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FIT FOR MISSION – DESIGN TAILORING ASPECTS OF THROTTLEABLE DUCTED ROCKET PROPULSION SYSTEMS

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[Abstract] A series of successful flight tests of Meteor (Fig. 1) with a development standard Boron loaded Throttleable Ducted Rocket (TDR) has demonstrated the capability and maturity of this superior propulsion system. Meteor is the medium to long range air to air missile, selected by six European nations (UK, Fr, It, Sp Swe, GE) for air superiority of their fighter aircraft Gripen, Rafale and EF2000 Typhoon. The paper summarizes the basic function of the TDR, the technical status and the major design drivers. Based on the existing technology from Meteor and multiple additional technology programmes, TDR propulsion systems for alternative missions are outlined with respect to the discussed design driving parameters. The Boron loaded TDR is a most promising candidate for future missile propulsion, providing a superior kinematic performance and mission flexibility.

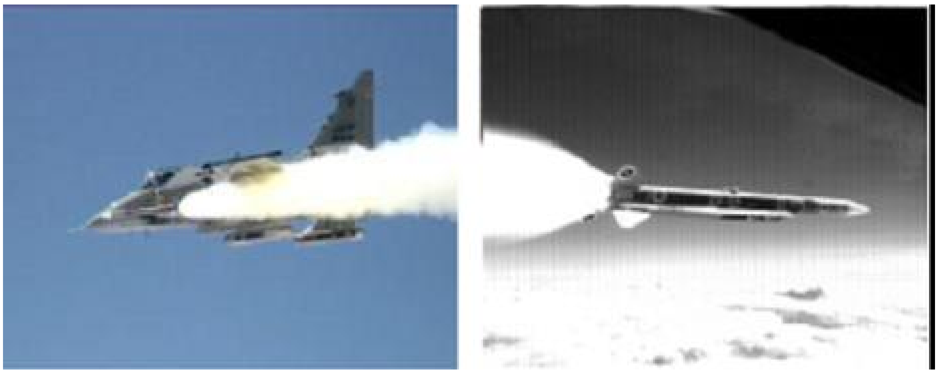

Figure 1: Meteor flight testing, launch and early boost phase (photos courtesy of MBDA Missile-Systems)

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Nomenclature

Symbols

		Unit
A_b	burning area	m^2
D	Missile / motor diameter (caliber)	m
L	combustor length	m
M	Mach number	-
H	altitude	m
n	pressure exponent of burn rate law	-
p_{GG}	gas generator pressure	MPa
r	burning rate	mm/s
η_{Φ}	combustion efficiency based on theoretical-to-experimental equivalence ratio	-
η_{ke}	kinetic energy efficiency of air intake	-
ρ	density	kg/l
Φ	equivalence (fuel-to-air) ratio	-

I. Introduction

Throttleable Ducted Rocket (TDR) technology with high energy Boron sustain propellant was built up in Germany since the early 1960's by continuous R&D funding by the German MoD and engaged industry as well as by several key feasibility and demonstration programmes [1, 2]. Important milestones were

- first demonstration of extraordinary stable DR ramcombustion in the DLR Cologne vertical wind tunnel in 1971,
- first flight demonstration in 1981 - EFA-Demonstrator, (Fig.2),
- predevelopment of a TDR for an anti ship missile (ANS) in 1981 – 1987,
- German feasibility programmes for an advanced air to air missile (A3M, DEM, EURAAM) in 1995 – 1999

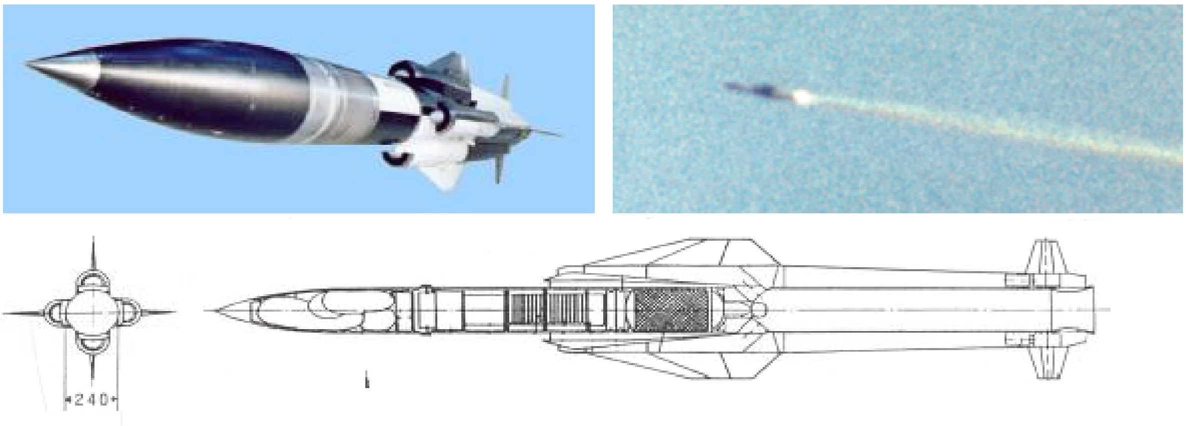

Figure 2: EFA demonstrator missile – design, missile hardware and test flight

A TDR motor using a high energy Boron loaded solid propellant for the sustain operation was selected as propulsion system for the European medium to long range air to air missile Meteor (Fig. 1) in 2002. This propulsion system provides kinematic superiority of Meteor over all existing comparable missiles by

- factor 2.5 propulsion performance superiority compared to a conventional solid rocket motor,
- high average velocity and minimum time to target by sustained propulsion,
- high g intercept manoeuvres even at maximum range,
- continuous optimization of the intercept trajectory by active thrust control.
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The paper explains the functionality of the TDR and highlights shortly the technical status achieved today in context with the Meteor propulsion system. The paper outlines further, how TDR design needs to be tailored to give all performance required but also to lead to an affordable product. Ambitious requirements for

- range
- speed
- wide operational envelope wrt altitude and Mach number
- manoeuvring capability (angle of attack and sideslip)
- high environmental loads
- low volume and mass
- integrated booster/ramjet design
- insensitivity

altogether drive design complexity and cost of the propulsion module. A well considered balance of prioritized requirements and potentials for limited performance compromises is a means to arrive at a high performing and cost effective system.

The paper reflects the influence of individual requirements on TDR motor component design to give indications for most appropriate concepts considering benefits and compromises to be made.

II. The Solid Propellant Throttleable Ducted Rocket – functional Principle

The TDR is a variant of the classical ramjet with the key feature that fuel for the sustain operation is provided by burning a solid rocket type propellant which has an oxygen deficient formulation and produces fuel rich combustion products. These fuel rich primary combustion products are exhausted into the ramcombustor and after burnt with the air provided by the air intakes.

A schematic of the propulsion system is given by Fig. 3.

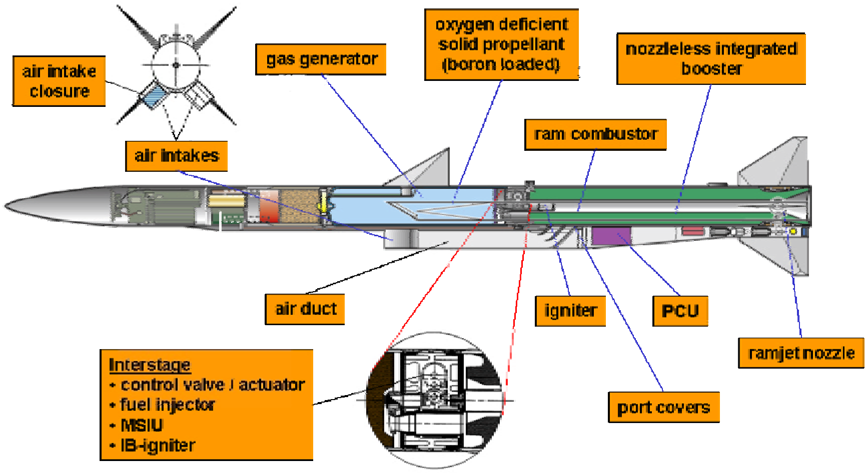


Figure 3: Schematic of the Throttleable Ducted Rocket

This paper deals with systems, where the gas generator propellant has an especially high volumetric heating value due to the incorporation of Boron in the formulation. Due to its high density (2.22 g/cm^3), the volumetric heating value of Boron (131.6 MJ/l) is far above other typical metallic propellant additives and Kerosene (34 MJ/l). The TDR using boron loaded propellants, besides its advantage in performance, allows autoignition of the afterburning and is not sensitive to flameout and combustion instabilities.

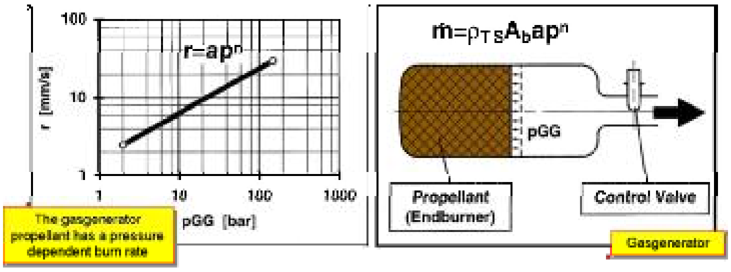


Figure 4: Principle of gasgenerator control

A pressure sensitive burn rate of the propellant together with a valve to control the gas generator pressure allows active thrust variation. The functional principle is shown by Fig. 4. The sustain propellant (called gas generator propellant) typically has a cylindrical endburning configuration featuring a constant burning area (A_b). Outflow of the gas generator is throttled by a control valve to adjust the pressure p_{GG} for burning the propellant. The gas generator propellant needs to be tailored for having a high pressure exponent (n) of the burn rate (r), thus allowing for a high variation of burn rates within a usable pressure bracket, defined by a minimum pressure ratio for outflow into the ramcombustor and a structural pressure limit of the gas generator case.

An additional boost motor is needed to accelerate the missile from launch speed to the takeover speed (minimum operational speed) of the ramjet. In modern systems, a solid rocket motor (integrated booster) is accommodated in the ramcombustor, typically in a case bonded configuration. This boost motor may have a nozzle, which needs to be ejected at the transition from boost to ramjet operation or may feature a nozzleless configuration, if ejecta must be avoided.

Air intakes and air inlet ports into the ramcombustor have to be closed during operation of the integrated booster and need to be opened in very short time during the transition phase to achieve minimum deceleration between the boost and the sustain phase. The intake covers and port covers may be ejected at boost end or retained in the motor depending on the design.

Both gas generator and ramcombustor cases need insulation systems to protect the structure from heat generated by combustion and to minimize thermal flow from the structure to the propellants during storage or captive flight to avoid non uniform or non allowable soak temperatures of the propellants. Long endurance missions pose significant challenges to these insulation systems.

III. Technical Status of the Meteor TDR

Today, the most advanced technical status of the TDR is represented by the propulsion subsystem (PSS) for the Meteor Beyond Visual Range Air to Air Missile (BVRAAM). The European BVRAAM Meteor (for Gripen, Rafale and EF2000 Typhoon) has a diameter of 178mm to allow full compatibility with all AMRAAM launcher interfaces. The technology of the Meteor TRD is based on the results from a series of German national technology programmes, funded by the German MOD :

- within the A3M Programme the general functionality and performance potential of the motor including high altitude ramcombustor operation was demonstrated in experimental HW;

- during the DEM Programme the technology was transferred to near flight weight HW;
- in the EURAAM Programme functional demonstrations were performed with flight weight HW for the first time.

Based on the aforementioned achievements the development of the METEOR PSS first prototype “M1 Standard” started in September 2000 funded by a pre-contract from MBDA. Full contract award was achieved in 2003 after the decision of the six collaborating nations (UK, Fr, Ge, It, Sp, Swe) for Meteor in late 2002.

The Meteor PSS development was subdivided into a staged prototype phase (Fig. 5 shows an M2 development std. Motor) leading to the first flight demonstration in 2006.

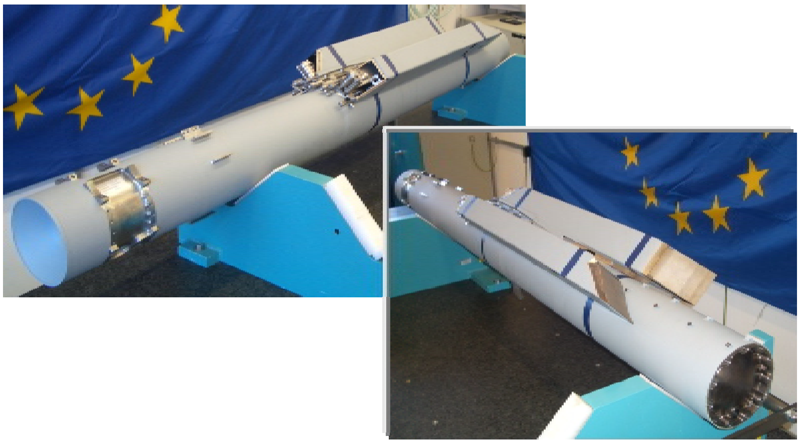


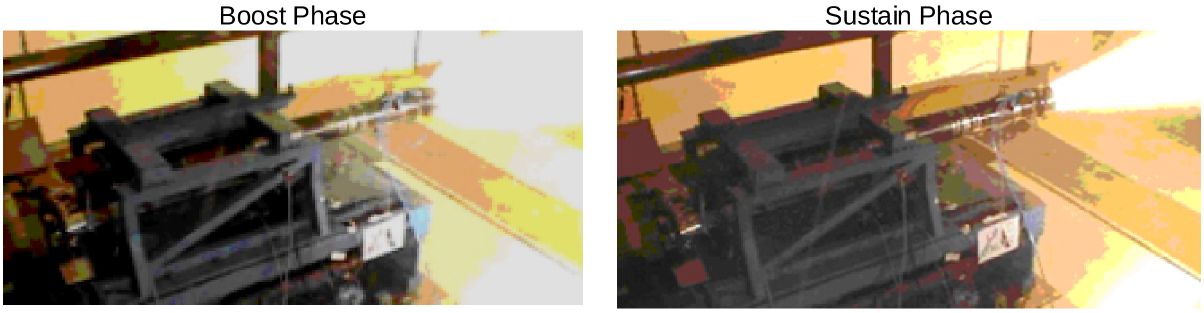
Figure 5: Meteor M2 development standard motor, front and rear view

The motor design incorporates:

- motor case made of high strength stainless steel
- flow formed tubular sections combined (welded) with integral machined sections like front interface, front hanger/umbilical plug section, middle hanger/ramcombustor air-inlet port section, rear hanger section and ramcombustor nozzle/fin actuator section
- a lightweight buttress thread used as center joint between gas generator and ramcombustor/booster cases
- an integrated valve control unit including an electromechanical drive, the inner control loop control electronics and the MSIU (Motor Safety and Ignition Unit). The MSIU is based on the exploding foil igniter (EFI) technique and directly connected to the booster igniter.
- consumable port covers with retaining and opening system
- a C/SiC sustain nozzle with sophisticated sealing, insulation and retaining system

Titanium air intakes and air ducts. The opening system (moving ramp) features a pyrotechnical actuation system

Validation of the Meteor development std. motor in ground tests is finished today. Boost and sustain operation and performance has been proven in numerous tests. Full sequence tests in direct connect (Fig. 6) and Quasi Free Jet (Fig. 7) have shown the safe and reliable functionality of the PSS.



Boost Phase

Sustain Phase

Figure 6: Full operational sequence testing of the Meteor M2 development standard motor in cp test; 2005

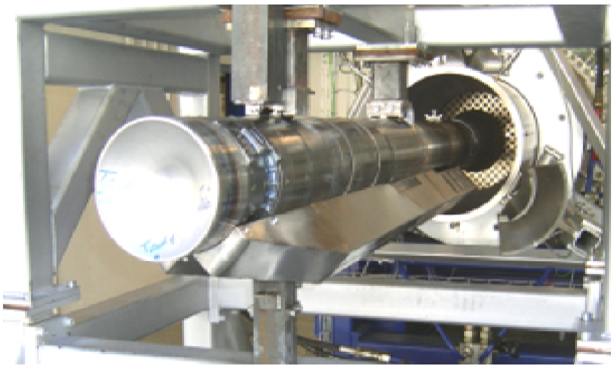


Figure 7: Meteor M2 development standard motor mounted on Quasi Freejet test rig

Prior to flight testing a series of wind tunnel tests in with a fullscale missile at the ONERA facility in Modane demonstrated functionality of the M2 motor at incidence. Figure 8 shows the missile in the windtunnel at Modane.

Figure 8: Meteor M2 development standard motor with forebody mounted in the Modane windtunnel (photo courtesy of MBDA)

Six free flight tests were performed including a high altitude supersonic launch with mission extending over the full projected range. A recent achievement was the first guided firing demonstration, where a manoeuvring target drone was successfully intercepted and after a controlled very close bypass a series of extraordinary manoeuvres going beyond the specifications for the operational missile could be performed without malfunction. Thus, a substantial functional and design margin could be demonstrated .

In the meantime tests with an upgraded PP (pre production) hardware is under way, which is widely representing the later production standard. The PP HW is in quantity production and will be available for testing and verification issues in the third quarter of 2008. Following full qualification(expected by 2010) the series production of the operational missile motor will be started.

A detailed description of the technical development status of the TDR components is also given in [1].
The development history for the TDR technology is outlined in [2] .

IV. General Drivers for the TDR Design

The following aspects have a fundamental influence on the conceptual design of a TDR. Most of the presented arguments are however applicable to alternative rampropulsion systems too. The listed impact parameters will be discussed subsequently to a limited extend :

- Missile architecture
- Missile steering concept and manoeuvring demand
- IDD constraints
- Missile drag coefficient
- Forebody geometry and seeker concept
- Operational envelope requirements (M, H, α, Range)
- Environmental and design load requirements
- Safety and IM requirements

Missile Architecture

With regard to cost and maintenance aspects, a modular missile with separate forebody and propulsion sections (as shown in Fig. 3) is typically the preferred concept for the missile architecture.

However, the unfavourable distortion of side mounted air intakes under severe manoeuvres, as shown by Fig. 9 for the upper leeward air intake, imposes substantial limitations of air intake performance and motor thrust. In addition, the multiple air intake configuration exhibits the risk of subcritical air intake coupling instabilities, which can lead to detrimental reversed flow in individual air intakes, when compromised by manoeuvre induced flow distortions.

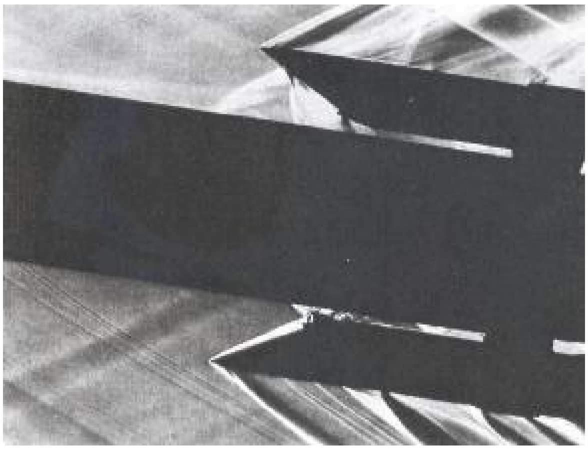


Figure 9: Wind tunnel model with four inverted rectangular air intakes at M= 2.3 manoeuvre conditions [6]

The alternative non modular missile concept with non propulsive and propulsive components being integrated, enables realisation of configurations with a front air intake like Sea Dart, Brahmos / Yakhont or a chin air intake like ASALM. The advantage of such a design is the minimisation of the missile wave drag in combination with superior STT Skid to Turn) manoeuvre capabilities. The potential for drag reduction increases with flight Mach number (Fig. 13, 14 and 15 depict according design concepts).

Fig. 10 gives a comparison of modular and non modular concepts from a German Anti-radiation missile study, where the integrated concept provides superior kinematic performance on the expense of increased interface complexity and potential component interaction.

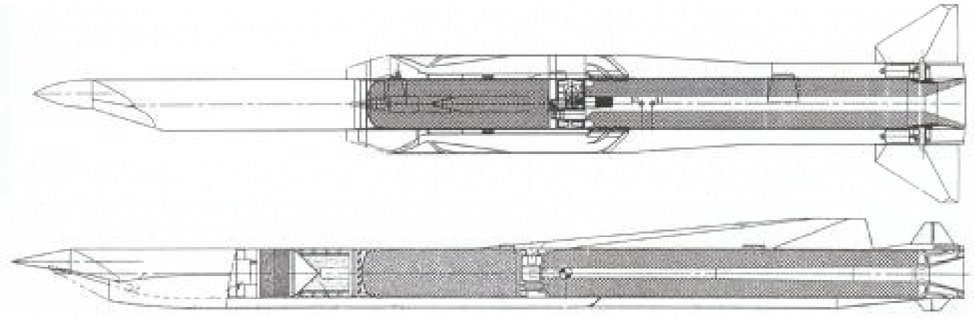


Figure 10: Modular (top) and integrated (bottom) missile configurations

Missile Steering Concept and Manoeuvring Demand

The definition of the steering concept BTT (bank to turn) or STT (skid to turn) is fundamental for the selection of the air intake configuration [3] and integration.

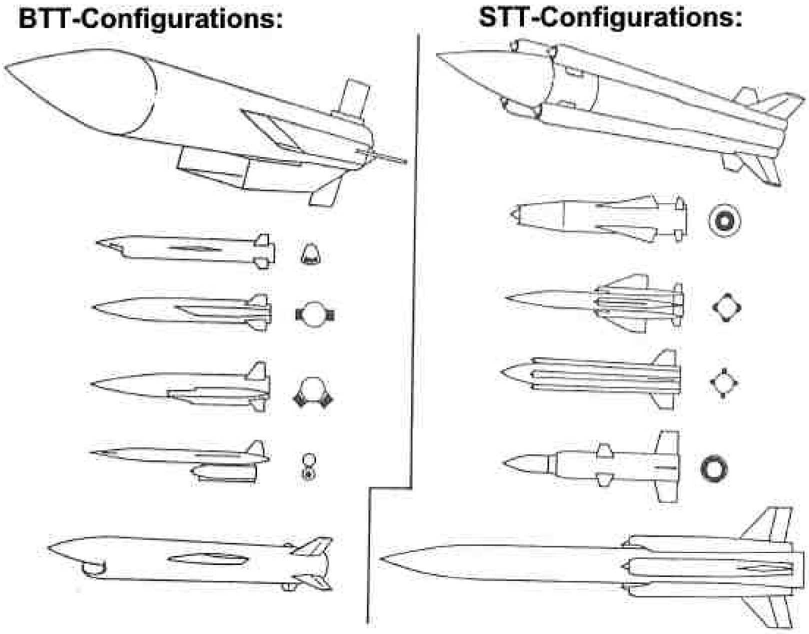


Figure 11: Typical STT and BTT air intake integration concepts

To provide optimum STT manoeuvrability a front air intake arrangement with an integrated (non modular) missile architecture is required, while an alternative four side air intake configuration gives significant limitations in incidence and sideslip. To enable highest possible lateral acceleration during sustain, a BTT missile control is mandatory with any air intake arrangement similar to supersonic fighter aircraft.

Fig.11 depicts typical STT and BTT missile configurations.

Missile Interface Definition Constraints

Restrictions in the external missile dimensions (as imposed by internal weapon bay constraints) can result in a non optimum air intake geometry and integration.

In case of an overall diameter limit combined with a need for a modular architecture, a four side air intake arrangement might be demanded. However with multiple air intake configurations the risk of irreversible flow reversal (caused by flight and / or combustor distortions) and subsequent loss of the missile increases

- with the number of air intakes operating with a common combustor
- and especially with flight Mach number.

Alternatively a configuration with one ventral air intake or two side air intakes with minimized span can be used as illustrated by Figure 12.

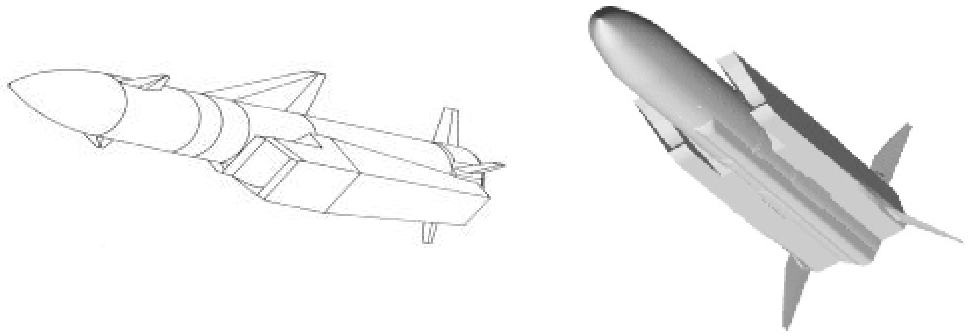


Figure 12: Minimum radial span ventral (left) and side (right) air intake configuration

Missile Drag Coefficient

During stationary sustain, the missile thrust and drag coefficients need to be identical. In contrary to a rocket motor the fuel consumption of a TDR increases with drag in a two fold manner :

- the higher thrust demand requires a higher fuel to air ratio, while
- the specific impulse of rampropulsion systems decreases with the reduced air excess at the same time.

In addition, the higher combustor temperature asks for an increased heat shield thickness and provides a less favourable exhaust plume signature.

A significant drag increment can be caused by bulky missile hangers. Thus, ground based box launched systems without hangers have a substantial sustain performance advantage.

The optimisation of the ramcombustor concept is significantly influenced by the demanded average thrust coefficient. While a high thrust demand with a near stoichiometric combustion asks for optimum mixing of the complete air flow with the propellant in the ramcombustor dome regime, a low drag configuration with high amount of excess air is best suited for a staged air injection design. Here, the excess air should be injected downstream from a stoichiometric primary combustion zone. Dimensioning of the combustor segments and air mixing configurations need careful optimization for combustion performance and avoidance of highly non uniform thermal loading of the ramcombustor heat shield.

Forebody Geometry and Seeker Concept

The forebody shape influences missile drag and air intake distortions. An acceptable compromise between system drag, forebody volume, seeker demands and air intake performance asks for an integrated missile motor lay out to generate an optimum overall missile design.

In case of an infrared seeker, a non modular chin air intake missile configuration can provide a superior missile performance, if the significantly inclined seeker window forms part of the air intake compression surface well within the capture stream tube and thus without generation of missile external wave drag.

Fig. 13 shows a corresponding BC air intake concept which was tested in the wind tunnel of the DLR Cologne.

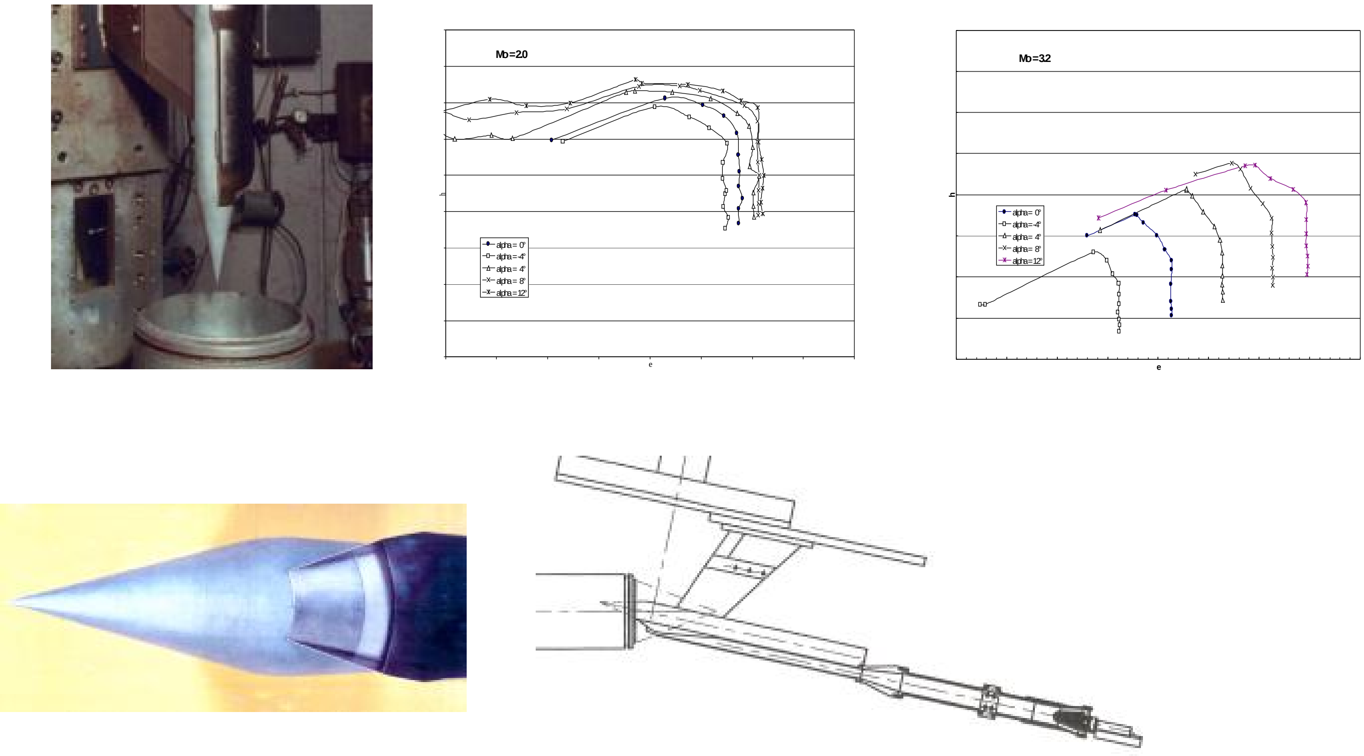


Figure 13: Chin air intake providing most efficient multi purpose seeker integration; wind tunnel testing setup and model and performance results

Operational Envelope Requirements (M, H, a, Range)

The flight Mach number envelope is a key design driver for the air intake supersonic compression system geometry, but it also defines the structural material and mass due to the imposed pressure and temperature loads. The ramcombustor heat shield concept restricts the flight Mach number by limited allowable kinetic heating to ensure the integrity of an ablative heat shield. An embedded heat shield retention system could be used to prevent catastrophic debonding of the heat shield from the pressure vessel. A radiation heat shield is needed in the gas generator to prevent coning of the end burning gas generator grain during extended kinetic heating missions.

The TDR gas generator grain configuration the desired burn rate and mass flow control characteristics are mainly dependent on

- the operational Mach number and flight altitude envelope and
- the excess thrust / acceleration requirements.

The air intake design is also significantly affected by the incidence and in case of STT control also by the sideslip envelopes.

In case of extraordinary range requirements, a minimum drag front intake design might be demanded, especially in case of a high flight Mach number (above 3.5), where the subsonic air duct requires a small part of the missile cross section [4, 5]. Here, a special concept was developed by Bayern-Chemie, which allows closing of the air intake during storage, air carriage if applicable and the boost phase. Fig. 14 shows the concept featuring a translation of the intake cone from closed to partially open and fully open position

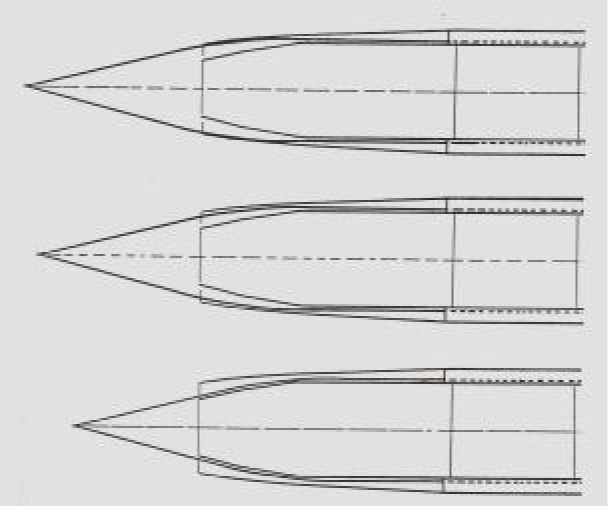


Figure 14 : Mach 5+ air intake, center body translation for start of mixed supersonic compression and opening of capture area.

During wind tunnel tests with rapid translation of the centre body cone the automatic starting of the internal supersonic compression shock system could be verified.

Figure 15 shows a proposed high flight Mach number missile front section with a gas generator integrated into the air duct centre body of a closeable high performance mixed compression air intake.

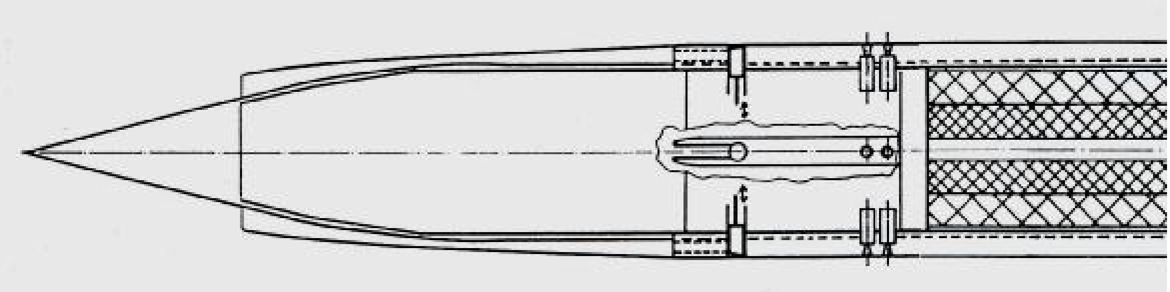


Figure 15: High Mach number minimum drag missile front section with closeable mixed compression air intake

Environmental and Design Load Requirements

A wide environmental temperature bracket (storage, air carriage) can reduce the web thickness and the volumetric loading of the integrated booster, especially in case of nozzleless grain configurations. A high temperature exposure aggravates the propellant ageing process and might ask for extraordinary good mechanical properties of the propellants. In addition, the extent for the insulation of critical electronic components needs to be increased.

EMC requirements define the amount of shielding and the volumetric demand for the integration of cables and connectors, which can be significant and needs to be sufficiently taken into account in early programme concept phases.

Storage, handling and life requirements can impose significant sealing problems.

The structural design and the motor mass is impacted by the design load requirements; especially missile air carriage and launch loads together with fixed interfaces can result in complex local structural enhancement problems.

Safety and IM Requirements

Safety requirements can provide a limitation on the web thickness of nozzleless booster grains.

Prohibition of ejecta asks for a nozzleless integrated booster and consumable port covers in combination with non ejectable air intake closures.

To fulfil the requirement for a moderate FCO response, a special mitigation device, and in addition local extra insulation of critical motor regimes may be necessary.

The configuration of a TDR motor with two separate pressure chambers tends to aggravate the accomplishment of the IM requirements.

V. Design Tailoring of Throttleable Ducted Rocket Propulsion Systems for Different Missile Applications

The aforementioned drivers for the TDR design will be illustrated for some typical missions, which could highly benefit from TDR propulsion.

Supersonic Ground to Air

An air defence variant could be easily derived from a BVRAAM missile like Meteor. Such a derivative could feature both performance improvement and design simplification (cost reduction). With a design for container launch, the hangers for aircraft carriage could be eliminated leading to a substantial reduction of the missile drag. This would give an over proportional range improvement due to lower thrust demand and a shift of the TDR operation into fuel lean regimes with enhanced specific impulse.

The integrated booster of a BVRAAM is sized for minimum launch speed of the aircraft and therefore, for ground launch, a relatively simple tandem boost motor would be needed (Fig. 16). A tandem booster with a moderate thrust level combined with a substantial burn time would lead to a 1st stage burnout at appr. M 1.6 in 3500 m altitude. Subsequent operation of the integral booster would result in transition at M > 2.5 in > 4000 m of altitude, enabling ample acceleration capability of the TDR. The tandem booster for a BVRAAM (diam. . ~ 178 mm) as shown in Fig. 17 has a diam. ~ 330 mm and a length ~ 1.1 m including adapter / conical section (about 25°).

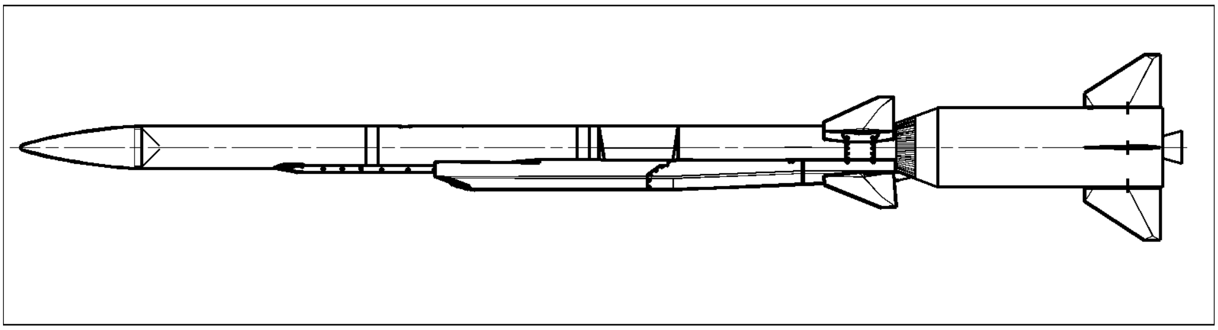


Figure 16: BVRAAM based high performance Ground to Air missile

Long Range hypersonic Ground to Air

In case of very long range time critical air defence missions (including ballistic missiles) the kinetic heating restrictions with the associated low level acceleration limits and the corresponding time to target characteristics of an upgraded BVRAAM according to Fig. 16 might be not adequate. A more suitable concept is shown below. It incorporates a non modular missile configuration together with a tandem booster for launch.

To cope with minimum propellant consumption required for long range, a minimum drag configuration combined with excellent total pressure recovery is needed. This can be achieved by the use of a closeable mixed compression front air intake [4]. Such geometries (see Fig. 14) were successfully tested and discussed in [5]. Due to the extraordinary low drag a sustain range of over 160 km might be realised with a TDR propellant mass corresponding to less than 7% of the launch mass. The velocity of the missile, depicted in Figure 17 is mainly restricted by the impact of the kinetic heating on the metal structures and the ramcombustor heat shield.

In case of highest kinematic requirements, a ceramic motor structure can be used, to overcome kinetic heating limitations. In spite of the necessary larger pressure vessel case thickness, the smaller material density and the omission of bulky insulations would provide significant advantages in mass and volume.

To provide the required manoeuvrability at high altitude, a powerful side thrust rocket module using a gel propellant is integrated into the centre body which also houses the gas generator. Thus a complex high temperature fin actuation system can be avoided. In addition, the side thrust control is more effective at high intercept altitudes.

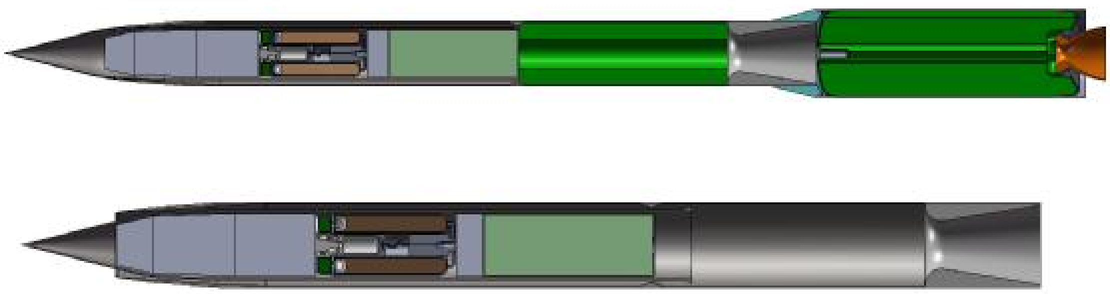


Figure 17: Highest performance Ground to Air missile configuration (top: launch configuration with closed air intake; bottom: sustain configuration with open air intake)

Anti Ship Missile

In comparison to the present BVRAAM a larger payload (warhead and seeker) and a longer range at SL will be required. The resulting missile calibre and TRD design is dependent on the intended mission task.

In case of a small scale anti-ship missile an up scaling of the BVRAAM motor might be sufficient. With growing ramcombustor diameter and reduced chamber L/D the single control valve and blast pipe design however needs to be replaced by a double blast pipe configuration, to enhance the mixing process, as discussed in [1].

Large scale anti ship missiles can demand TDR ramcombustors with low and less favourable L/D ratios. Here a multiple air intake and port geometry might be more beneficial for a good mixing / combustion efficiency [1] and would avoid detrimental structural design problems caused by large port cross sections. A configuration with four inverted rectangular (or axisymmetric) air intakes could be considered. A corresponding integration concept was tested in the wind tunnel and later on in boost and coast supersonic free flight under contract of the German BWB.
The symmetrical side air intake configuration might also be required by the low level flight steering concept, especially when severe weaving manoeuvres are needed for the end game to defeat target defence.
The extensive BC experience regarding TDR configurations for anti ship missiles is reported in [2].

In case of a new anti ship missile development the air intake configuration could be easily scaled from the multiple tested designs [3] to cope with larger calibres, the detailed air intake integration, the air injection port configuration and the motor control valve however would need to be optimized with respect to the ramcombustor geometry as outlined in [1].

Air Launched Multi Purpose Weapon

A multi purpose weapon might be designed such, that it could be used against different targets on the ground like vehicles, buildings or air defence radars. An additional option might be a mission against stand off jammers.

Furthermore, the missile could be used against smaller ships. Based on the selected mission scenarios a best compromise for the required payload and missile steering concept has to be defined in order to derive the appropriate motor calibre and air intake arrangement concept. A multi purpose missile could also use different forebodies together with the same motor. This excludes the use of front or chin air intakes.

The BVRAAM type air intake configuration would be well suited for this application, unless a need for rapid and severe STT manoeuvring is induced by the mission. In this case, a symmetrical four air intake arrangement would have to be selected. A careful trade off needs to be done between performance advantages at sideslip conditions and the risk of coupling instabilities (resulting in stable backflow conditions in the worst case).

Several remarks provided for the aforementioned anti ship missile TDR design drivers might be applicable. However, a further constraint might arise from volumetric restrictions imposed by the geometry of an internal weapon bay. Here, the air intake arrangement need to be defined, to cope with the volumetric limitations. An according configuration is depicted in Fig. 18.

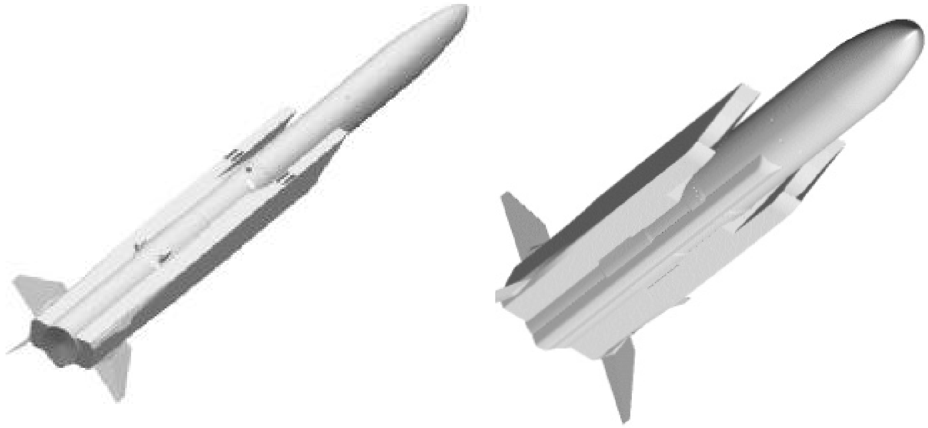


Figure 18: Possible Configuration for an air launched multi purpose TDR propulsion system with restricted air intake dimensions

VI. Summary

The technology for Variable Flow Ducted Rockets was funded in Germany by the MoD for several decades and culminated in the development of the propulsion system for the METEOR medium-to-long-range air-to-air missile. Following extensive ground testing the development standard motor was successfully demonstrated in a series of flight tests including supersonic launch and long range missions including manoeuvres beyond the specifications of the operational missile. Verification of the pre-production standard motor will be started in 2008.

Based on the achievements the technology is ready for new missile applications with minimum development risk. This technology enables significant superiority over existing systems with respect to kinematic performance and mission flexibility.

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