hour	R7={1 if Assembly Time < 1 hour, 0 if not
R_8	Assembly Cycles ≥ 20	R8={1 if Assembly Cycles ≥ 20, 0 if not

3.5.2 Objectives

The A-G Ship objectives are found below in Table 3-10.

Table 3-10: Air to Ground Anti-Ship Objectives

Objective Number	Objective	Values
O_1	A-G Ship ≥ 150-mile range (241 km)	$O1=\{\frac{R-100}{50}$ if $R \leq 150$ miles, 1 if $R > 150$ miles
O_2	A-G Ship Internal Carriage	O2={1 if Internal Carriage capable, 0 if not
O_3	A-G Ship ≤ 1000 lbm Max Weight (453 kg)	$O3=\{\frac{2000-m}{1000}$ if $m \geq 1000$ lbm, 1 if $m < 1000$ lbm
O_4	A-G Ship Fire and Forget	O4={1 if Fire and Forget capable, 0 if not

3.6 Common Ancillary Objectives

As many ancillary objectives are for the platform as a whole and not unique to each mission this section shows the ancillary objectives.

Table 3-11: Common Ancillary Objectives

Ancillary Objective Number	Ancillary Objective	Values
AO_1	No new tools for assembly	AO1={1 if no new tools required, 0 if new tools required

AO_2	3D Printable Training Modules	AO2={1 if modules able to print, 0 if modules unable to print
AO_3	Minimal Additional Maintenance	AO3={1 if < 2 new maintenance procedures, 0 if > not
AO_4	No new pilot procedures	AO4={1 if no new pilot procedures, 0 if new pilot procedures
AO_5	Widely distributed supply chain	AO5={1 if distributed more than competition, 0 if not
AO_6	Tube launch capability	AO6={ 1 if tube launch capable, 0 if not tube launch capable

Figure 3-1 shows the flow down charts derived from each requirement.

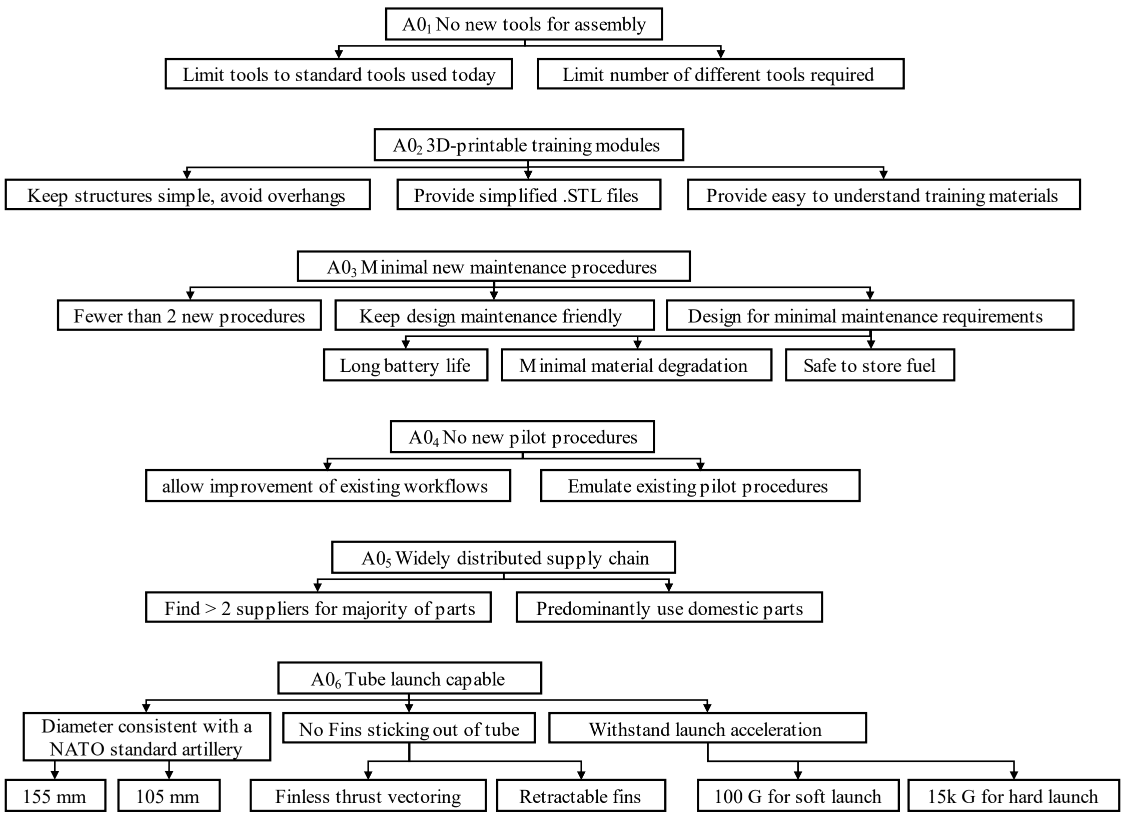


Figure 3-1: Common Ancillary Objectives Flow Down Charts

4 Statistical Time and Market Average Predictive Engineering Design Analysis

Statistical analysis of past trends is an important market analysis tool used to predict future trends. To use this tool effectively, standardized data sets need to be collected for all five types of missiles. Some of this data can be found in the literature, other stats must be acquired through reverse engineering of missiles and therefore come with a higher uncertainty. STAMPED data trends can be used to size the system predicting the competition in the future by following current and historical trends.

4.1 Methodology

As many stats were not available to the public, estimates had to be made. In this section, the methods used to obtain missing stats are described.

4.1.1 Propellant volume estimates

None of the relevant missiles had publicly available information on either propellant weight or volume. However, the outside dimensions of all missiles can be found in the relevant literature. In addition, cutaway drawings, missiles divided into functional sections or photos of disassembled missiles were available for many of the portraited systems. As shown in Figure 4-1, the motor section of the MICA missile can clearly be distinguished in this explosion drawing. The length units in the drawing are relative units. These can be converted into inches by dividing the total relative length by the known missile length and multiplying it with the motor length.

The propellant volume is then calculated as shown below, where 6.5 in is the diameter of the missile. The propellant volume can now be used for further calculations.

Figure 4-1: Propellant volume estimation of the MICA missile [27]

If no information about the inside assembly of the missile is available, the propellant volume had to be estimated based on the average propellant volume per missile volume of the other missiles within the same mission category. Whenever this method was used, this was highlighted as a rougher estimate.

4.1.2 Thrust estimation

Missile manufactures do not publish any information on the thrust of the missiles. Thus, the thrust had to be estimated. Publicly available videos show the launches of many missiles. If either the missile length or the length of the launching aircraft can clearly be determined, these videos can be utilized to track the speed of the missile frame by frame.

As shown in Figure 4-3, the distance of the missile from the launching aircraft can be measured for every frame. This can then be scaled according to the aircraft size, in this case the length of the SAAB JAS 39 of 14.9 m. Based on the difference in distance, the speed was calculated for every frame in the video and graphed in Figure 4-2 on page 26. The slope of the trendline now shows the acceleration in m/s². According to this, the IRIS-T missile accelerates 41 g at launch. As the launch weight is known, the thrust can be calculated:

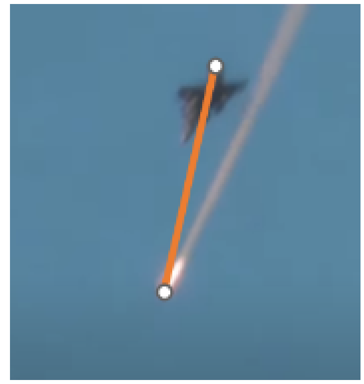


Figure 4-3: IRIS-T launch distance estimation

$$F = \frac{a}{g} \cdot m_0 = \frac{398 \frac{\text{m}}{\text{s}^2}}{9.81 \frac{\text{m}}{\text{s}^2}} \cdot 193\ \text{lbm} = 7.8\ \text{klbf}$$

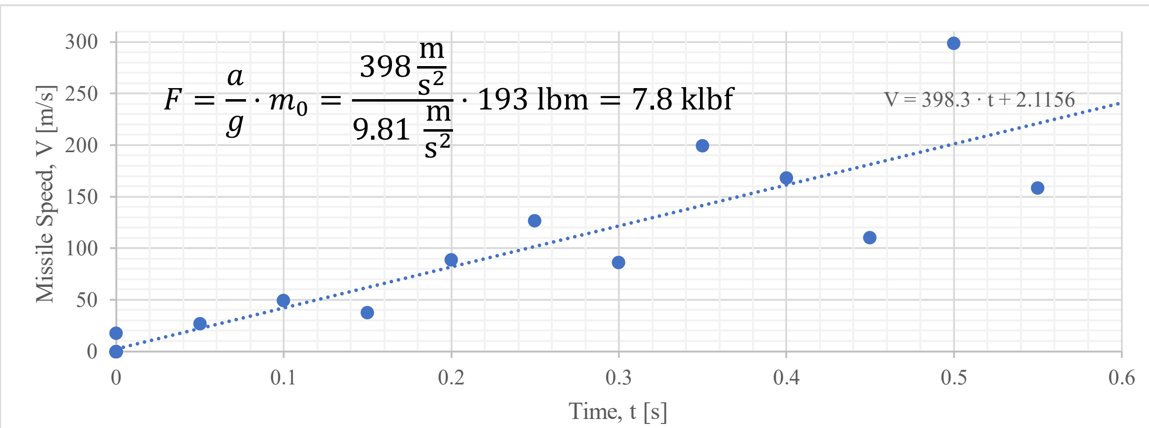
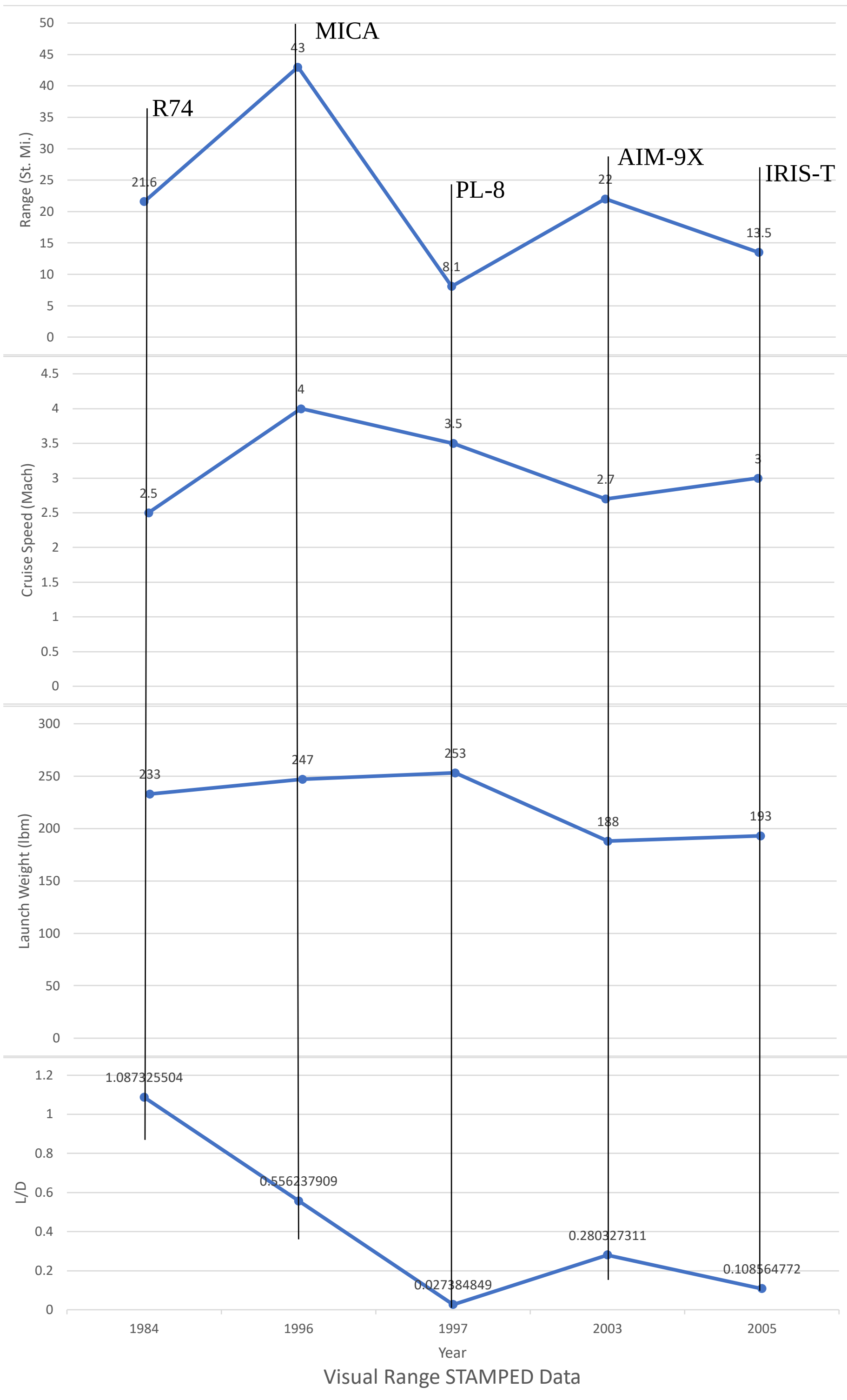
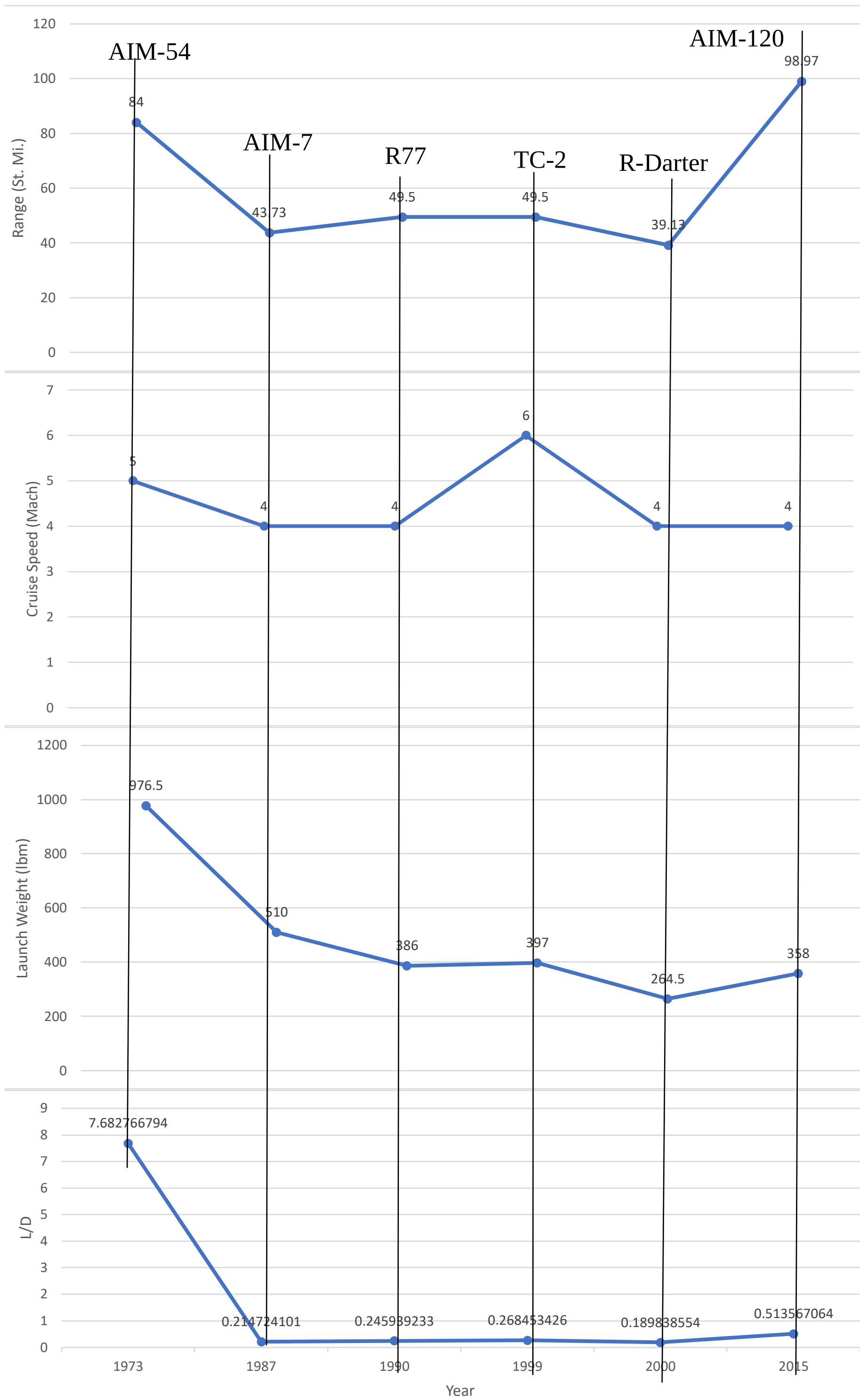


Figure 4-2: IRIS-T acceleration

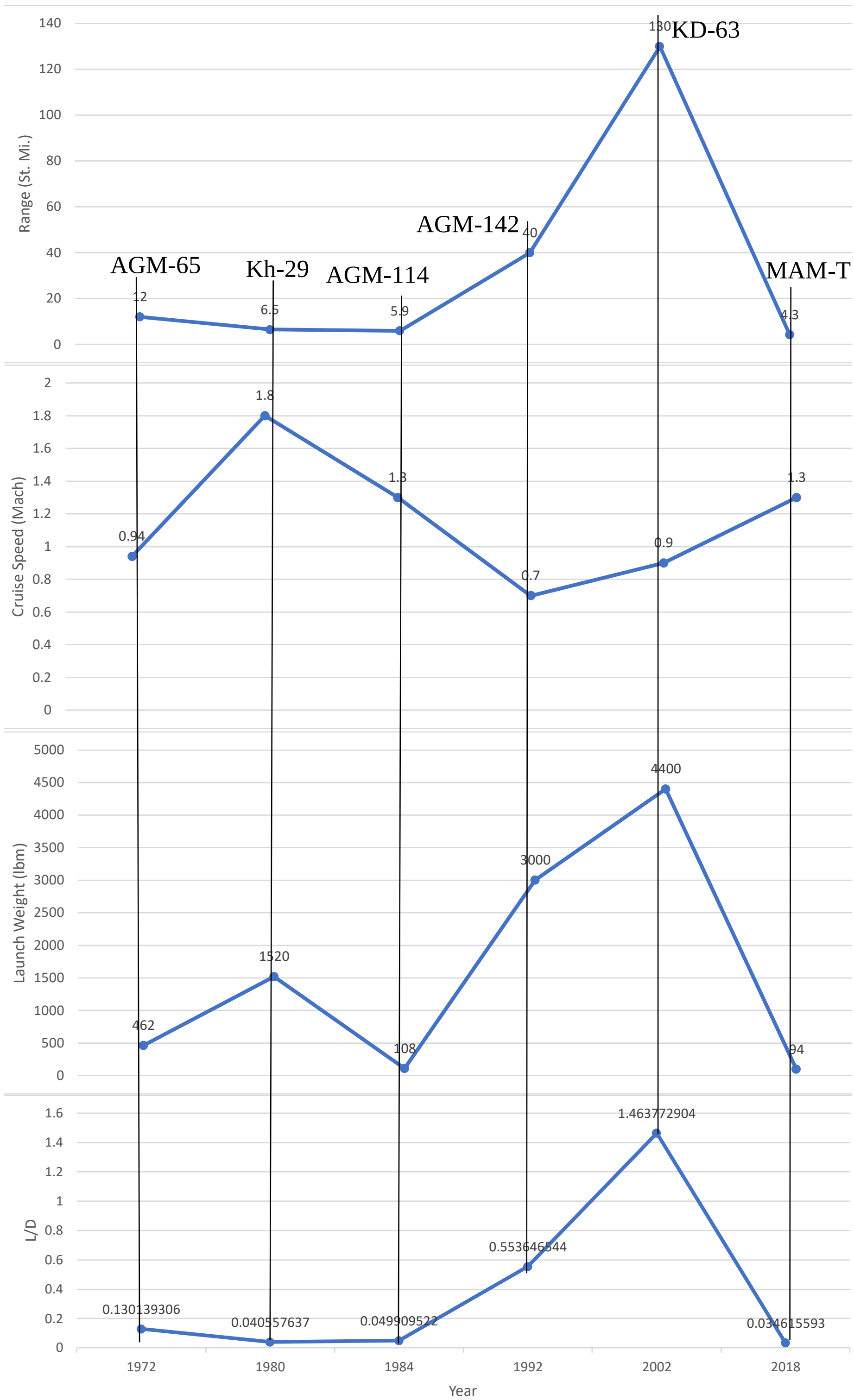
4.1.3 <u>STAMPED Calculations</u>

Once the thrust and propellant weight are calculated the following steps are followed to produce the L/D for each missile. With this and the entry into service of each missile trends can be found over time. Below are a selection of the graphs produced from this method.

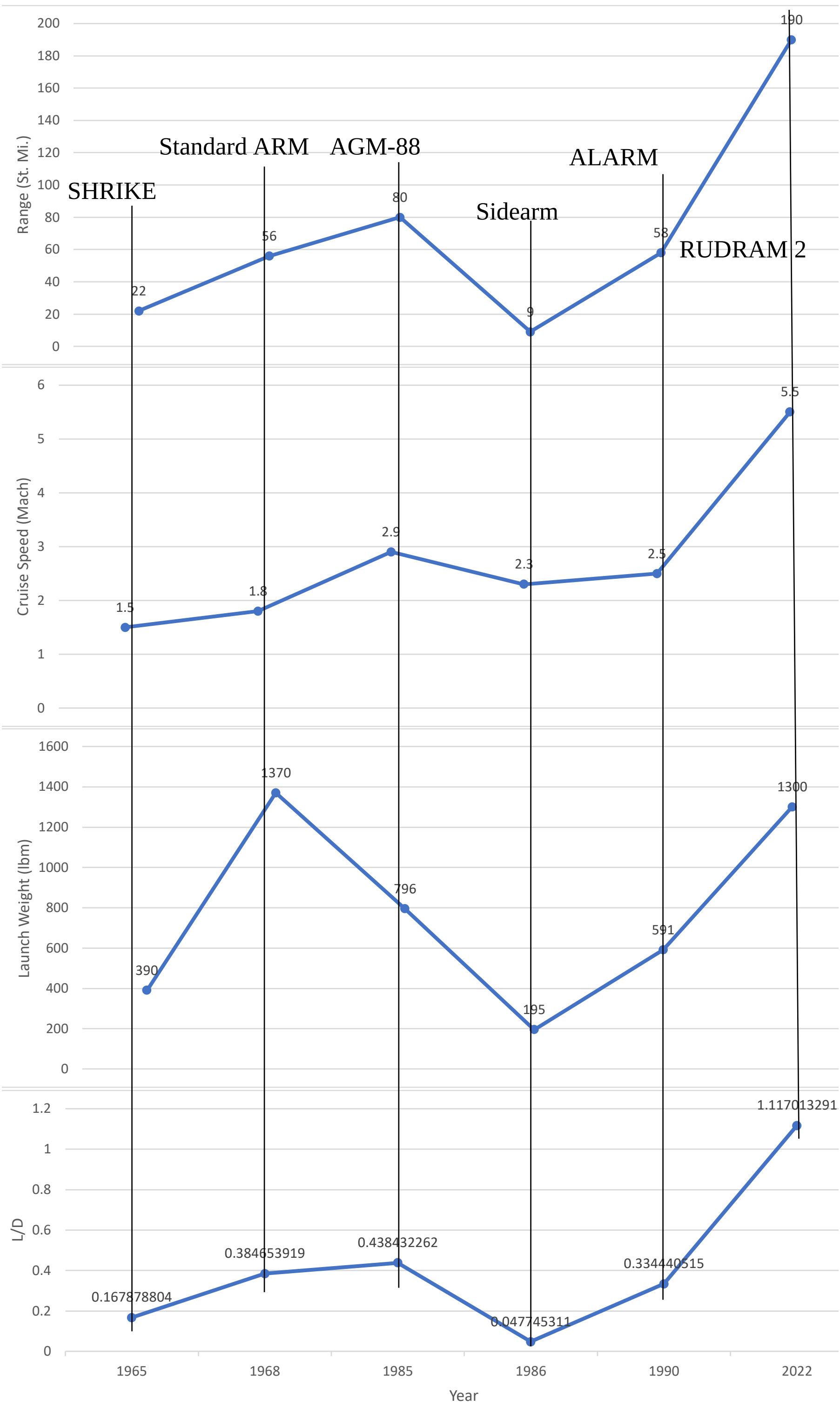

MICA
R74
PL-8
AIM-9X
IRIS-T
Range (St. Mi.)
50
45
40
35
30
25
20
15
10
5
0
21.6
43
8.1
22
13.5
Cruise Speed (Mach)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
2.5
4
3.5
2.7
3
Launch Weight (lbm)
300
250
200
150
100
50
0
233
247
253
188
193
L/D
1.2
1
0.8
0.6
0.4
0.2
0
1.087325504
0.556237909
0.027384849
0.280327311
0.108564772
1984
1996
1997
2003
2005
Year
Visual Range STAMPED Data



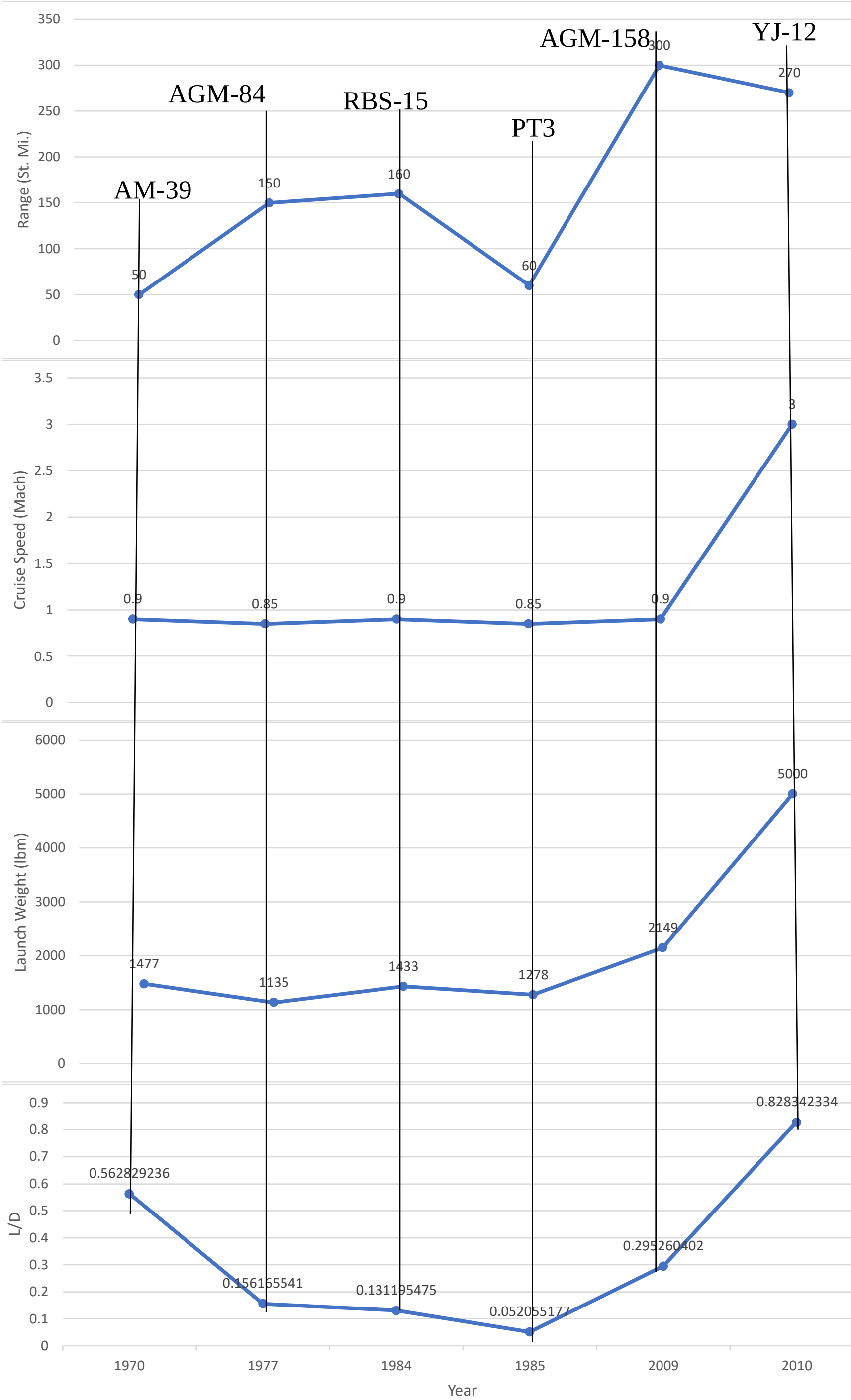
Beyond Visual Range STAMPED Data



Air to Ground Moving STAMPED Data



Anti-Radiation STAMPED Data



Anti-Ship STAMPED Data

5 Configuration Constraint Establishment

Using the design philosophy and the optimization function a basic configuration constraint is constructed. From this, modular missiles can be derived to fit the individual mission.

5.1 Configuration Constraint

In this chapter, configuration constraints and the reason for their introduction are described.

5.1.1 Tube launched missiles

Launching missiles from aircraft is traditionally done using internal carriages or wing rails. This comes with significant downsides: Wing mounts significantly increase stealth aircrafts' radar cross-section while missiles are attached. [38] For stealth missions, aircraft are limited to

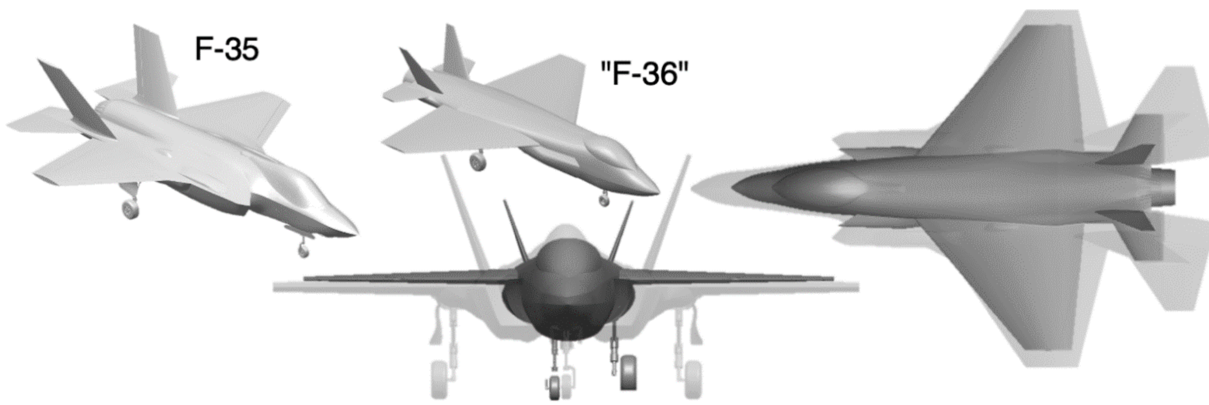


Figure 5-1: Improvement in Aircraft Designs according to [54]

internally carried armaments [39]. Additionally, wing loads significantly reduce the airframes bending frequency; hence reducing structural life and requiring heavier wing spars.

Tube launch shrinks the delay of an internally carried missile launch from over 4 seconds with conventional weapon bay doors to an almost instantaneous launch giving a huge combat advantage. Replacing the entire weapon bay with 12+ ft tubes with 155 mm diameter shielded holes for missile launch vastly improves aircraft capabilities: The unit price would decrease by 29 %, the wing size would decrease by 16 % and the MGTOW could be 19 % lower. This case study shows the huge improvements that would come with a switch to Tube launch in future aircraft. [54]

Disadvantages of traditional armament include the large space requirements of the internal storage, partly due to the room high maneuverability missiles' large fins require. Opening the weapons bay temporarily severely compromises aircrafts' stealth capabilities [39], thus making them detectable by enemy radar. Opening the weapons bay induces flow separation, leading to high levels of noise, drag and vibration and therefore increasing the structural loads. [38]

Tube launch technology is commonly used in tanks and submarines. Surface ships and ground vehicles use a variation consisting of rectangular tubes. [38] Two main launch system types are in use: Hot launched missiles ignite within the launch tube, making them cost effective and lightweight. No separate system is required for launch. However, exhaust gases need to be dealt with. Hot launch puts a lot of stress on the launch system and requires sturdy and therefore heavy launch tubes. For cold launch, a gas generator is used to propel the missile out of the launch tube before igniting the missile's engine. This is more complex and slightly slower but allows for bigger missiles to be launched. [40] Launch tubes offer a high potential in future aircraft and missile development.

For an entry into service date of 2035, compatibility with current internal and external weapon mounts will be of high importance. A tube launched missiles also must fit on current mount systems.


Figure 5-2: FIM-92 Stinger Launch [42]

To follow the motto a few constraints on the design are implemented. First the missile must be launched from a tube. This necessitates either no control surfaces or deployable control surfaces. Standard NATO sizes are then placed on this tube of either 4.1 in [105mm], 4.7 in [120mm], or 6.1 in [155mm]. These are chosen to ease logistics as well as potentially introduce new tactics in the future. Another constraint is that the missile, as well as the tube, must fit in the 15 inch by 15 inch by 144 inch box for internal carriage.

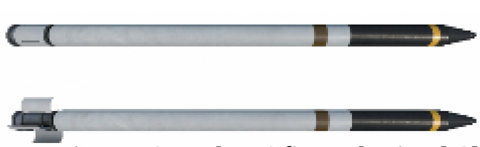


Figure 5-3: Hydra-70 fin mechanism [43]

Previously, a series of tube launched missiles have been deployed and proven in combat. Figure 5-2 shows the Stinger missile's fins being deployed just after launch from a tube. In Figure 5-3, the wrapping fins of the Hydra-70 can be seen. Even though this missile is much smaller than our design (70 mm diameter), the use of this fin mechanism proves its reliability and could be scaled up for our mission.

6 Candidate Configuration Matrix Establishment

This section outlines potential configurations of the missile.

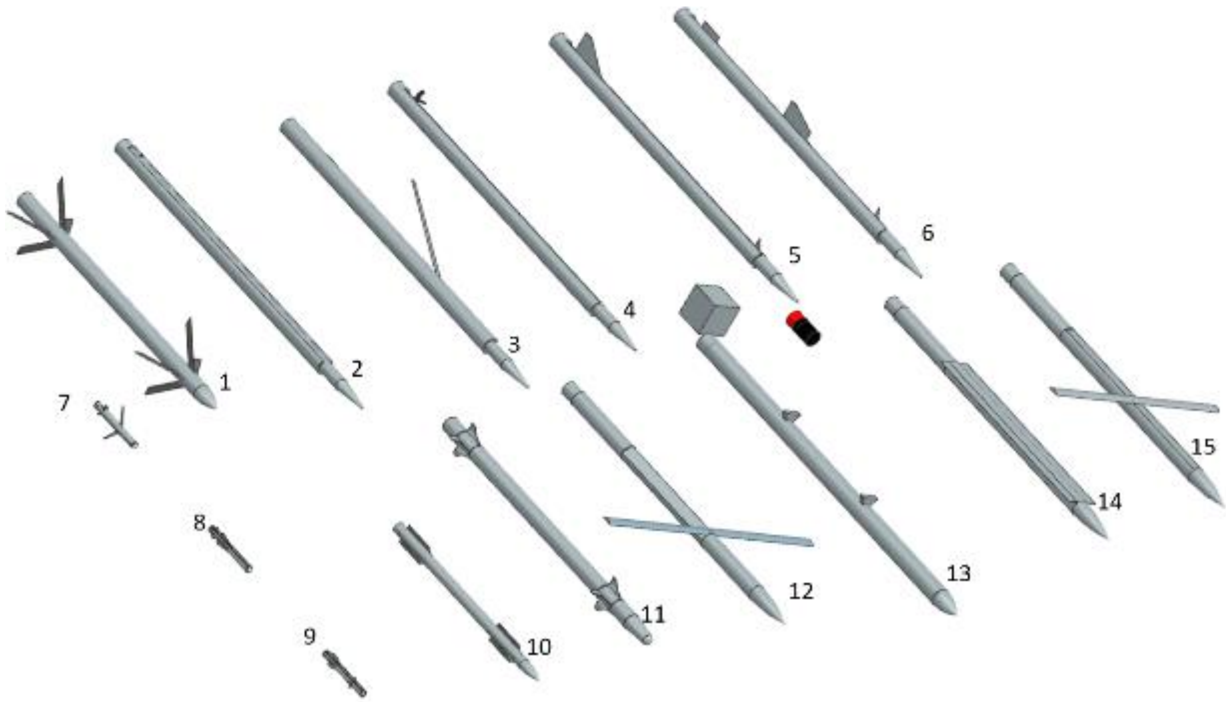


Figure 6-1: Configuration Sweep 1

The cube represents one cubic foot. Also shown is an expulsion charge intended for a hard launch from a tube. Configuration 1 utilizes deployable high aspect ratio fins and canards and a diameter of 155mm to meet a standard NATO size. The high aspect ratio allows for a large area while keeping width low to allow for easy folding. Configuration 2 utilizes airbrakes in the aft section for maneuvering and a diameter of 120mm to meet a standard NATO size. The airbrakes are small and conforming to allow for tube launch. Configuration 3 utilizes a folding high aspect wing and a diameter of 120mm. This allows for maneuvering and conforms to the missile body for tube launch and to meet a standard NATO size. Configuration 4 utilizes lattice fins to maneuver and a diameter of 120mm to meet a standard NATO size. The lattice fins fold in and allow for good maneuverability at both high Mach flight and subsonic flight. Configuration 5 utilizes canards and fins that wrap around the missile body to meet tube launch requirements. Configuration 6 utilizes fins, wings, and canards for maneuvering and a diameter of 120mm to meet a standard NATO size. This allows for a greater distribution of total control area. Configuration 7 is designed as a small folding wing anti-tank missile. Configuration 8 uses strakes and fins while also having a low profile. Configuration 9 uses fins and canards in a small form factor. Configuration 10 uses a split strake design to meet the necessary normal force and a diameter of 105mm to meet a standard NATO size. The strakes are split as different missions do not need the same area so those missions would only need to be configured with one set of strakes. As the strakes have a low overall width they deploy by extending from the missile body after launch. Configuration 11 utilizes fins and canards that are shaped to match the curve of the missile body when folded in. While folded out they retain the curve. A diameter of 155mm is utilized to meet a standard NATO size. Configuration 12 utilizes a wing on opposite sides that pivot at the root to deploy and a diameter of 155mm to meet a standard NATO size. Configuration 13 utilizes only thrust vector control. Configuration 14 utilizes wings with a long chord that fold to conform to the missile and a diameter of 120mm to meet a standard NATO size. Configuration 15 utilizes a wing that pivots at the middle to deploy and a diameter of 120mm to meet a standard NATO size.

7 Application of Optimization Function and Requirements

Utilizing flowdown charts and the optimization functions the configuration sweep is narrowed to a few optimal configurations.

7.1 Flowdown Charts to Configurations and Downselection

Configuration 5, configuration 10, and configuration 11 prove to have features that are optimal. While comparing these three configurations a combination of the three appear to work extremely well. Utilizing strakes like in configuration 10. Utilizing the diameter of configuration 11. As well as utilizing the wraparound controls in configuration 5. Combining these would result in a new configuration that has a 155mm diameter and strakes that bend around the missile body. The larger diameter increases the payload and fuel quantity compared to the smaller configurations. The strakes are much simpler to produce than fins as well as they can be made with a smaller span allowing for large area while wrapping around the missile. Later in the design when the range issue was more understood the strakes became engine ducts and fins were added for maneuverability.

8 Weight Sizing

The trend in air-to-air missions is a decreasing launch weight in the missiles. The anti-radiation mission has an increasing weight trend. If the trend is extrapolated to 2035 the A-A VR weight is 138 lbm, the A-A BVR weight is negative 108 lbm, and the A-G Anti-Rad is 1140 lbm. This is utilizing a linear trend and clearly has some issues. As a missile will not have a negative weight the BVR missile is not -108 lbm. This is due to the AIM-54 being such a large missile and having the oldest model entry date. Removing the AIM-54 outlier the A-A BVR weight becomes 225 lbm, which is much more reasonable.

9 Wing, Powerplant and Empennage Sizing

As the missiles travel at high speeds, wings will mostly serve the purpose of maneuverability not lift. Therefore, to ease tube launch, the goal is to avoid the use of wings entirely for as many configurations as possible. The missile’s body can provide a sufficient amount of lift in supersonic speeds.

Since the missile should standardize modular components the powerplant section is designed to meet the requirements of the smallest missile type Air to Ground moving target.

9.1 Wing Sizing

To size the wings the total area of the current market leaders is used as the standard. This is the AIM-9X, AIM-120D, AGM-114, AGM-88, and Exocet. The sizing is not entirely accurate as the Modular Missile will utilize thrust vectoring for maneuvering. This will reduce the area required for each of these missiles with a possibility of eliminating the need for wings all together for some configurations. A strake configuration will also be the primary configuration analyzed as it reduces the complexity of folding control surfaces.

This results in the following areas being necessary to accomplish the mission 130 in^2, 185 in^2, 74 in^2, 130.5 in^2, and 469 in^2 for the Visual Range Air to Air, Beyond Visual Range Air to

Air, Air to Ground Moving Target, Air to Ground Anti-Radiation, and Air to Ground Anti-Ship missions respectively. The AIM-9X also already utilizes thrust vectoring so it is likely that the required area for that mission will not be reduced. It should also be noted that the Exocet missile oscillates in flight which is the likely cause for such a large area.

9.2 Powerplant Sizing

In the AIGM-138, two different engines will be used for the different missions. For the long range mission, the fuel tank comes in two sizes depending on the mission.

9.2.1 Short range missions

This powerplant is suitable for the Air-to-Air Visual range mission. As only a short range is required, a simple conventional solid propellant with an ISP of 250 s is used. As acceleration consumes most of the fuel, the short range missile is only designed to reach Mach 3.5 which is still faster than any fighter aircraft in service today. Table 9-1 shows the amount of fuel needed for this performance. The 90 kg missile consist of 41.5 kg of fuel. The cruise is only 22 miles of the 25 mile mission because 3 miles are covered during the acceleration. The thrust is set to 25 kN. This enables an almost instant acceleration from Mach 0.85 to Mach 3.5 within 10.2 s. After a 45 s cruise, the target is destroyed less than a minute after launch at maximum range.

Table 9-1: Propellant weight for short range missile

	Weight [kg]	
Launch weight	90	
Propellant for acceleration to Mach 3.5	31.4	41.5
Cruise for 22 mile cruise	5.1	
Margin	5	
Powerplant	5	
Structure	21.5	
Warhead	12	
Seeker	10	

The performance of this missile can be further improved by updating to a tube launch system. This gives it a larger initial velocity and enables higher speeds and greater ranges. The initial calculations assume a conventional rail launch.

For the Air to Air visual range mission, the 40.5 kg of solid propellant with a density of 1716 kg/m³ [38 p.211] are used. The propellant makes up 1.35 meters of the missile length. The propellant chosen for this mission is Ammonium perchlorate oxidizer (ClO_4NH_4) with HCl fuel. This offers reduced smoke with a high ISP and good storage capabilities. [38 p.210f]

9.2.2 Long range missions

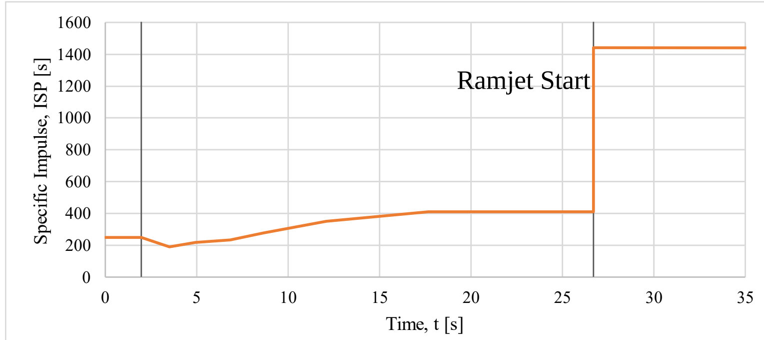


Figure 9-1: ISP increase over time

The powerplant of all missions except the visual range mission is identical to reduce cost and meet the similar performance requirements. However, the anti-ship mission carries larger amounts of fuel and oxidizer to carry a heavier warhead and cover the increased range compared to the other missions.

All medium-range missions start by burning a solid fuel booster which is more thoroughly described in chapter 11.2.2. This burns 20 kg of solid rocket fuel at an ISP of 250 s. This brings the 250 kg anti-ship missile to a speed of Mach 1.5 in a horizontal acceleration phase. For the lighter, 158 kg launch weight AA-BVR, AG-MT and AG-Anti-Rad missiles, this initial charge propels them to Mach 1.8 while climbing at 45° angle to reach an altitude of 39,200 ft.

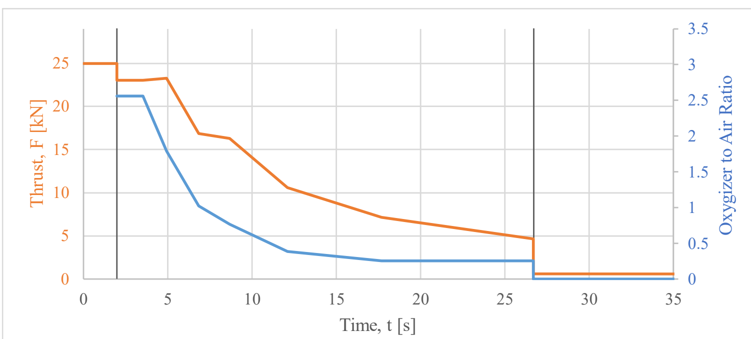


Figure 9-2: Thrust and Oxidizer use

Starting at this point, the oxidizer-assisted ramjet activates. It starts with a high amount of oxidizer that lowers as the required thrust decreases. Therefore, the ISP continuously increases during this flight phase as shown in Figure 9-1. The first vertical line shows the start of the ramjet operation, the second vertical line is the point where the cruise speed of Mach 5 is reached and the ramjet switches to operating without liquid oxygen. Figure 9-2 shows the corresponding thrust profile: As the missile climbs, weight and air density decrease and less thrust is required. At Mach 2.7, the incoming airflow is sufficient to match the ISP of the solid booster at 250 s. From this point onwards, the specific fuel consumption is lower than that of a solid rocket. The ramjet can operate without the liquid oxidizer anywhere above Mach 1.5, but the thrust produced is too low effectively accelerate the missile. High acceleration is needed to lower intercept times and avoid countermeasures.

Figure 9-3 shows the climb of the missile. After the acceleration phase, lasting less than 30 s, no more oxidizer is used except the air from the ramjet intake. This is enough to let the missile climb to a 90,000 ft altitude for reduced drag before entering the terminal dive to the target. This is the most fuel efficient flight trajectory.

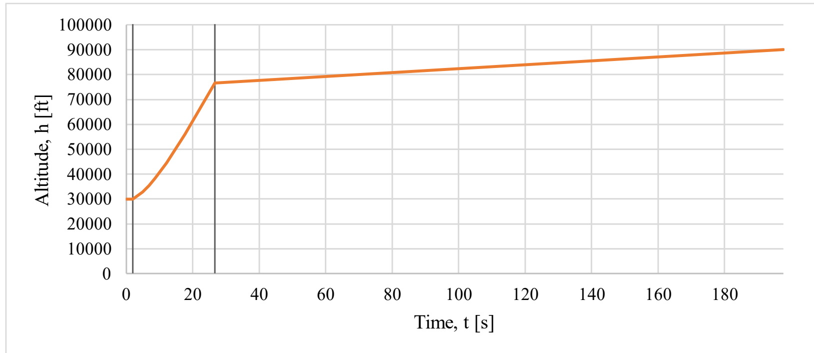


Figure 9-3: Altitude vs time

Table 9-2: Long range weights

	Weight [kg]			
	100 mile range		150 mile range	
	Anti-Rad AA-BVR Anti-Tank		Anti-Ship	
Launch weight	142		172	
Solid rocket fuel	20	72.1	20	87.8
Oxidizer	33.5		44.4	
Ramjet fuel	18.6		23.4	
Powerplant	15	69.9	15	84.2
Structure	15		16	
Warhead	29.9		43.2	
Seeker	10		10	

Table 9-2 shows the propellant needed for all the long range missions as well as the weight dedicated to each key component. This enables effective cruise to the target at Mach 5 and minimal time to intercept.

9.3 Class I Stability and Control Analysis

Using modern control theory and high frequency actuators, the missile can be stabilized artificially. However, the larger concern is the coupling of controls and blanking of control surfaces. Using Open VSP, a vortex lattice solver was used to simulate the aerodynamic effects of the burner tube strakes as well as the fins. It was found that between two and three degrees of angle of attack, the upper set of fins experience significant reductions in lift cue to the vortices shed by the burner tubes. In this condition, if the missile were to attempt a yawing maneuver, it would experience a rolling moment due to the differentiated side forces generated by the fins above and below the strakes.

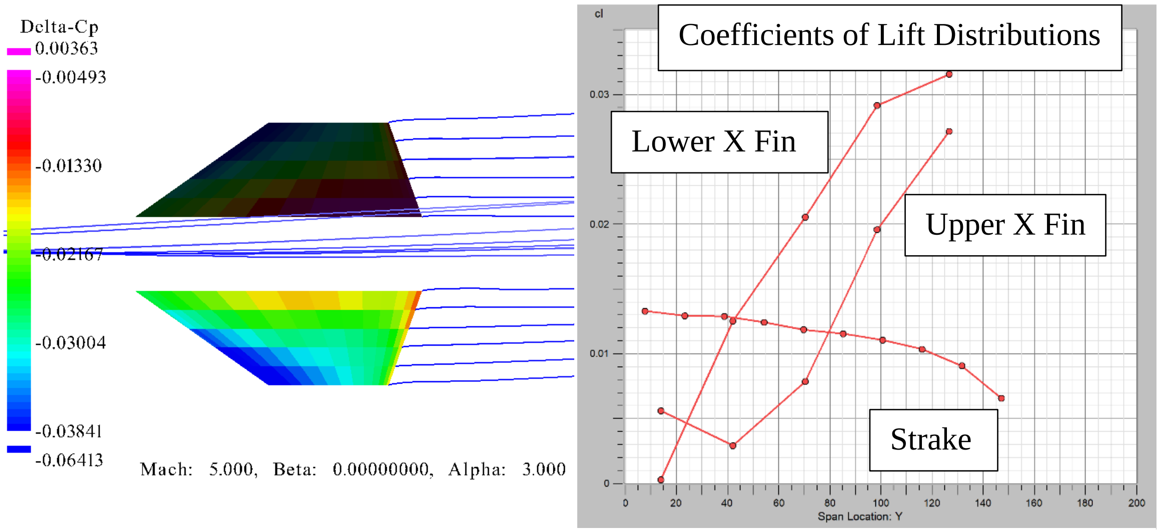


Figure 9-4: Open VSP Aerodynamic Analysis

9.4 Class I Drag Polar

The total zero-lift drag of a missile can be calculated using the equation below [38 p.76]. This will aid in analyzing the performance of each missile.

$$C_{D_0} = (C_{D_0})_{Body} + (C_{D_0})_{Wing} + (C_{D_0})_{Tail}$$

Some assumptions were made in the equation above to simplify the calculation. It is assumed that the cross-section of the missile is elliptical instead of circular, thereby including the wing portion (the duct tubes) of the equation to the body. To calculate the total zero-lift drag coefficient of the body in supersonic flight, the skin friction drag, base drag and wave drag must be found using the equation below [38 p.45].

$$(C_{D_0})_{\text{Body}} = (C_{D_0})_{Body,Friction} + (C_{D_0})_{Base} + (C_{D_0})_{Body,Wave}$$

The body wave drag coefficient equation is based on Bonney [38 p.45] and can be seen below. This equation is a function of Mach number (M) and nose fineness ratio (l_N/d), where l_N is nose length and d is body diameter. It is assumed that the missile will be traveling at Mach 4 at 30000ft and has a nose fineness ratio of 3.

$$\left(C_{D_0}\right)_{\text{Body,Wave}} = \left(1.586 + \frac{1.834}{M^2}\right)\left(\tan^{-1}\left(\frac{0.5}{\frac{l_N}{d}}\right)\right)^{1.69}$$

The base drag for coasting flight at supersonic and subsonic speeds can be approximated respectively using the equations below [38 p.45-46]

$$\left(C_{D_0}\right)_{Base,Coast} = \frac{0.25}{M} \quad \text{if M>1,} \qquad \left(C_{D_0}\right)_{Base,Coast} = 0.12 + 0.13M^2 \quad \text{if M<1}$$

During powered flight, this drag is reduced by the factor $\left(1 - \frac{A_e}{S_{Ref}}\right)$, where A_e is nozzle exit area and S_{Ref} is the reference area. The reference area is assumed to be the cross-sectional area. The base drag is negligible if the nozzle area is close to the missile base area, which it is in this case.

Lastly, to calculate the skin friction drag, the equation below is used [38 p.46].

$$\left(C_{D_0}\right)_{Body,Friction} = 0.053\left(\frac{l}{d}\right)\left(\frac{M}{ql}\right)^{0.2}$$

From the above equation, skin friction drag is primarily driven by body fineness ratio. It is also dependent on the flight conditions. This equation assumes the body has no boattail, the flow over the body has a turbulent boundary layer, changes in the free steam speed of sound with altitude is relatively small and the wetted area of a noncircular lifting body can be approximated as circular cross-sectional cylinder.

To see the effect of Mach number on the missile's body drag coefficient, these equations will be swept through Mach numbers ranging from 1 to 5 (supersonic region). This can be seen in the figure below.

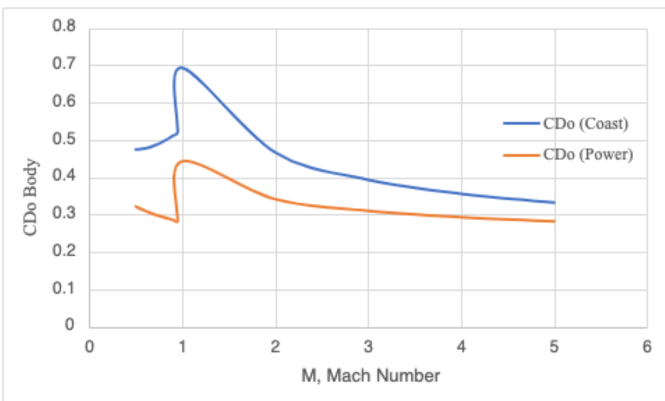


Figure 9-5: Missile Body Drag Coefficient at 30000ft Altitude

As seen in the figure above, the body drag coefficient decreases with an increase in Mach number. It can also be noticed that the drag coefficient drops from coasting flight to the powered flight.

For aerodynamic efficiency, lift-to-drag ratios must be calculated using the equation [38 p.52]

$$\frac{L}{D} = \frac{C_L}{C_D} = \frac{C_N cos\alpha - C_{D_0} sin\alpha}{C_N sin\alpha + C_{D_0} cos\alpha}$$

For a lifting body missile without wings, the equation of normal force coefficient (C_N) is

$$|C_N| = \left(\frac{a}{b}\cos^2 \emptyset + \frac{b}{a}\sin^2 \emptyset\right)\left(\left|\sin(2\alpha)\cos\left(\frac{\alpha}{2}\right)\right| + 1.3\frac{l}{d}\sin^2\alpha\right)$$

a/b in the above equation refers to the lifting body configuration (a/b > 1). It is assumed that this is a symmetric flight, therefore $\emptyset = 0$ deg. To fully capture the aerodynamic efficiency, the C_N will be swept through different angles of attack and lifting body configurations. The figure below shows these effects.

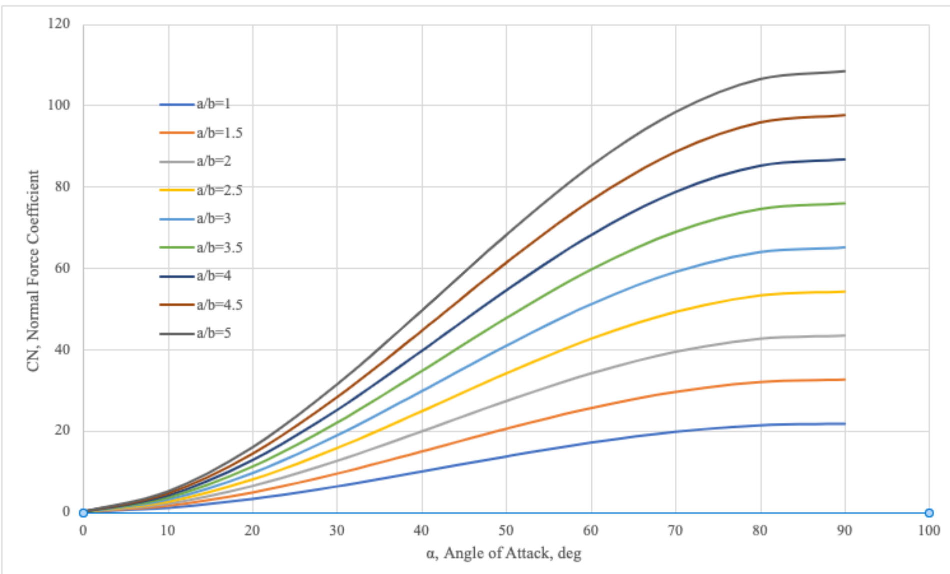


Figure 9-6: Effects of Lifting Body Configuration and Angle of Attack on C_N

As seen in the figure above, the maximum normal force of a lifting body is higher than that of an axisymmetric body. The body normal force curve slope will be used in sizing the tail in order to meet static stability requirements.

Similarly, the L/D will be swept through different angles of attack and a/b and these effects are captured in the figure below.

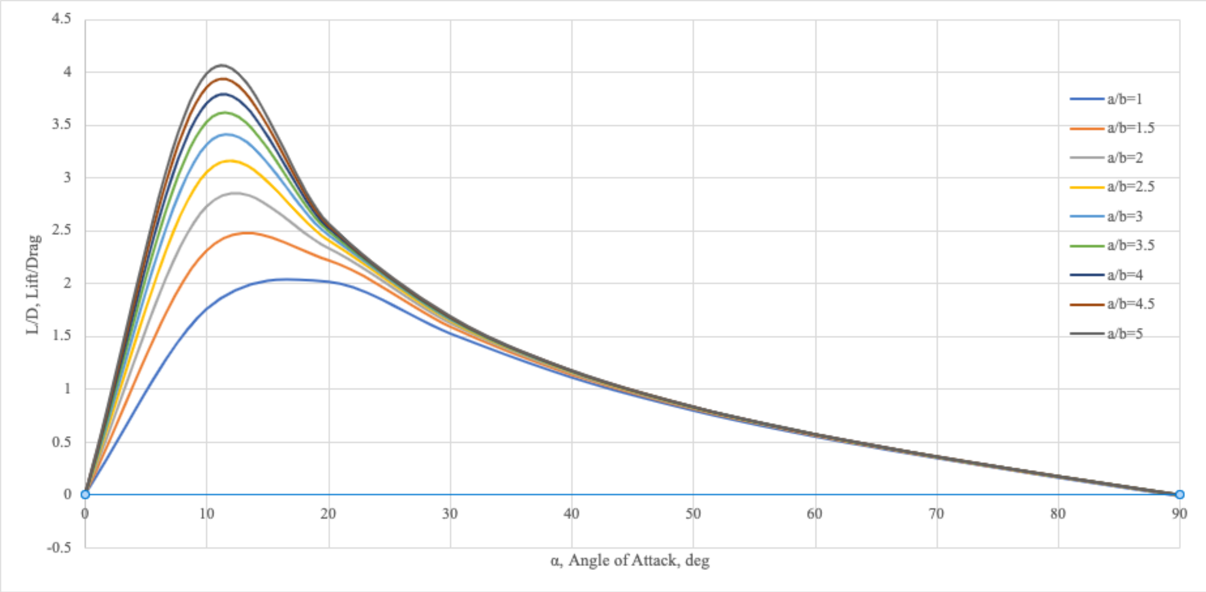


Figure 9-7: Impact of a/b and Angle of Attack on L/D [38]

L/D can be increased by reducing the zero-lift drag coefficient and increasing the body fineness ratio as seen in the L/D equation above. Providing a lifting body configuration and decreasing the angle of attack at which the maximum L/D is achieved can also produce a higher L/D, as seen in the figure above. Using the same process for the tail, the table below shows the parameters for the drag polar for the missile.

Table 9-3: Drag Polar Parameter

Parameter	Value
C_{D0}	0.45
L/D	2.7
a/b	2
Mach	5

9.5 Empennage Design

For the design of the empennage, fins will be used due to the low aspect ratio, which will greatly impact stability, control and performance. There are different types of surface panel geometry considered. A trapezoidal shape with an aft-swept leading edge will be used as it has high control effectiveness and does not have any major weaknesses in its other attributes [38 p.78]. Four tail surfaces are used for static stability. These tail surface orientations: the x orientation and the + orientation are considered, but the x configuration is chosen due to launch platform compatibility, higher lift-to-drag ratio, high static stability, and control effectiveness in pitch and yaw. The only drawback is a statically unstable roll moment in subsonic flight, which will not be a problem for the supersonic missions. To integrate the surfaces, Nitinol smart memory alloy will be used, this allows the fins to wrap-around the surface of the missile. This is perfectly suited for tube launch. The table below shows the design parameters for the tail fin.

Table 9-4: Tail Fin Geometric Characteristic

Design Parameter	Value (Units)
Aspect Ratio, AR	1 (~)
Span, b	7.707 (in)
Root Chord, C_r	6.560 (in)
Tip Chord, C_t	1.148 (in)
Taper Ratio, λ	0.175 (~)
Sweep Angle, Λ	54.548(˚)
Surface area, S	59.405 (in^2)
Airfoil	Flat Plate

10 Advanced Technologies and Design Concepts

To compete with future missiles being sold in 2035 and beyond, our missile will utilize advanced new technologies, some of which have not been seen in missiles before. This chapter introduces the key innovations of our missile family.

10.1 Tube Launch

Tube Launch is an approach not yet commonly used in aircraft. We want to launch our missiles from standardized launch tubes providing maximum compatibility with existing systems used in tanks, submarines and ships. Currently, missiles are either carried internally which limits payload due to large space taken up by fins, or they are carried externally on external mounts. This, however, limits stealth capabilities.

Limiting the storage dimensions to standard tubes does come with serious constraints in the design, especially considering the maximum diameter and the usage of fins. However, this will enable future aircraft to carry large missile payloads with minimal radar cross section and drag. However, attack helicopters are currently the only aircraft that use launch tubes on a large scale.

Hence, the advancement in missile technology will have to push future aircraft development. With an entry into service date of 2035, today's aircraft will still be in use at the time of the missile's entry into service. Accordingly, combability with state-of-the-art internal carriage and external mounting points is essential for economic success of the missile. Hence, our propulsion is sized to fulfill the missions without tube launch. A future implementation of tube launch would significantly increase the range of our missiles.

Relying on launch tubes could potentially enhance stealth capabilities of future aircraft, fasten their response times to threads, increase internal storage capacity drastically and allow for missiles to be stored within the wing structure.

Figure 10-1: AIGM-138 in Launch Tube

10.2 Adaptive Fins

Retractable fins have been used in missiles for decades to allow tube launch. The Hydra 70 is an unguided rocket relying on sideways folding fins. It's predecessor, the Mk 4 Folding-Fin Aerial Rocket, used fins folding forward after launch. [41] Photos of these systems can be seen in Figure 5-2 and Figure 5-3.

However, guided air-launched missiles have not been using folding fins on a large scale. Current missile systems can be mounted to the outside or an internal carriage bay within an

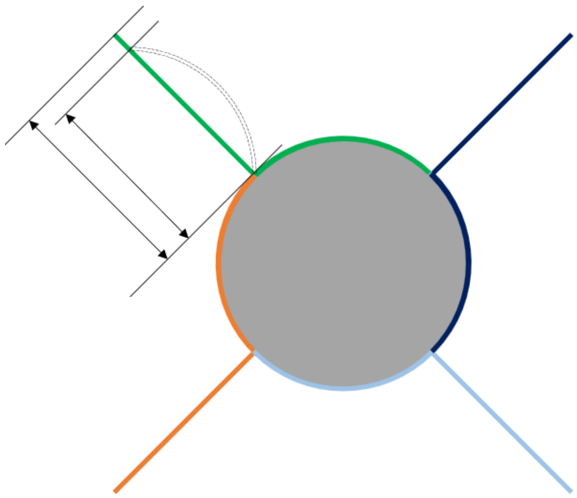


Figure 10-2: Flexible material fins

aircraft. This takes up a lot of space in aircraft design. Putting missiles closer together by retracting the fins can potentially increase storage capacity and allow for smaller internal carriage volumes of future aircraft.

Modern flexible structures allow for very advanced retractable fin designs. For example, wrapping the fins around the fuselage is possible for storage. After launch, the fins can either be instantly deployed or can be held to reduce drag and be deployed shortly before impact. Modern flexible memory shape materials as seen in Figure 10-2 allow for 11% larger fin wingspan (assuming four fins wrapping completely around the missile body) by straightening the bend fins after deploying.

A possible method to hold the fins in place is a plastic wrap with a tearing thread used to deploy the spring-loaded fins when needed. The tearing thread could either be pulled by an actuator or be burned. In case of unwanted deployment of the plastic wrap near the launch aircraft, a well combustible plastic must be chosen to account for engine ingestion.

Figure 10-3: Raytheon Coyote [48]

Tube launched missiles have demonstrated retractable wings in all sizes. The Raytheon Coyote deploys it's 58 inch wings [48] from a launch tube of only 5 in diameter [50]. The wings and the horizontal stabilizer are mounted to the top and the bottom of the missile and deploy immediately after launch [49]. This gives the electrically propelled surveillance system an endurance of 90 minutes due to its high aspect ratio wings [48]. It demonstrates that all sizes of wings can be fitted in launch tubes.

10.3 Modular missile design

To date, missiles are usually specified to meet one or few missions. There is not a single missile on the market that can fulfill all five air launched mission profiles our modular missile is designed to do.

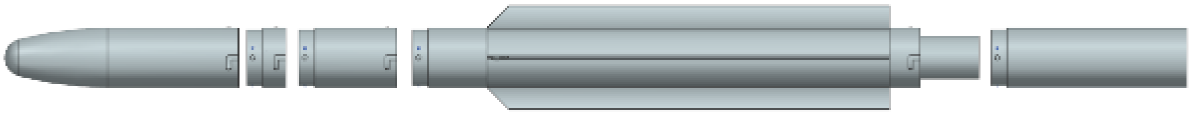


Figure 10-4: Modular AA-VR Configuration design study

Therefore, we have to come up with standard parts that can be used for different mission. Figure 10-4 shows a disassembled example configuration sized for an Air-to-Air visual range mission. This mission uses an IR seeker unique to this mission. This can be mounted to a computer capable of fulfilling all five mission profiles. The warhead is the same as for the Air-to-Air beyond visual range mission. The rocket motor and wing section is unique to this mission. The aft section of the rocket motor is standardized and is inspired by the IRIS-T and MICA missile design. Both of these feature a cylindrical tube of smaller diameter than the missile itself. It extends to the inside of the thrust vectoring unit. The latter unit is the same for all missiles. It consist of a naval nozzle designed for an exhaust speed of Mach 3 and four thurst vectoring nozzles and their corresponding actuators as shown in Figure 10-5.

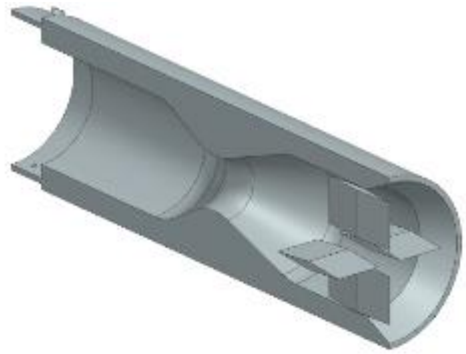


Figure 10-5: Thrust vectoring section

The coupling mechanism is the centerpiece of a modular missile. The design displayed in Figure 10-6 allows for easy assembly and disassembly by simply fitting the three pins of each coupling in the notches and then rotating it to the locked position. Then, it can be secured with a screw. This form of coupling movement provides a strong mechanical connection while also enabling the integration of electrical connectors that will be automatically plugged in with the

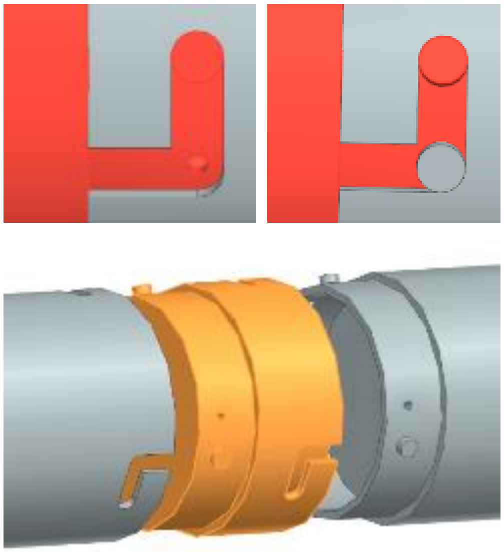


Figure 10-6: Coupling mechanism

rotational movement of the coupling process. As both the thrust vectoring section and the thrust vectoring section need electrical power, every coupling must include an electric connector.

Table 10-1 shows what components may be shared between missions. The warhead can be narrowed down to two different types, one of them being much larger than the other. Propulsion can be narrowed down to three different rocket motor sizes. All of them share the same thrust vectoring nozzle. The control surfaces will be identical for all missiles that require control surfaces. For the B configuration used in AA-MVT and AA-ARAD, no wings or fins will be needed. As the guidance is very specialized to the mission requirement, a separate seeker is required for each mission.

Table 10-1: Shared components

<table>
<tr><th></th><th>AA-VR</th><th>AA-BVR</th><th>AA-MVT</th><th>AA-ARAD</th><th>AA-Ship</th><th>Variants</th></tr>
<tr><td>Warhead</td><td colspan="4">Dynamically Configurable Warhead</td><td>Tungsten Penetrator</td><td>2</td></tr>
<tr><td>Propulsion</td><td>Solid Rocket</td><td colspan="3">Solid Rocket Boost, Ramjet Cruise (SRBRC)</td><td>SRBRC + Additional Fuel</td><td>3</td></tr>
<tr><td>Aerodynamic Surfaces</td><td>Fins Only</td><td colspan="4">Burner Tube Strakes and Fins</td><td>2</td></tr>
<tr><td>Guidance</td><td>Multi-spectrum</td><td>Active Radar</td><td>Multi-Spectrum</td><td>Passive Radar</td><td>GPS/Satellite Datalink</td><td>4</td></tr>
</table>

10.4 Constrained Layer Damping

The Constrained Layer damping method works by laminating a sandwich of aluminum sheets and a kinetic energy absorbing damping layer. This has been well established in aircraft design, but the technique is new to missiles. It allows higher length to diameter ratios that would create first eigenmodes in undesirable frequencies using conventional methods. The first body bending frequency should be at least twice the actuator bandwidth [38, p.42].

Experiments have shown that constrained layer damping can increase the damping factor by 10 times compared to an undamped beam [44]. Applying this technique to missiles would enable significantly higher fineness ratios (l/d). Therefore, the longer-range missiles can be fitted into 155 mm launch tubes. Additionally, the drag increases proportionally to the square of the diameter [38, p.35], so high fineness ratios are desirable for longer range.

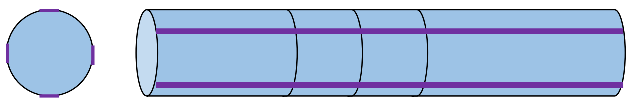


Figure 10-7: Constrained layer damping tape

A challenge to the use of constrained layer damping is the modularity of the missile that requires mechanical couplings between the sections. To constrain the first body bending eigenmode, tape can be applied along the missile after assembly as illustrated in Figure 10-7. This can absorb the vibration’s kinetic energy. Aerospace approved damping tapes are already commercially available. They are suitable for low temperature environments and require a surface coverage of only 10% to be effective. [45] A disadvantage of this tape is that it needs to be removed for disassembly and new tape will be required for each assembly cycle.

Our design plans to integrate the constrained layer damping tape into the air duct tubes of the tube launch capable ramjet described in chapter 10.5. This way, the burner tubes would serve the dual purpose of damping the vibrations and being part of the propulsion system.

10.5 Tube launch capable Ramjet

At high supersonic speeds, Ramjets are the most efficient propulsion method. Using traditional solid rocket motors, a 150 nmi flight at 30,000 ft requires a propellant weight fraction of at least 53 %. Table 10-2 compares Mach 4 cruise performance at 30,000 ft. L/D was picked according to market trends [38] and an example calculation for a 100 lb payload was done. To make missiles smaller and more efficient, Ramjets can be used. These offer specific impulses up to five times higher than rocket fuels. Fleeman [compare 38 p.348] provides range estimate equations for Ramjets. However, even more efficient Ramjets can be designed using quasi-isentropic inlets. By this method, propellant weight can be reduced to 12 % of total weight for a 150 nmi mission.

Table 10-2: Comparison of propulsion methods for 150 nmi mission

	solid rocket fuel	Ramjet according to fleeman	isentropic inlet Ramjet
Range [nmi]	150	150	150
V_i [m/s]	1213	1213	1213
Mach Number	4	4	4
specific fuel consumption C_{TL}	0.003636	0.001111	0.000625
ISP [s]	275	900	1600
Lift to drag L/D	1.1	1.1	1.1
propellant weight fraction [%]	53%	21%	12%
Payload, seeker and structure [lb]	100	100	100
fuel [lb]	113	26	14
Total weight	213	126	114

To estimate a Ramjets ISP, complex sizing calculations are required. Firstly, the inlet efficiency needs to be determined. This can be done using Oswatitsch analysis [47] or alternatively by using a quasi-isentropic inlet. The latter has the advantage of gaining a high total pressure recovery. Disadvantages are that it can only be placed at the tip of the missile, requiring a more complex seeker integration and requiring the air to be guided through the entire missile to the nozzle at the end.

Once the total pressure recovery p_{t2}/p_{t0} is known, several assumptions need to be made for the thrust calculation. Most importantly, atmospheric conditions, Burner Mach number, and thrust need to be known to size a Ramjet. From there, a dimensionless mass flow parameter can be derived. Depending on the static temperature T_{t0}, the ideal burner temperature of a slightly

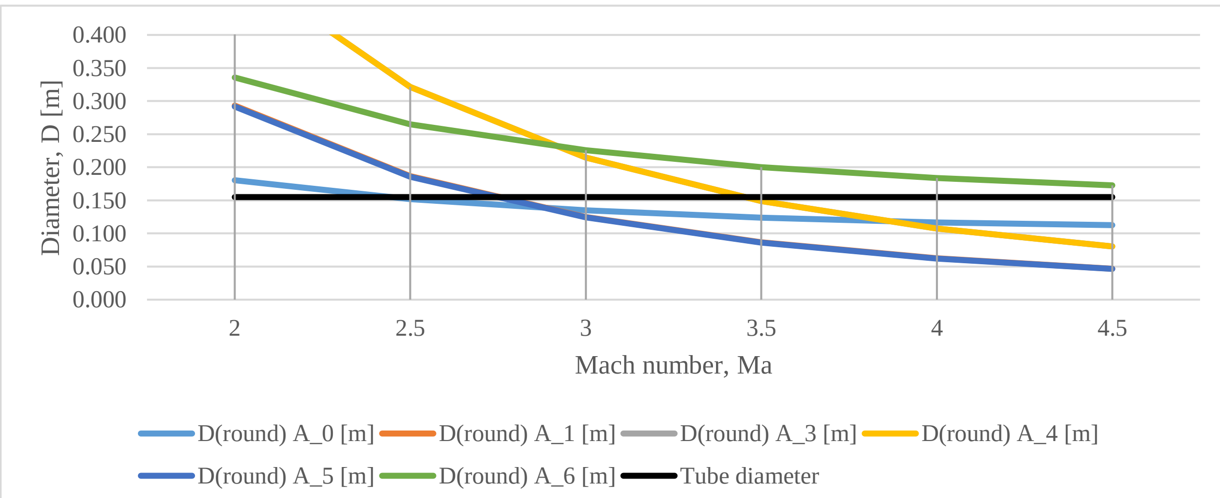


Figure 10-8: Ramjet diameter estimation

fuel-rich mixture can be read from a graph. Using multiple dimensionless parameters, Area ratios can be computed. These can be scaled to find the required diameter for a set amount of thrust. A constraint for the maximum diameter is the launch tube. [46]

As seen in Figure 10-8, the Ramjet diameter for an equal thrust engine decreases with growing Mach number. The graph shows the required diameters of the different engine sections (0: inlet, 1: smallest diameter of inlet, 3: burner entry, 4: burner exit, 5: smallest diameter of nozzle, 6: nozzle exit). By not expanding to ambient pressure, the nozzle diameter can be limited to 155 mm and the thrust only decreases slightly as the pressure difference of the nozzle exit produces a thrust component.

To make a Ramjet tube-launch capable, Adaptive materials are used.

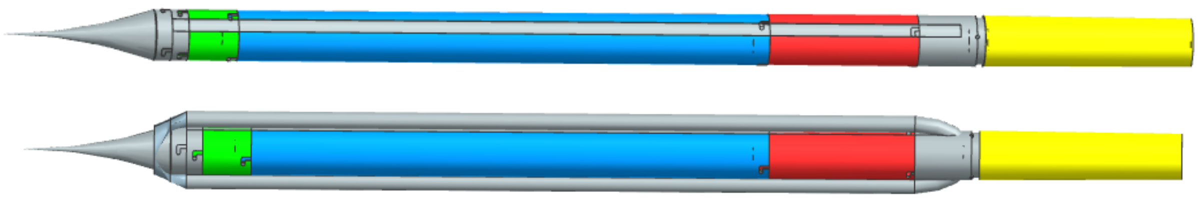


Figure 10-9: Stowed vs Expanded Tubes

10.6 Smart Warheads

Figure 10-10: Artist rendering of Air-to-Air Beyond Visual Range Missile

Across the five missions of the missile system, different effects are desired and different environments will be encountered. All possible targets for our missile can vary in size, armoring, and maneuverability affecting miss distance. To address these challenges, two unique warheads were developed: the dynamically configurable warhead and the tungsten penetrator.

The dynamically configurable warhead, shown below in Figure 10-8 consists of a high explosive core with two sets of detonators implanted within. The first set of detonators are aligned along the centerline of the explosive charge. Activating this set of detonators will cause the explosive front to propagate from the center of the warhead out cylindrically. The front will equally affect the titanium fragmentation rods along their lengths, optimally turning them into a annular pattern of shrapnel. This pattern of shrapnel will be ideal for the missile when its miss distance to an aircraft is too large, when it encounters a soft ground target such as a truck or small boat, or when it desires a large area of effect as in the anti-radiation mission.

Alternatively, the second set of detonators can be activated. These detonators are arranged in a conical pattern offset from the concave copper disc at the warhead's front. These detonators will generate an explosive front that will optimally compress the copper disc to turn it into an explosively formed penetrator suited for hardened targets such as tanks and direct hits on aircraft. This detonation option will also produce shrapnel from the titanium fragmentation rods affecting the nearby area, although less optimally. The dynamically configurable warhead allows the missile to optimally affect the desired target depending on miss distance and the nature of the armor that needs to be defeated.

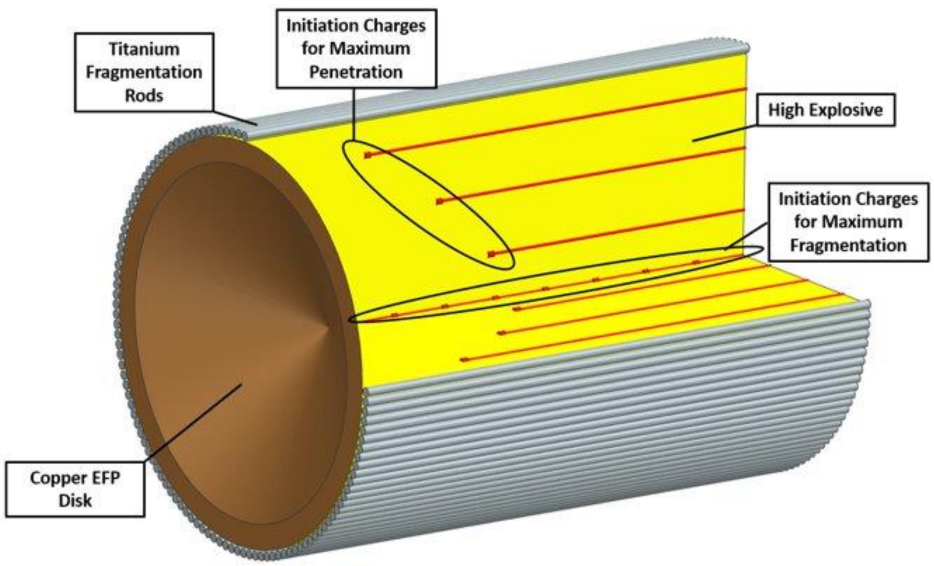


Figure 10-8: Dynamically Configurable Warhead

For the anti-ship mission, high forces are required, forces beyond what can be achieved by a titanium fragmentation or even an explosively formed penetrator. To keep the missile weight minimal, A trade between warhead weight and kinetic energy can be made. By using a tungsten penetrator, the warhead can be brought to the bottom of the ship through the decks. There, it is more effective and can neutralize a ship with minimal explosive mass used. To do so, the missile cruises to the target at Mach 5 at over 70,000 ft and then enters a vertical dive towards the ship. The ramjet is used to maintain the speed of Mach 5 and compensate for the drag forces. The terminal guidance is achieved through GPS navigation, so hypersonic speeds must be avoided in order not to disrupt the signal by the plasma formed at higher speeds.

An effective way to sink a known ship is to aim for a specific target on the ship's deck using GPS and to penetrate as many floors as required to achieve maximum damage with the warhead

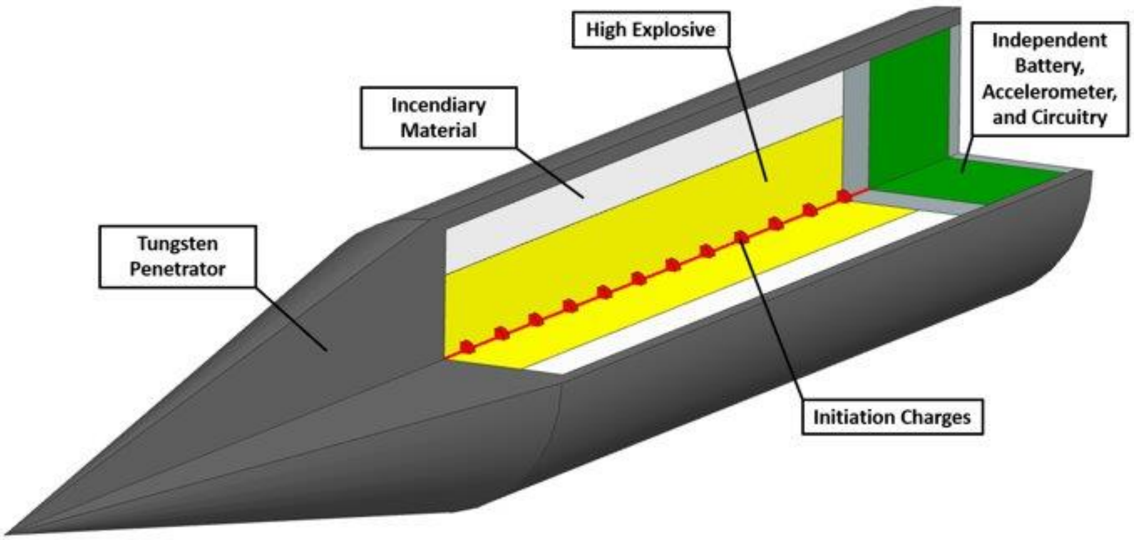


Figure 10-9: Tungsten Penetrator

explosion. An independent battery and accelerometer are included within the warhead to allow it to count the number of decks penetrated before detonating its charge at the desired depth. Depending on the ship type and available intelligence, the ideal penetration depth for the explosion can be chosen. Tungsten alloy is the ideal material for this because of its low ductility, density and heat resistance and has been used in kinetic penetrators for years. Figure 10-9 below shows the tungsten penetrator used for the anti-ship mission.

11 Powerplant Modules and Integration

Figure 11-10-1: Artist rendering of Anti-Ship Missile

As the range varies between the missions, separate propulsion systems are required. While there is a variety of propulsion systems easily able to meet the 25 nmi range requirement of the air-to-air visual range mission, longer range objectives of up to 150 nmi demand more efficient propulsive systems to decrease the weight of the missile. Hence, solid fuel rockets can be used for short range missions while ramjets offer lightweight propulsion solutions for long range missiles.

11.1 Short range missions

After the solid rocket booster is sized for long range missions, it will be evaluated if the performance meets the requirements to fly short range missions without the use of a ramjet.

11.2 Long range missions

For the high demands of long-range missions, a combination of separate systems is used to reach the target: An explosive charge propels the missile out of the tube and gives its initial velocity. After that, a small solid fuel booster propels the missile to the operating Mach number of the ramjet. Then, the cruise speed is maintained by the ramjet.

11.2.1 Tube launch compatibility for recoilless and hard launch

Tube launch compatible missile are the future of fighter aircraft for the inherent advantages gained from increasing munitions packing factors and maintaining low observables during deployment. While none of the missiles presented herein are required to be tube launched, they are specifically designed to be compatible with recoilless launches and hard launches in the future after further development.

Modern fighter jets are not designed to take the loading of recoil on their hard points which is why mounting a recoilless gun tube would be ideal for augmenting launch capabilities on current aircraft. An explosive charge would be used to rapidly accelerate the missile on launch to allow it to deploy its ramjets and enter a more efficient cruise sooner during its mission. Hard launching achieves the same benefits but to a more extreme degree. Current aircraft are not designed to accommodate the forces associated with hard launching a projectile as massive as the missiles designed in this report, but future aircraft will.

The gun barrel used could dramatically increase the weight of the total missile system. For this reason, carbon fiber tape can be would around the barrel to alleviate hoop stresses created by the explosive charge and lighten the barrel. Barrell degradation is also a concern. High explosive has been used in the past to propel tank projectiles but was found to be damaging to the barrels of the tank guns. Low volatility ammunition can be used to prevent excessive wear on the gun tubes for repeated use.

11.2.2 Solid fuel booster

The combustion chamber of the ramjet will initially be filled with solid rocket propellant to accelerate the missile from its initial velocity to cruise speed. At launch, the flexible burner tubes are not yet expanded, so no reverse flow is possible. The connection between the inlet and the burner is blocked by constraining the inflation of the flexible ramjet tubes.

By placing the solid rocket propellant in the ramjet combustion chamber, the same thrust vectoring nozzle can be used for both the ramjet and the rocket.

To estimate the performance and the fuel needed, the velocity gain ΔV can be computed as seen below:

$$\Delta V = -g_0 \cdot I_{sp} \cdot \left[1 - \frac{D_{avg}}{T} - \left(m_{launch} \cdot g_0 - \frac{1}{2} m_{fuel} \cdot g_0\right) \cdot \frac{\sin(\gamma_{path})}{T}\right] \cdot \ln\left(1 - \frac{m_{fuel}}{m_{launch}}\right)$$

[38 p.348]

Because the ISP of a solid rocket booster is much lower than that of a ramjet, only the initial acceleration is performed with the solid fuel booster. After reaching Mach 1.5 for the anti-ship mission or Mach 1.8 for the other long range missions. After that, the ramjet is operating.

11.2.3 Ramjet

For the performance estimation of the ramjet, the same equation as in the previous section was used after the specific impulse was computed for each phase of flight.

The ramjet relies on a good air inlet that is effective across the speed range between Mach 1.5 and Mach 5. The key goal of a supersonic inlet is to achieve a high total pressure recovery. This can be achieved by increasing the number of oblique shocks. However, a high number of shocks also increases weight,

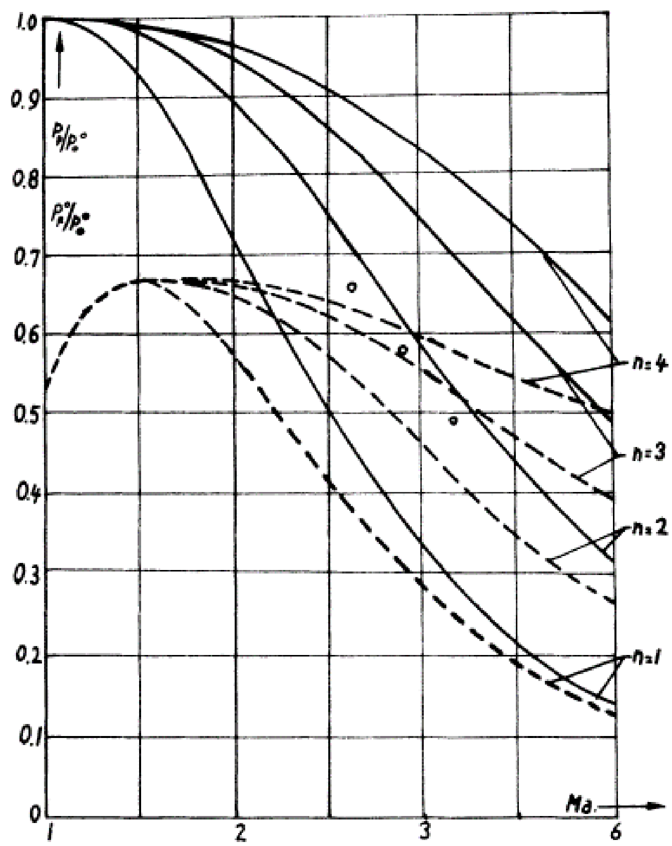


Figure 11-2: ideal Oswatitsch-analysis of ramjet inlets [47]

length and operational range of the inlet. Therefore, the Oswatitsch analysis provides us the ideal total pressure recovery of an ideal inlet with n shocks and Ma_0 represented on the x-axis. However, an even higher pressure recovery of almost 100 % can be achieved by using a quasi-isentropic inlet. However, this geometry only works at the design Mach number. For our missile, the quasi-isentropic inlet does create an oblique shock pattern that is fed into the inlet using a variable geometry inlet system that moves the inlet lip backwards with increasing flight speed. That way, the first shock is positioned at the inlet lip in all flight phases until the inlet becomes quasi-isentropic near Mach 5.

11.2.3.1 Ramjet sizing

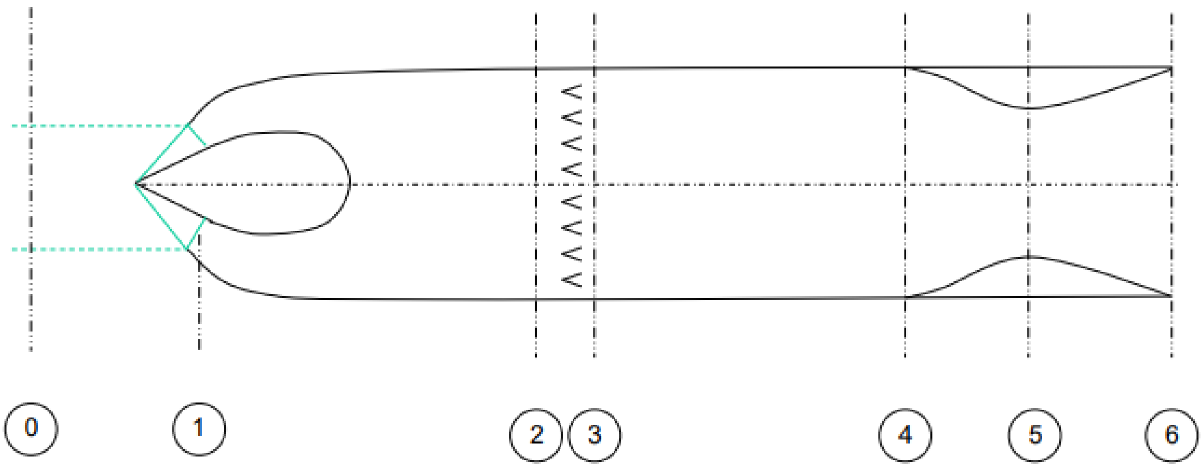


Figure 11-3: Ramjet Engine planes [46]

To design ramjets for the missile, the area of each engine section needs to be known. After the inlet pressure recovery $\frac{p_{t2}}{p_{t0}}$ is known, the total temperature T_{t0} is computed assuming isentropic compression with $\gamma = 1.4$ and Ma_0. An estimate for the burner pressure loss $\frac{p_{t4}}{p_{t3}}$ is assumed. From this, the burner parameter *s* is computed:

$$s = \left(1 + \frac{\dot{m}_f}{\dot{m}_0}\right) \cdot \sqrt{\frac{T_{t5}}{T_{t0}}}$$

This assumes the gas constant *R* to stay constant throughout the engine. While Dr. Leitner suggests using a *f* of 0.086 (fuel rich combustion), lower *f*s can be used to decrease temperatures. However, the smaller the *f* gets the bigger the ramjet needs to be to provide the same thrust. An advantage of Ramjets is that they do not need to limit the turbine temperature and can combust at much higher temperatures than turbojet engines. The naming of the engine planes and the corresponding area indexes can be found in Figure 11-3. From this, the area relation A_0/A_5 is estimated:

$$\frac{A_0}{A_5} = \frac{p_{t5}}{p_{t0}} \cdot \frac{1}{s} \cdot \frac{\left(\frac{(1+f) \cdot \sqrt{T_{t5}}}{p_{t5} \cdot Ma_5}\right)}{\left(\frac{\sqrt{T_{t0}}}{p_{t0} \cdot Ma_0}\right)}$$

As it is the nozzles critical section, $Ma_5 = 1$. To continue the analysis, a combustor Mach number $Ma_3 = Ma_4$ needs to be chosen. From this, the burner area $A_3 = A_4$ can be computed:

$$\frac{A_3}{A_5} = \frac{1}{Ma_4} \cdot \left(\frac{2}{\gamma_4 + 1} \cdot \left(1 + \frac{\gamma_4 - 1}{2} \cdot Ma_4^2\right)\right)^{\frac{\gamma_4+1}{2(\gamma_4-1)}}$$

From this, the Relationship between A_0 and A_3 can be determined:

$$\frac{A_0}{A_3} = \frac{A_0}{A_5} \cdot \frac{1}{\left(\frac{A_3}{A_5}\right)}$$

To size the engine, a thrust parameter is needed. This can be related to A_3.

$$c_{F\ 0\to5}^3 = \frac{\left(\frac{A_5}{A_3}\right)}{\frac{1}{2} \cdot \gamma_0 \cdot Ma_0^2} \cdot \left(\frac{p_5}{p_0} \cdot (1 + \gamma_5 Ma_5^2) - 1\right) - 2 \cdot A_0/A_3$$

$$\frac{p_5}{p_0} = \frac{p_{t0}}{p_0} \cdot \frac{p_{t5}}{p_{t0}} \cdot \frac{p_5}{p_{t5}}$$

The thrust parameter also needs to be known for the divergent part of the thrust nozzle:

$$c_{F\ 5\to6}^3 = \frac{\frac{p_6}{p_{t5}} \cdot \frac{A_6}{A_5} \cdot (1 + \gamma_4 \cdot Ma_6^2) - \frac{p_5}{p_{t5}}(1 + \gamma_4 \cdot 1^2) - \frac{p_0}{p_{t5}}\left(\frac{A_6}{A_5} - 1\right)}{\frac{p_0}{p_{t5}} \cdot \frac{1}{2} \cdot \gamma_0 \cdot Ma_0^2 \cdot \frac{A_3}{A_5}}$$

For any set thrust, the nozzle throat area A_5 can be chosen to achieve the given thrust for set engine parameters. For this, the ambient air density and flight speed need to be calculated using ideal gas relations:

$$\rho_0 = \frac{p_0}{R \cdot T_0}$$

$$V_0 = M_0 \cdot \sqrt{\gamma_0 \cdot T_0 \cdot R}$$

Then, A_5 is computed:

$$A_5 = \frac{F}{\frac{\rho_0}{2} V_0^2 \cdot \left(\frac{c_{F\,0\to5}^3}{\left(\frac{A_5}{A_3}\right)} + \frac{c_{F\,5\to6}^3}{\left(\frac{A_5}{A_3}\right)} \right)}$$

All the other areas can be computed using the previously calculated area ratios and the relations for critical state area relations. To get the actual thrust, the regular engine thrust calculation is performed as this only gives an estimate. The real engine may not have a nozzle capable of expansion to ambient pressure due to size constraints. To do so, the critical area relations are saved in a table for different Mach numbers:

$$\frac{A}{A^*} = \frac{1}{M} \cdot \left[\frac{2}{\gamma + 1} \cdot \left(1 + \frac{\gamma - 1}{2 \cdot M^2} \right) \right]^{\frac{\gamma+1}{2(\gamma-1)}}$$

Then, the corresponding Mach number for a set area relation is looked up from this table:

$$M_6 = M\left(\frac{A}{A^*}\right)$$

To get the thrust, the mass flow needs to be known:

$$\dot{m}_0 = A_0 \cdot V_0 \cdot \rho_0$$

The temperature and pressure can be computed through isentropic flow relations in the nozzle. Then, the actual thrust is calculated:

$$V_6 = M_6 \cdot \sqrt{\gamma_6 \cdot T_6 \cdot R}$$

$$F = V_6 \cdot \left(\dot{m}_0 + \dot{m}_f\right) - V_0 \cdot \dot{m}_0 + A_6 \cdot (p_6 - p_0)$$

Depending on the expansion in the nozzle, this can be lower than the thrust estimation. [46]

Figure 11-4 shows the relationship between the fuel to air ratio *f* and the inlet diameter D_0 as well as the burner exit total temperature T_{t4}. Operating conditions are Mach 4 at 30,000 ft in standard atmosphere conditions. The pressure recovery of the quasi-isentropic inlet was assumed to be 0.8 and the pressure losses due to boundary layer affects were assumed to be 0.1. Each of the engines was designed to provide enough thrust to propel the missile with the additional wave drag of the burner tubes and provide 500 N of excess thrust for surface drag and other effects.

$$F = 500\text{ N} + D_{Wave}$$

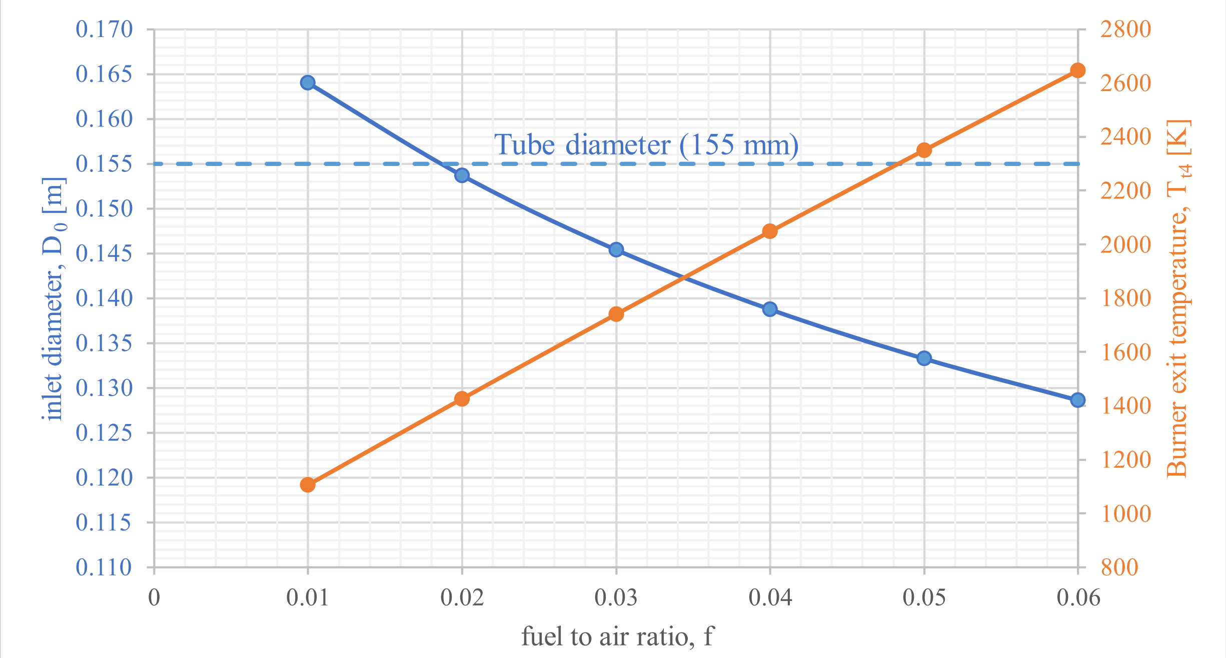


Figure 11-4: Influence of the fuel to air ratio on the burner exit temperature and inlet Diameter

The fuel to air ratio must be greater than approximately 0.019 to fit the engine within the missile. To make an efficient and small engine, a fuel rich mixture is to be favored. However, concerns about material choice and NO_X emissions push towards lower fuel to air ratios. With modern jet engine turbine entry temperatures exceeding 2000 K [51] and the lack of a turbine, fuel to air ratios of 0.04 and greater can be realized with ramjets.

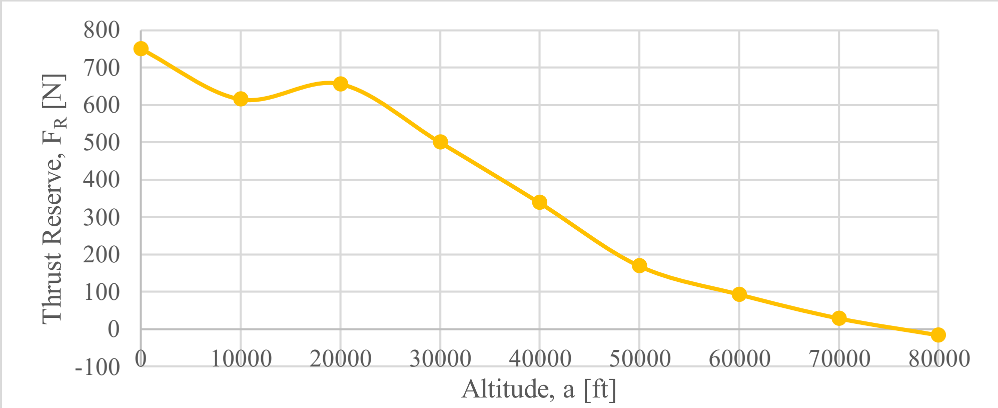


Figure 11-5: Thrust reserve vs. Altitude

Figure 11-5 shows the excess thrust and the altitude of the ramjet engine. This is computed by doing the ramjet thrust calculations and subtracting the wave drag by the ring around the ramjet inlet and the drag of the burner pipes. This example ramjet is sized to have 500 N of excess thrust at 30,000 ft, which is smaller than the ramjet chosen for the missile. Therefore, the inlet diameter in this example is 139 mm. As seen in Figure 11-5, the excess thrust decreases by altitude until it becomes negative above 75,000 ft. The excess thrust is needed to compensate for all forms of drag not part of the wave drag such as wetted surface area drag. This shows that a ramjet sized this way can only maintain its flight Mach number at 70,000 ft or lower. For the ramjet chosen for the mission to feature maximum high-altitude performance, the inlet grows to 155 mm diameter. This enables flight at 95,000 ft ceiling altitude.

As Figure 11-6 shows, the fuel consumption per distance travelled decreases significantly with growing altitude. Therefore, a high cruise altitude is desired. To see how feasible this is, the climb performance of the missile needs to be evaluated. This led to the introduction of the added oxidizer for added thrust for acceleration.

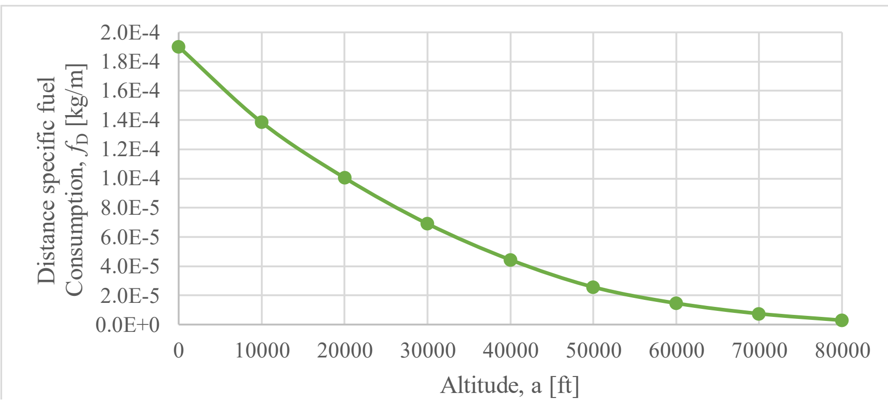


Figure 11-6: Distance specific fuel consumption vs. altitude

At the chosen combustor Mach number Ma_3=0.2, the required dwell time of 2 ms gives us a combustor length of at least 300 mm.

12 Weight and Balance Analysis

In this section, the weight and balance analysis of the AIGM-138 is presented. The weights and center of gravity locations (C.G) of each group of components are calculated by the designer which based on the Airplane Design Part V by Roskam [53]. And a preliminary three-view of the missile is shown in Figure 12-1 below.

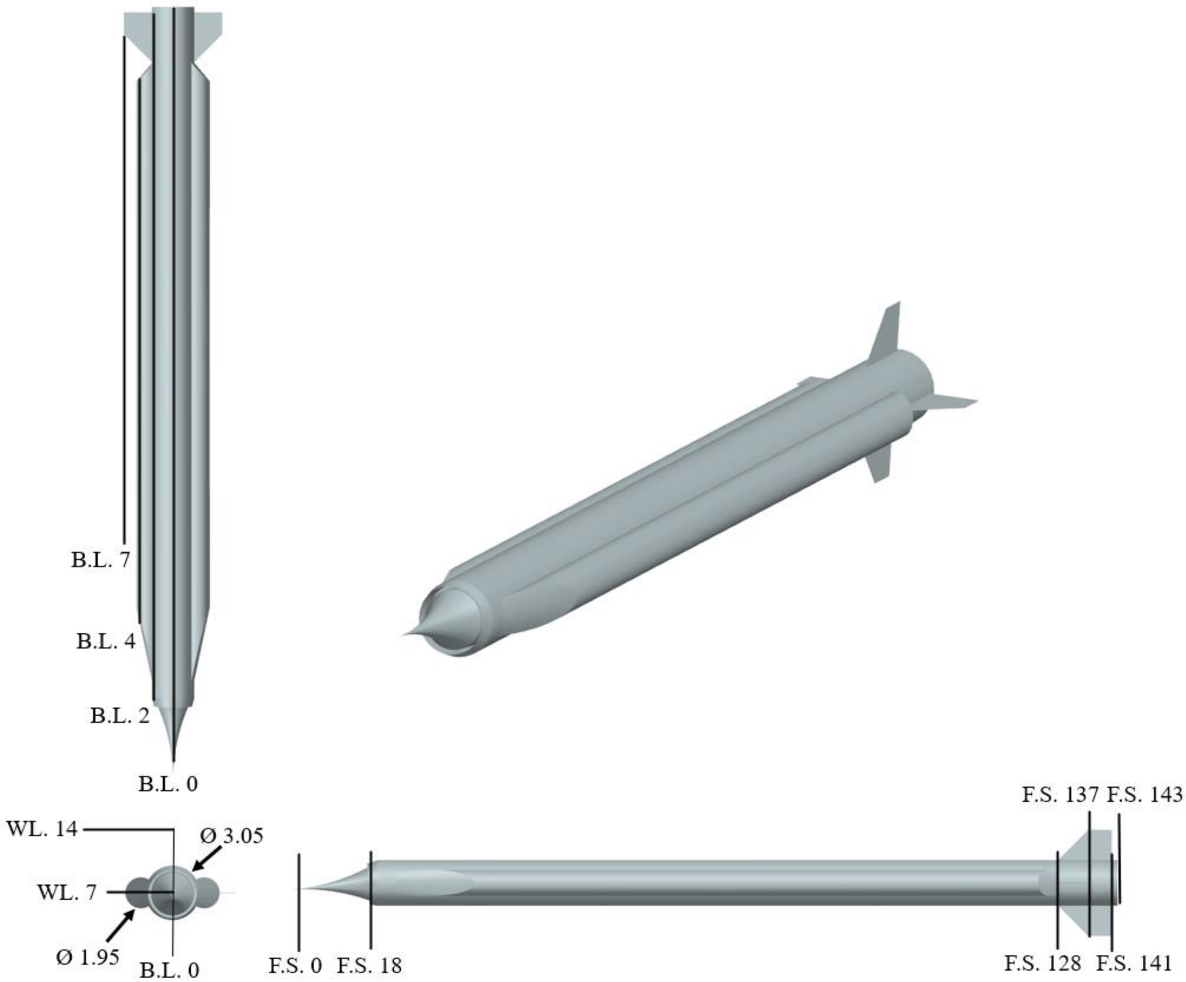


Figure 12-1: Preliminary Three-View of the Missile

12.1 Class I Weight and Balance Calculation

Due to the modular design, the designer classified the various components of the missile into Six parts: Structure, Fixed Equipment, Warhead, GNC (guidance, navigation, and control), Powerplant and Propellant.

Since the individual component weights are found and listed, the C.G respect to fuselage stations (F.S) and water line (W.L) for each missile is obtained by designer. The component weights, weight fractions of each part and the final C.G. position of each missile is calculated and presented in Table 12-1 and 12-2 below.

$$Weight\ Fractions = \frac{Component\ Weight}{Gross\ Weight} \qquad Ref.53$$

$$C.G_{total} = \frac{\sum(W_{component} * C.G_{component})}{\sum W_{component}} \qquad Ref.53$$

In those two Tables, the grids with the same color in each column mean the missile is sharing same type of components.

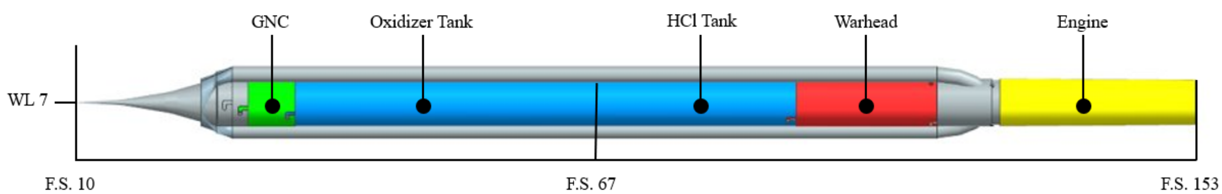


Figure 12-2: Component CG Locations (1:80 Scale)

Table 12-1: Sharing Components

	AA-VR	AA-BVR	AA-MVT	AA-ARAD	AA-Ship	Variants
Warhead	Dynamically Configurable Warhead				Tungsten Penetrator	2
Propulsion	Solid Rocket	Solid Rocket Boost, Ramjet Cruise (SRBRC)			SRBRC + Additional Fuel	3
Aerodynamic Surfaces	Fins Only	Burner Tube Strakes and Fins				2
Guidance	Multi-spectrum	Active Radar	Multi-Spectrum	Passive Radar	GPS/Satellite Datalink	4

Table 12-2: Individual Component Weight and Weight Fractions of Air-to-Air Missile

Component	AA-VR			AA-BVR		
	Weight (lb)	Weight Fraction	C.G Fuselage Station	Weight (lb)	Weight Fraction	C.G Fuselage Station
Structure	47.4	0.235	63.5	33	0.105	44.24
Warhead	26.5	0.13	33.5	65.2	0.21	83.44
Fixed Equipment	5	0.025	1.5	4.5	0.015	1.4
GNC	22	0.11	6.8	22	0.07	6.8
Powerplant	11	0.055	17.75	33	0.1	53.25
Propellant	91.5	0.445	72.7	159	0.5	126.3
Gross Weight	203.4	1	~	317.4	1	~

Table 12-3: Individual Component Weight and Weight Fractions of Air-to-Ground Missile

Component	AG-AT			AG-AR			AG-AS		
	Weight (lb)	Weight Fraction	C.G Fuselage Station	Weight (lb)	Weight Fraction	C.G Fuselage Station	Weight (lb)	Weight Fraction	C.G Fuselage Station
Structure	33	0.105	44.24	33	0.105	44.24	33	0.086	44.24
Warhead	65.9	0.21	83.44	65.9	0.21	83.44	95.2	0.256	120.5
Fixed Equipment	4.5	0.015	1.4	4.5	0.015	1.4	4.5	0.012	1.4
GNC	22	0.07	6.8	22	0.07	6.8	22	0.058	6.8
Powerplant	33	0.1	53.25	33	0.1	53.25	33	0.087	53.25
Propellant	159	0.5	126.3	159	0.5	126.3	193.5	0.501	153.7
Gross Weight	317.4	1	~	317.4	1	~	381.2	1	~

12.2 C.G Excursion

Each missile will have 4 sets of C.G location data due to the various load conditions which are: empty weight, empty weight with warhead, empty weight with full fuel and the final take-off weight. Therefore, from those 4 sets of C.G data, a C.G excursion diagram for each of missile can be obtained and represent a visual for the change of C.G location of the missile during the boost phase until it hits the target after the missile is fired from the aircraft. As Figures 12-3, 12-4, 12-5 shown, the shift of C.G location of each missile in different load conditions are presented. The largest shift of C.G location usually occurs during the flight, which is shifting backward with the decreasing of the fuel.

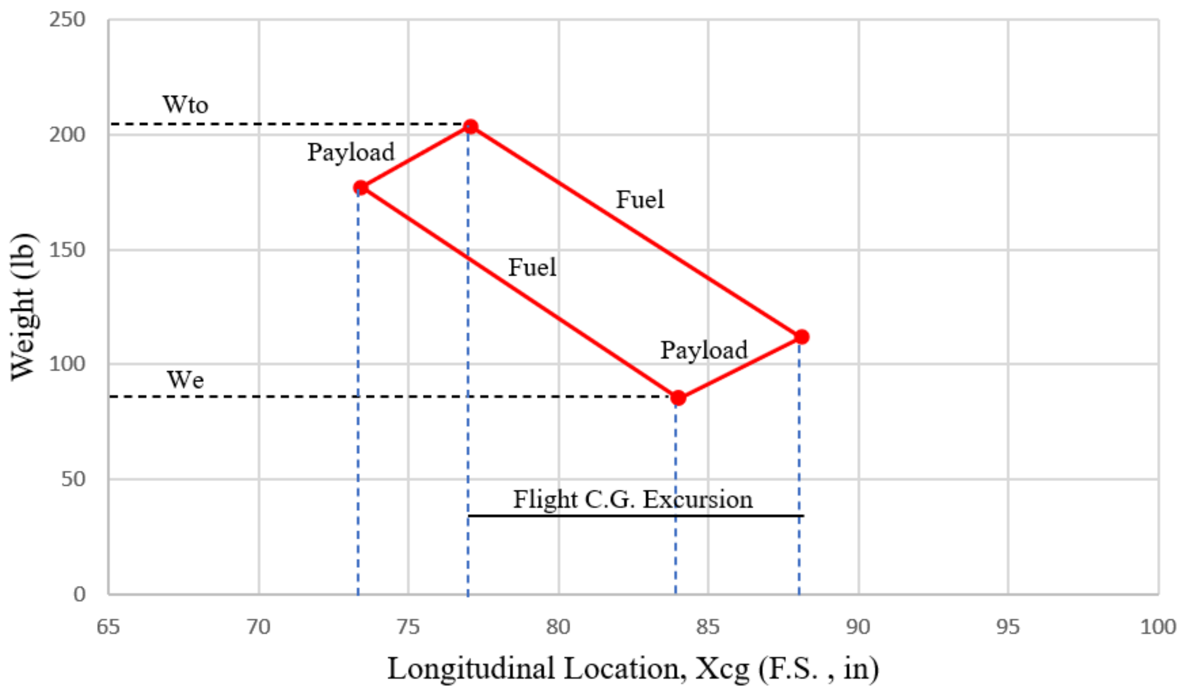


Figure 12-3: C.G Excursion Diagram for AA-VR Missile

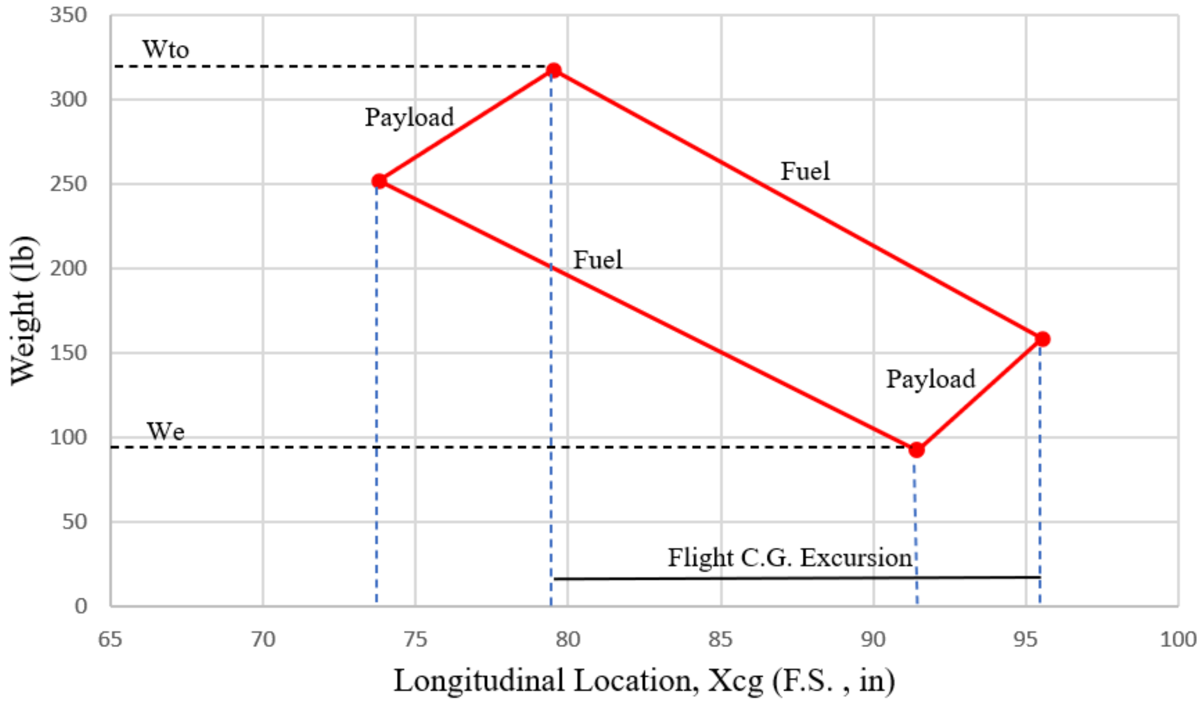


Figure 12-4: C.G Excursion Diagram for AA-BVR, AG-AT, AG-AR Missile

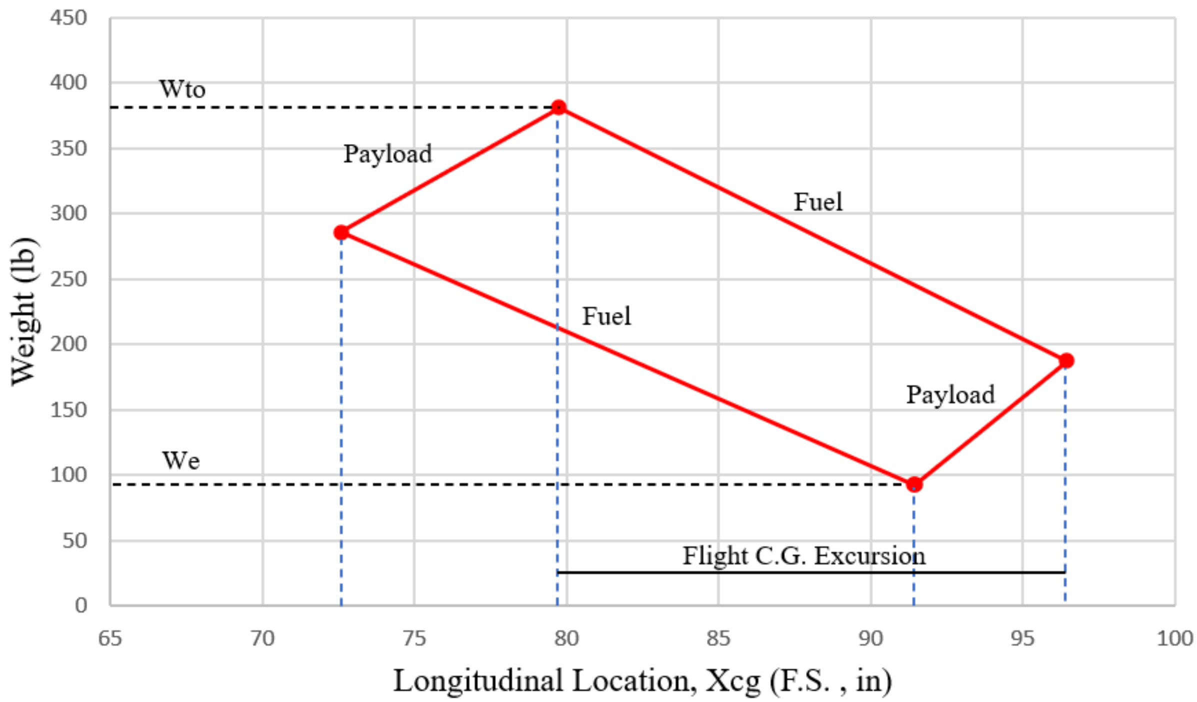


Figure 12-5: C.G Excursion Diagram for AG-AS Missile

13 Layout of Major Systems

Figure 12-1: Rendering of Launch from Conventional Trapeze Rail Launcher

Some systems were already explored in detail in the previous chapters and are therefore not mentioned in this section.

From Table 10-1, the components that are shared between missions are shown. There are two different types of warheads, with size being the difference between the various air-to-air missions and the other missions. For propulsion, there will be three different rocket motor sizes, with AA-VR and AA-MVT having the same size, AA-BVR and AA-ARAD having another, and AA-Ship will have another as well. The same thrust vectoring will be used for all missiles. The control surfaces will also be identical for all missiles that require control surfaces. There will be no wings or fins for the AA-MVT and AA-ARAD missiles. For each mission, there will be a different seeker required as guidance is very specialized to the mission requirement. The basic configurations will be shown in the sections below.

13.1 Flight Control Systems

This section talks about the actuator sizing, basic arrangement, and control routing for the flight controls. As mentioned earlier, the missiles will use four aerodynamic tail control surfaces and have combined integrated control of all three-axis. For lower cost and easier packaging, two-axis flight control (pitch/yaw, pitch/roll) will be deployed because only two actuators are needed. The missiles will use irreversible actuators, which missiles commonly deploy. This is used based on the fact that there are no physical controls on the tail fins. The power that the actuators use will be drawn from an electric system, whose input signal is fiber optic. Fiber optic plays an important role in reducing the induced-electromagnetic interferences when the missiles are subjected to a wide range of electric currents during lightning. For the flight control actuators, a balanced actuation control will be used, thereby lowering hinge moment and drag. The actuators were sized by finding the stall torque and corner frequency. The stall torque required will be sized for 15g maneuvers assuming harshest environmental conditions. The team found the stall torque on the fins by assuming that the normal force was acting at 35% of the mean geometric chord. Therefore, this location will be where the actuators will connect to the tail fins. The actuators are powered using the electrical system, by running wires from the system to each of the actuators. Combined with the tail control, thrust vectoring will be utilized for more control effectiveness and/or reduced response time. There are different thrust vectoring options, but the jet vanes are selected. This is due to simplicity and to save costs. The jet vanes are integrated into the tail fins. The tail fins will extend around the nozzle of the ramjet so they may direct the thrust. The thrust vectoring can be seen in Figure 10-4. The Figure 13-2 shows the layout of the fully extended tail fins.

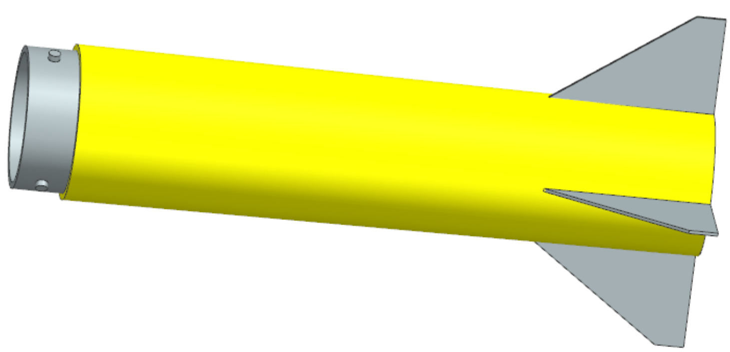


Figure 13-2: Tail Fins Fully Extended

13.2 Fuel System

This section covers the design and the integration process of the fuel system of the AIGM-138. The missile has three different powerplant due to the different range requirement of the mission which are: Solid Rocket for short range missile (AA-VR), Solid Rocket Boost and Ramjet Cruise (SRBRC) for middle range missile (AA-BVR, AG-AT, AG-AR), and SRBRC with oxidizer for long range missile (AG-AS). The total amount of fuel increases with the combat distance and warhead weight.

To fulfill the requirement of the low cost and the combat range, ammonium perchlorate (ClO_4NH_4) is chosen as the oxidizer and hydrochloric acid (HCl) as fuel for the propellant that missile used. This will not only reduce the smoke that missile made, but also has high ISP as propellant and good storage capabilities for the logistics.

The fuel system is consisted with oxidizer tank and fuel tank which located in the middle section of the missile between the GNC and warhead section. The oxidizer tank is in the forward part and 75% larger than the fuel tank size in order to fulfill the range requirement. Both oxidizer and fuel tank are made with aluminum for safe storage and weight reduction, and high-grade steel can be considered as secondary substitute for the cost reduction.

The fuel will be stored in a pressurized tank with a nitrogen-filled bladder sustaining the pressure. By storing fuel at high pressure, intake pressure losses can be compensated by injecting high pressure fuel into the burner pipes. The valve control system of the oxidizer is attached to the bottom of the oxidizer tank to ensure proper control of the tank. The fueling-defueling system is located above the valve system with a filter and vertically aligned with the fueling-defueling system of the fuel tank. The fueling-defueling line of oxidizer and fuel tank will extend over the warhead section and connect to the engine that ignited by a booster igniter. The fuel system in visual is shown in Figure 13-3 below.

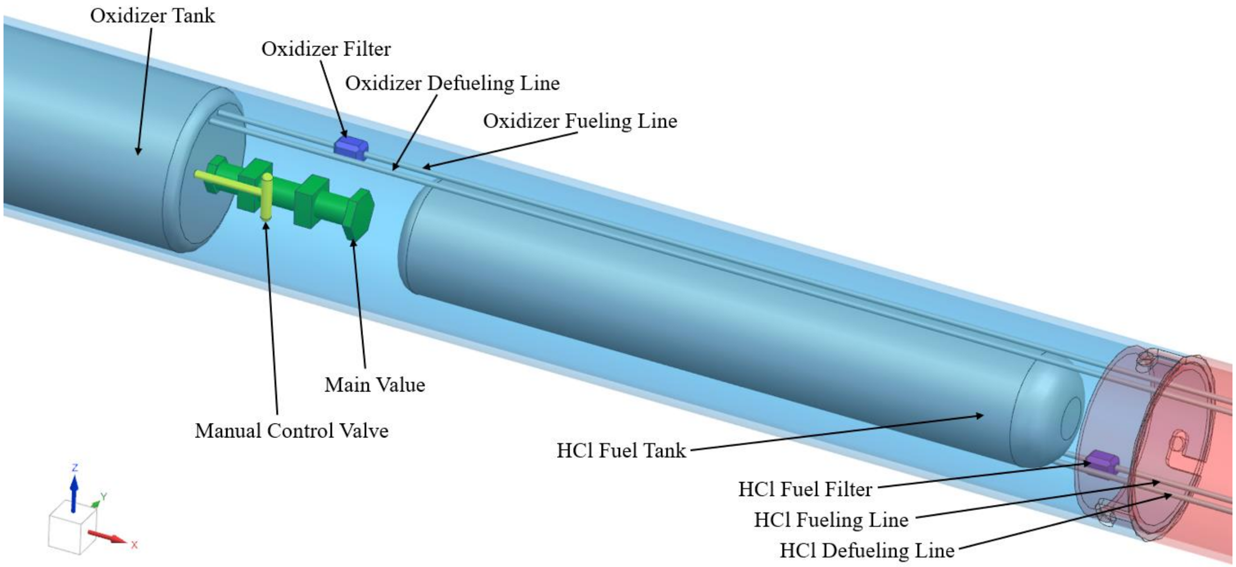


Figure 13-3: Oxidizer and Fuel System

13.3 Electrical System

This section covers the electric components in the AIGM-138 which consists of three parts: flight control system (FCS), powerplant, sensors and the ground wire for them. Each of the three systems is powered by a lithium battery which is installed inside the nozzle in front of GNC section to ensure the cooling and safety when the missile is flying in supersonic. For the antiship penetrator, an accelerometer is added to detect when decks of ships are penetrated, a separate onboard computer calculates the amount of decks penetrated and will detonate the warhead when the missile reaches an optimal location near the hull or fuel. The estimated power required of each electrical components in different flight phase is shown in Table 14-2.

The required sensors can be seen on the table below for the various missions.

Table 13-1: Required Sensors

Sensor	Position	Function
Static temperature	Side	Mach number computation
Static pressure	Side	Altitude measurement
Total temperature	Tip	Mach number computation
Exhaust gas temperature	Nozzle	Ramjet thrust controlling
Gyroscope	Computing unit	Attitude control
GPS	Computing unit	Flightpath control
Acceleration sensor	Anti-ship Penetrator	Counting penetrated decks on ship
GPS sensor #2	Anti-ship Penetrator	Guiding hypersonic penetrator

Table 13-2: Power Breakdown in Each Flight Phase (unit in W)

	Take-Off and Climb	Cruise	Terminal	
Actuators	5	3	6	
Autopilot	5	5	5	
Data Transmitter	0	50	50	
GNC	4	3	6	Detonation
Powerplant	3	3	3	
receiver	2.5	2.5	2.5	
Seeker	4	4	6	
Total	23.5	70.5	78.5	

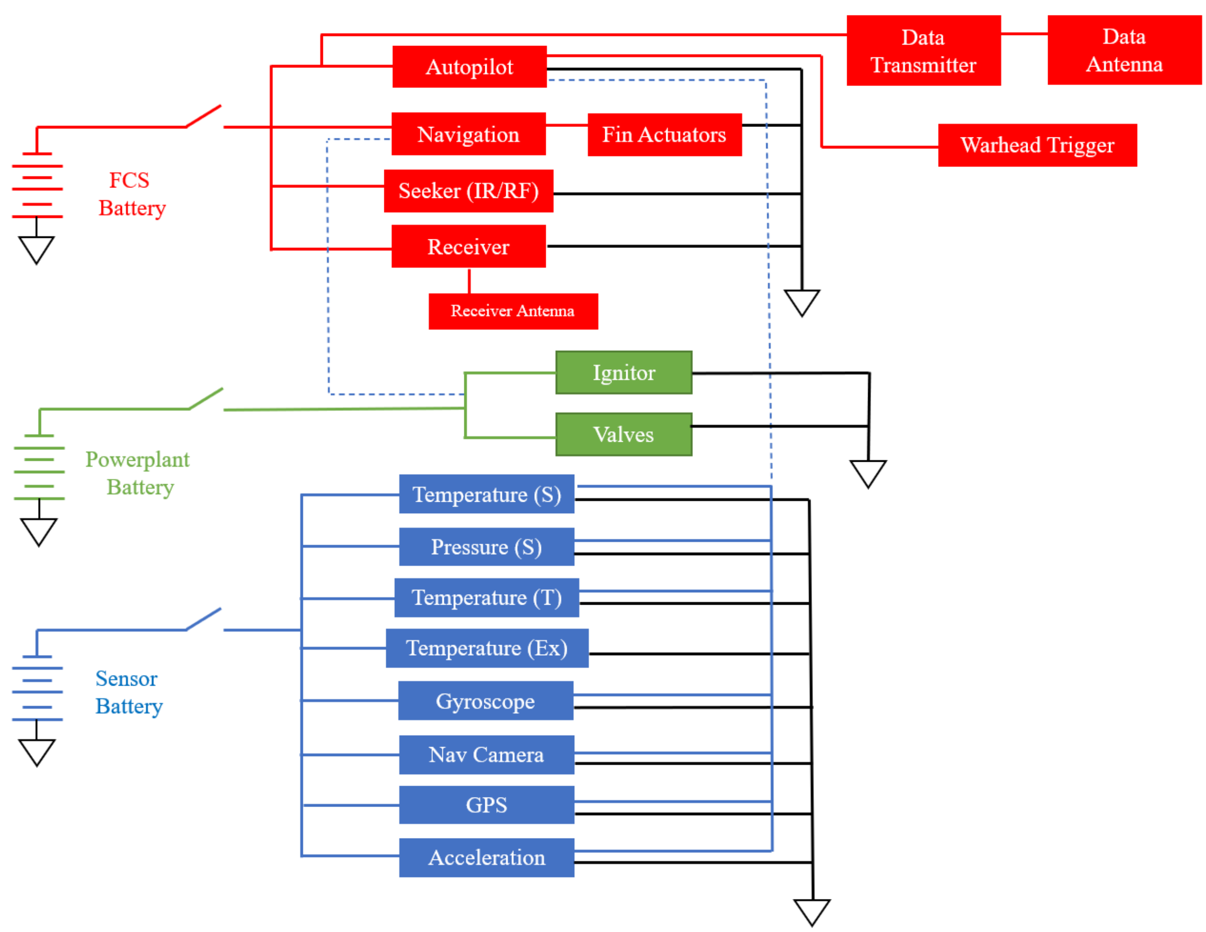


Figure 13-13-4: Missile Wiring Diagram

14 Cost Estimation

To estimate the cost of this missile modified techniques from Dr. Jan Roskam's Airplane Design Part VIII are used. To determine the total cost of this missile throughout the entire program the costs of four sections are first found. These include the Research Development Test and Evaluation costs (Crdte), Manufacturing and Acquisition costs (Cma), Operating costs (Cop), and Disposal costs (Cdisp). With the assumption that over the total lifetime of this missile 500000 will be acquired the costs are as follows Crdte $2.06 billion, Cma $1.36 trillion, Cop $136 billion, Cdisp $25 billion. This results in a total lifetime cost of $1.53 trillion. The resulting price per missile is $300 million. While this is more expensive than most other missiles currently this price is likely to decrease as the manufacturing continues as less time will be needed to create each missile. It also should be noted that while this missile is more expensive than any missile in each of the mission categories this missile can complete each of the five selected missions while the competitors cannot. [55]

14.1 Manufacturing Processes

The manufacturing processes for the missile sections involve specialized materials, precise shaping and assembly techniques, and rigorous testing to ensure mission reliability. The nose section of the missile would be made of quartz composite in a high-strength metal mold and shaped using heat and pressure to form a high fineness ratio nose, while the main body sections would be made from rolling high strength steel into layers of a cylinder with a layer of copper braising added to bond the layers together.

The foldable ramjet engines for the missile would be made from shape memory alloy NITINOL, prepared in the folded form to unfurl after launch. The individual components would be assembled and tested to ensure their functionality and reliability. The rocket launch engine for the missile would not require any exotic material, using common manufacturing processes to quickly launch the missile away from the aircraft after launch. The propellant would be prepared by mixing fuel, oxidizer, and additives and pressing the mixture into the desired shape.

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