

# History of Ducted Rocket Development at Bayern-Chemie

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**[Abstract] After a very short introduction into the history and the business perimeter of Bayern-Chemie, the paper gives an overview of the development of ducted rocket technology at Bayern-Chemie in Germany during more than 30 years. The paper covers main phases of technology development and highlights important achievements. The paper concentrates on hardware design concepts, selected examples of test results and major technical milestones. Based on the advanced state of technology, a contract was awarded to Bayern-Chemie in 2000 for the development and production of the integrated throttleable ducted rocket motor for the European beyond visual range air to air missile Meteor. This propulsion system provides kinematic superiority of Meteor over all existing aircraft weapons and enables continuous optimization of the intercept trajectory by active thrust control. The paper provides a concept overview and a short status of the development of the Meteor propulsion system [1, 2, 3, 4]. The part of the paper dedicated to Meteor will be restricted to unclassified information.**

## Nomenclature

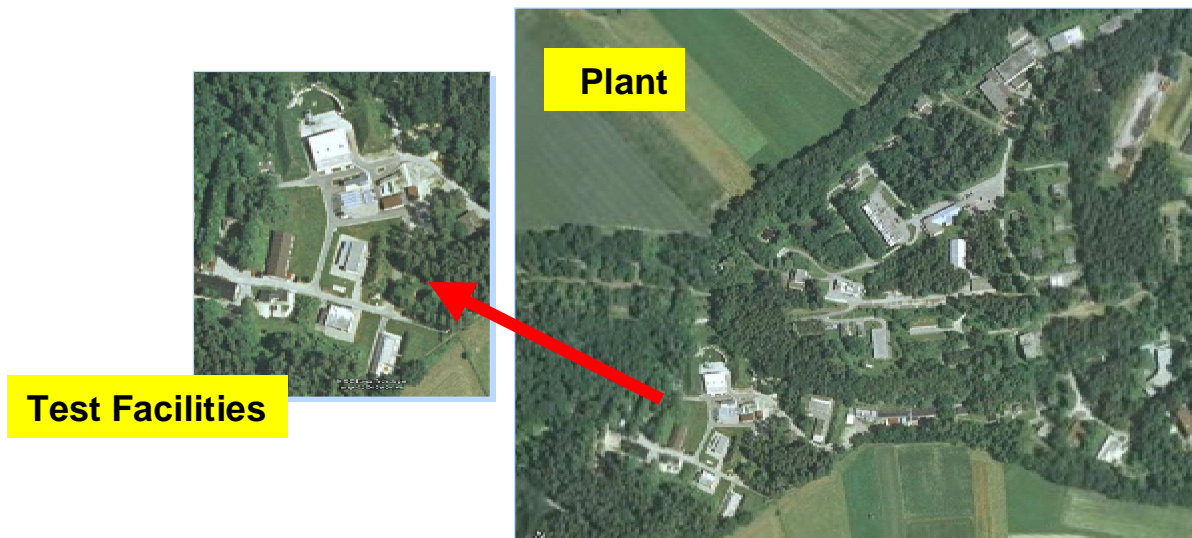
$A_b$	=	burning area)
$a$	=	constant in burning rate law
$D$	=	diameter (calibre)
$M$	=	Mach number
$n$	=	pressure exponent of burning rate law
$p_{GG}$	=	gasgenerator pressure
$r$	=	burning rate
$r_{TS}$	=	density of propellant

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## I. Introduction

Bayern-Chemie is a small company located at Aschau am Inn, approximately 60 km East of Munich in Bavaria/Germany. Bayern-Chemie is mainly engaged in propulsion for tactical missiles, which includes rocket motors with solid and gelled propellants as well as airbreathing ducted rockets and gas generators. Bayern-Chemie is expert in high performance cast Composite (HTPB, GAP ...) and extruded Double Base solid propellants. Fig. 1 shows an Google Earth view of the plant, which is spread out in the woods with many buildings due to the safety distances needed for the work with explosive material.



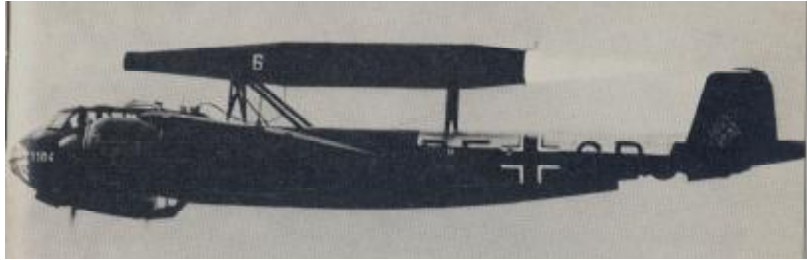
**Figure 1: Bayern-Chemie plant at Aschau am Inn/Germany**

Bayern-Chemie was founded in 1969 by merging the propellant activities of WASAG-Chemie AG and the propulsion activities of MBB (Messerschmitt-Bölkow-Blohm). In 1981, the shares of WASAG were taken over by MBB. Bayern-Chemie stayed a 100% subsidiary of MBB (MBB transforming into Deutsche Aerospace/DASA, DaimlerChrysler Aerospace and finally EADS by shareholder changes) until 1994. In 1994, Bayern-Chemie was merged with the propulsion activities of the French Thomson-Brandt Armaments. The new joint venture company Bayern-Chemie/Protac was owned by EADS and Thales (France) at equal shares. In 2007 Bayern-Chemie shares were taken over by MBDA Missile Systems and its subsidiary Protac was sold to the UK-French ROXEL propulsion company for consolidation of the French scenario in tactical propulsion.

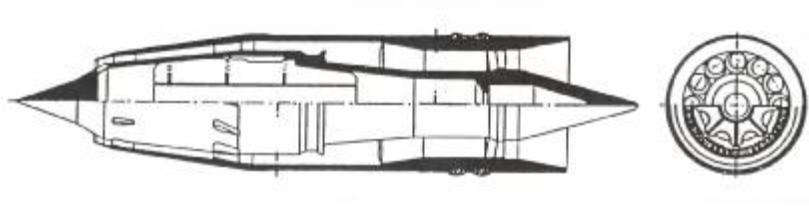
Highlights in Bayern-Chemie's activities were

- invention and development of the automotive airbag gas generator (this business was separated from Bayern-Chemie in 1992 into a new company owned by TRW today)
- Flight demonstration of a Ducted Rocket with Boron gasgenerator propellant
- licence production of the Patriot (PAC 2) rocket motor (Composite propellant)
- development and production of the boost/sustain rocket motor for the UK ALARM missile (Double Base propellant)
- development and production of the rocket motor (Composite propellant) for the VT1 M02 air defence missile made by Thales Air Defence (TADL UK) together with Protac
- development of a rocket motor for flight demonstration of a hypersonic missile reaching Mach 7 in ground level flight
- and last but not least the development of the Throttleable Ducted Rocket Motor for the European beyond visual range air to air missile Meteor

Airbreathing missile propulsion has been a core engagement of Bayern-Chemie together with its shareholders since the beginning. Roots of some early key staff go back to German ramjet activities in WW2 like the ‘Ofenrohr’ tested by Prof. Eugen Sänger on a Dornier 217 aircraft (Fig.2) and the work of Dr. Wolf Trommsdorff on ramjet propelled shells (Fig. 3).



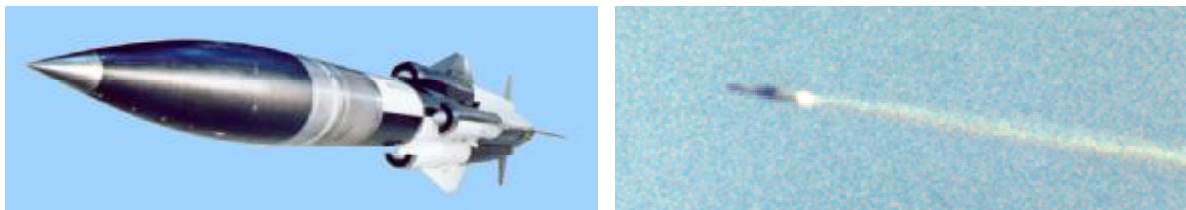
**Figure 2: ‘Ofenrohr’ ramjet mounted on top of a Do 217 [5]**



**Figure 3: ‘Trommsdorff’ ramjet propelled shell [6]**

Throttleable Ducted Rocket (TDR) technology with high energy Boron sustain propellant, being the topic of this paper, was built up at Bayern-Chemie since the 1960’s by continuous R&D funding by the German MoD and engaged industry as well as by several key feasibility and demonstration programmes. Important milestones were

- first flight demonstration in 1981 - EFA-Demonstrator, (Fig. 4),
- redevelopment of a TDR for an anti ship missile (ANS) in 1981 – 1987)
- German feasibility program for an advanced air to air missile (A3M, EURAAM) in 1995 – 1999
- selection of the TDR with Boron sustain propellant as propulsion system for Meteor in 2002
- successful flight tests of the Meteor prototype missile since 2006



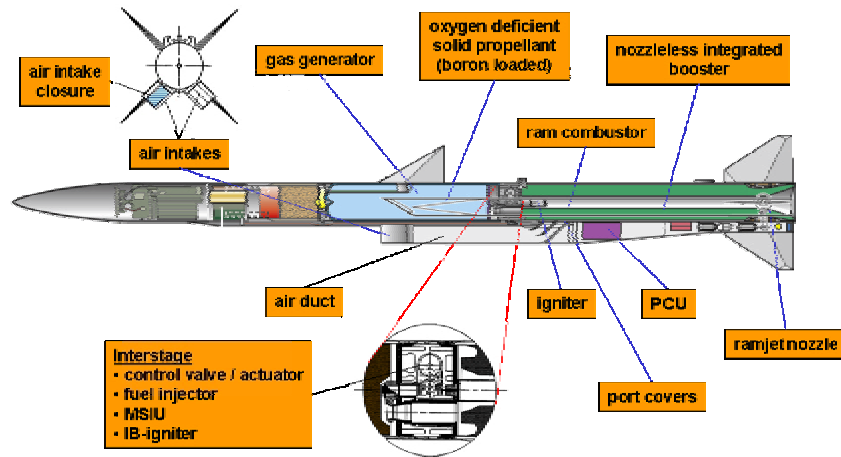
**Figure 4: EFA-Demonstrator missile and test flight**

## **II. Functional Principle of the Throttleable Ducted Rocket**

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.

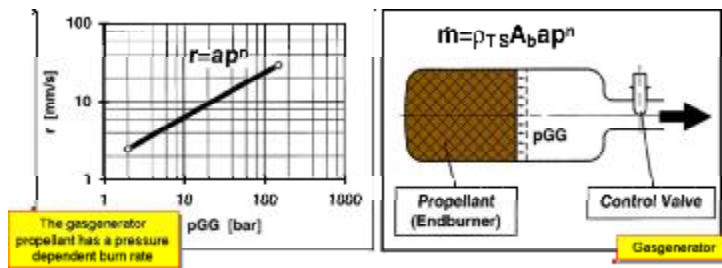
A schematic of the propulsion system is given by Figure 5.



**Figure 5: 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 ( $2.22 \text{ g/cm}^3$ ), the volumetric heating value of Boron ( $131.6 \text{ MJ/l}$ ) is far above other typical metallic propellant additives and Kerosene ( $34 \text{ MJ/l}$ ). 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.

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 Figure . The sustain propellant (called gasgenerator propellant) typically has a cylindrical endburning configuration featuring a constant burning area ( $A_b$ ). Outflow of the gasgenerator is throttled by a control valve to adjust the pressure  $p_{GG}$  for burning the propellant. The gasgenerator 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 gasgenerator case.



**Figure 6: Principle of gasgenerator control**

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 gasgenerator 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.

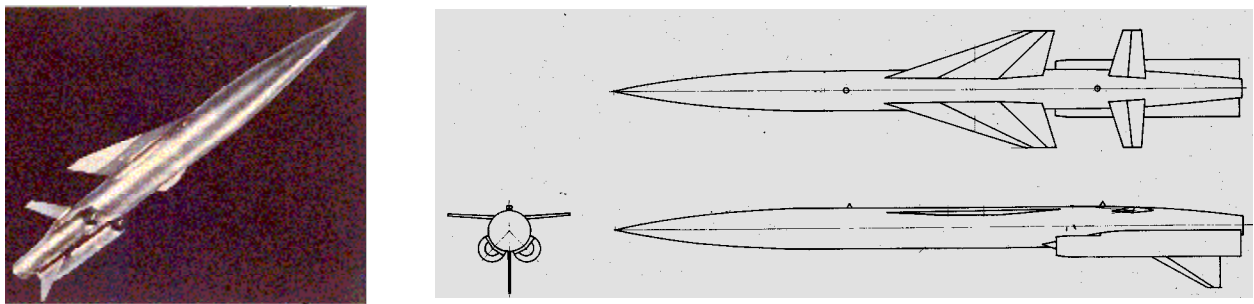
### III. Early development of Ducted Rocket Technology

First investigation of ducted rocket propulsion at MBB (Messerschmitt Bölkow Blohm GmbH) started in 1962, were funded by the German MoD. Associated gasgenerator propellant development at BC (Bayern-Chemie GmbH) began in 1964. Development of high energy boron loaded gas generator propellants for fixed flow ducted rockets started in 1970.

During the first two decades of DR technological and pre-development activities the investigations were focussed on anti-ship missile applications (HYDRA, FK80, ASSM, ANL, ANS).

#### HYDRA

A first propulsion concept was designed for the HYDRA missile. This is shown by Fig. 7.



**Figure 7: HYDRA missile concept**

A fixed flow gas generator was integrated into the body of the winged BTT (bank to turn) missile. It was to provide sustain fuel flow for two separate circular ramjet motors arranged in lateral pods at the missile rear end under + 45° smile angle. The ramjet motors were fed by half axisymmetric air intakes operating in the wing pre-compression flow field. Initial acceleration would have been provided by separate ejectable side boost motors. Within the HYDRA programme combustion tests with boron loaded gas generator propellants were started.

Tests of a full scale HYDRA engine pod a wind tunnel of the DLR Cologne (Fig. 8) demonstrated outstanding combustion stability of the new boron fuelled DR when due to test stand control problems, the free jet air mass flow was periodically throttled, between Mach 2 down to about Mach 0.2. Even when this resulted in a periodical switch between internal ramcombustion and external combustion no flame out could be provoked.



**Figure 8: Windtunnel testing of a HYDRA fullscale engine pod**

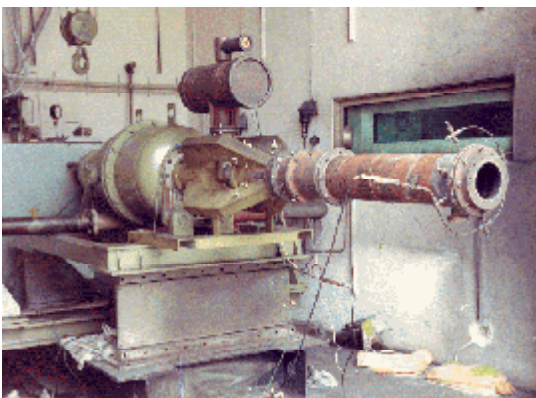
### **FK80 and ASSM**

FK80 was the first in a series of studies started in 1973 to look at STT (skid to turn) anti-ship missile concepts (diam. 350 mm) with four lateral air intakes connected to a central ramcombustor. In this fully integrated rocket/ramjet concept the ramcombustor was designed to house an integral boost motor. The NATO ASSM (Anti Ship Supersonic Missile) was the follow on programme starting in 1975. Requirements added here for high altitude flight and seaskim cruise at varying speed led to the need for throttleability of the ducted rocket motor.

The technology of boron loaded gas generator propellants was pushed forward during this period addressing

- manufacturing process
- pressure sensitive burn rate
- control valve concepts
- pressure
- afterburning characteristics in the ramcombustor

Testing was performed in the cp mode. Early tests used a subscale experimental motor (diam. 160 mm) with a gasgenerator (allowing a double endburner configuration) mounted on top of a bent feeding pipe to the ramcombustor (Fig. 9).



**Figure 9: Experimental Ducted Rocket test motor (diam. 160 mm), 1973**

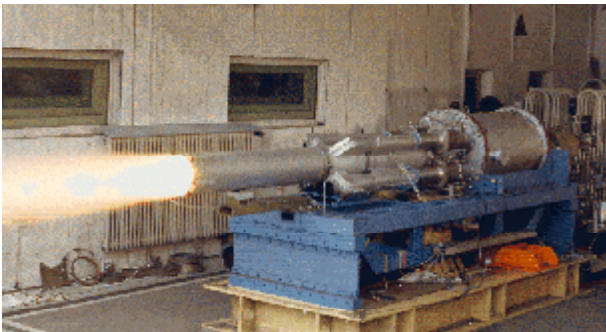
Later on, a half scale experimental motor (diam. 240 mm, Fig.10) as well as a full scale motor was used for connected pipe performance verification.



**Figure 10: Experimental ducted rocket test motor (diam 240 mm), 1975**

During this phase, major progress was achieved towards efficient burning of Boron particles. Propellant additives were found to mitigate the effect of a Boron oxide layer preventing complete particle combustion. Additionally, a longitudinally staged air injection into the ramcombustor prevented quenching of Boron particle combustion at low ramcombustor temperatures under fuel lean operating conditions (typical for cruise flight). This configuration provided a primary combustion zone with high temperature and nearly stoichiometric mixing ratio and reduced Mach number and a secondary zone for mixing with the residual air.

Also in this period, a first a lightweight motor (diam. 240mm) with axisymmetric air intakes was designed and tested in semi free jet mode where our circular Laval nozzles supplied air to the intakes of the motor (Fig. 11)



**Figure 11: Flightweight motor study (diam. 240mm), semi freejet test; 1976**

### **EFA**

In the final phase of the ASSM program in 1979, it was decided to demonstrate the boron fuelled ducted rocket in free flight. The EFA (Experimental Feststau Antrieb, i.e. experimental ducted rocket) missile was a half scale model (with respect to the reference cross section) of the anti-ship missiles (Fig. 4). The motor featured four half axisymmetric air intakes especially designed for full stability (no buzz) down to zero mass flow.

Due to budgetary limitations, a fixed flow ducted rocket concept was selected together with a tandem booster for acceleration from ground-launch up to Mach >2 staging velocity. Honest John boosters discarded by the German Army could be used. Fig. 12.shows the launch configuration.



**Figure 12: : EFA launch configuration**

Some key data of the EFA Ducted Rocket motor are given below:

- diam. 242mm
- propulsion length 2302mm
- propulsion mass 129kg
- gasgenerator mass 24kg
- sustain burn time ~ 25s
- range ~ 19km
- velocity regime, M 1.9 – 2.3

Development of the flight hardware was performed within two years only and culminated in ground validation of the motor in cp and semi freejet tests (Fig. 13)



**Figure 13: : EFA cp ground test**

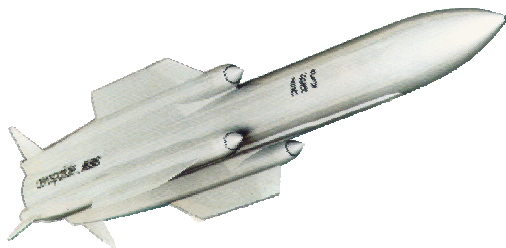
Two test flights were performed in Sardegna in 1981 (Fig. 14). In both cases the staging process was compromised such, that the initial lateral acceleration did exceed the specified limits by a factor of about 5. With the given four intake STT configuration, the air intake being in most unfavourable position went to back flow operation with flames exhausted at over Mach 2 flight conditions. Only due to the inherent stability characteristics of the special half axisymmetric air intakes, the respective air intake could be restarted immediately as the incidence decreased. Thus, the stable and reliable function of the boron loaded ducted rocket could be demonstrated even under extreme lateral acceleration.



**Figure 14: : EFA test flight, 1981**

#### **IV. Predevelopment of a TDR motor for ANS**

When ASSM was discarded as a NATO program in the early 1980's, a new French-German program was established for the anti ship mission named ANS (Anti Navire Supersonique). One major difference between the ASSM and ANS propulsion system (Fig. 15) was the application of axis symmetric air intakes.



**Figure 15: ANS Anti Ship Missile**

Significant progress was achieved in the ANS program for the functionality and performance of the TDR.

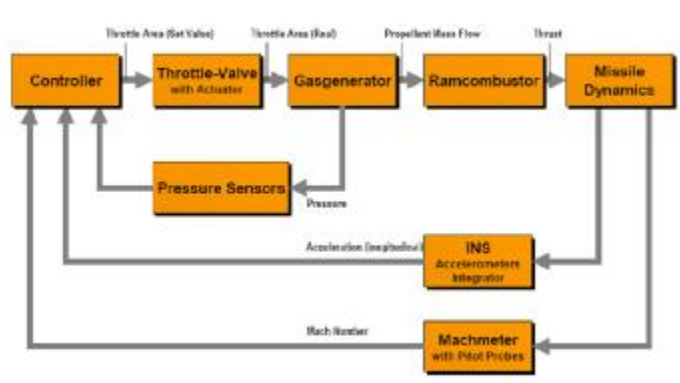
The formulation of the Boron sustain propellant was improved to allow a turndown ratio of about 4:1 in a gasgenerator pressure range from less than 4 bar to 100 bar. In the minimum mass flow regime at fully open control valve, applicable to high altitude flight, the gasgenerator was no more decoupled from the ramcombustor by a critical pressure ratio.

An improved control valve concept was developed, where two rotary sliders throttle two blast pipe inlets each. The concept is shown in Fig.16. The the circular control edges of the slider have a nozzle contour. This control valve featured a low actuation power demand and minimized susceptibility to depositing.



**Figure 16 : ANS gasgenerator control valve**

To control the motor thrust, a cascade control algorithm (Fig. 17) was developed and verified. Here, the first level control parameter is the Mach number. Based on comparison of the value demanded by the missile and the measured value, an increase or decrease of thrust is demanded to accelerate or to decelerate. In the second level, the gasgenerator pressure is controlled such that fuel flow variation leads to the required thrust response to achieve the demanded Mach number. This logic avoids the need for determination of the gasgenerator outflow which is difficult to achieve with reasonable accuracy with Boron gasgenerator propellants due to the high solids loading of the multiphase flow.



**Figure 17: Schematic of thrust control algorithm**

The flight regime of ANS induced a wide range of mixture ratios for the ramcombustor between nearly stoichiometric and fuel lean conditions. A comprehensive parametric ramcombustor investigation was carried out to optimize

- length ratio (approximately 1:2) between primary and secondary combustion zone
- split of primary and secondary airflow
- air injection port geometry
- fuel injection position (four blast pipes in X position according to the air intakes) and blast pipe geometry

With the optimized ramcombustor geometry a ramcombustor temperature rise efficiency of over 90% could be demonstrated.

Additional technical progress was achieved in the ANS predevelopment program with regard to:

- design of flight weight structures
- frangible glass port covers destroyed at boost sustain transition by pyrotechnic action
- pre-development of a nozzleed integral booster with extraordinary high degree of propellant loading due to a keyhole configuration
- verification of an ejectable booster nozzle
- an improved heat shield (filled silicone rubber with local char retention device) capable to withstand the full cruise flight trajectory of up to 2 minutes
- a ceramic ramjet nozzle, capable to withstand the extraordinary high heat flux from the boron combustion.



**Figure 18: Testing of the TDR motor for ANS, left cp test, right semi freejet test; 1987**

The ANS motor was ground demonstrated in lightweight hardware in cp tests simulating full sea skim and low-high low trajectories as well as in semi freejet with the boost and transition sequence .Fig. 18 shows a cp test of the sustain motor and the setup for the semi freejet test of the full IRR with the integrated booster.

## V. TDR Technology for Air to Air Application

After the cancellation of the ANS program, emphasis in Germany for the application of the TDR changed to Air to Air missiles with much smaller calibre. Some technology programs and feasibility studies paved the way to the propulsion system of the European beyond visual range missile Meteor.

### AMPT

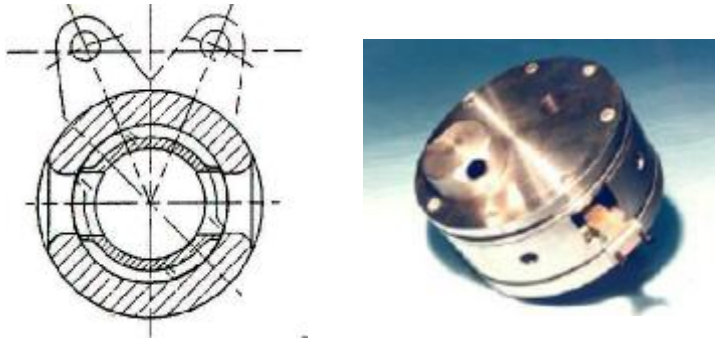
The joint German-US AMPT (Advanced Missile Propulsion Technology) program (1989 – 1994) aimed at progressing component technology of a Boron fuelled TDR for a future medium range air to air missile application. This program was performed in collaboration between Bayern-Chemie and Atlantic Research Co. (today Aerojet).

This new application induced significant challenges with regard to

- need for substantial increase of fuel flow variation capability to cover flight in a wide Mach number/altitude regime
- control valve and blast tube concept for a small motor calibre
- ramcombustor efficiency in a small diameter of 180mm and with an asymmetrical configuration with the air intakes arranged within the lower quadrant of the missile fuselage to allow for semi submerged air carriage
- concepts for ejecta free transition (nozzleless booster, port covers)

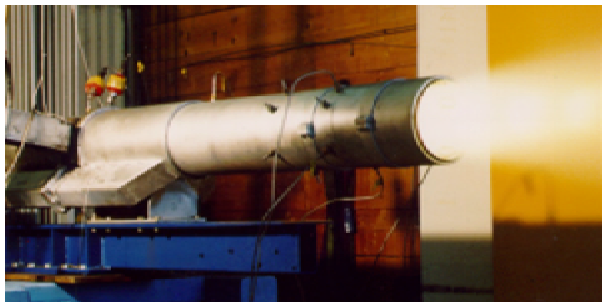
A broad parametric study on the sustain propellant was carried out with more than 15 different formulations to achieve at a pressure exponent of 0.55 and satisfactory burning characteristics at low and high pressure. A sustain propellant mass flow turn down ratio of 7 : 1 could be demonstrated.

A new control valve concept was developed to fit into the small diameter and to allow for fuel gas injection favourable for afterburning in the asymmetrical ramcombustor geometry. A single blast tube placed eccentrically in the lower section ramcombustor front end between the air injection ports proved to be an optimum solution. On the gasgenerator side, the blast tube had two inlets in perpendicular position. A fixed sleeve with two nozzle shaped ports covered the blast tube front end. Throttling of the gasgenerator throat was achieved by turning the blast tube and changing the angular position of the blast tube ports relative to the sleeve ports. The concept is shown by Fig.19.



**Figure 19: Control valve concept for small motor calibre**

Optimization of ramcombustion was another key issue. An experimental motor allowing to vary the shape of the air injection ports, the air injection angle and the longitudinal position of the air injection was used for this task (Fig.20).



**Figure 20: AMPT experimental motor (diam. 180mm); 1990**

The AMPT program was concluded by a conceptual design for a flightweight motor and performance demonstration in experimental hardware.

### **A3M / DEM / EURAAM**

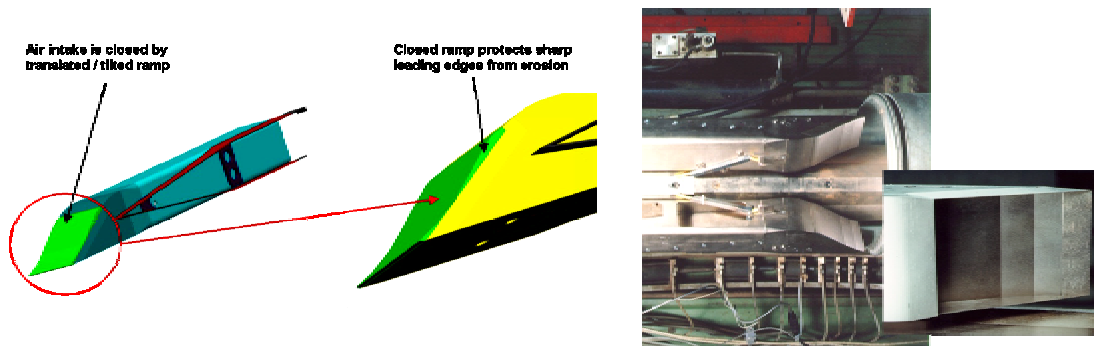
Between 1995 and 1999 a series of German MoD funded TDR Technology and Pre-development programs was carried out as a feasibility proof for a full scale development of a future medium to long range air to air missile:

- A3M (advanced technology programme mainly in experimental hardware, functional testing)
- DEM (transfer of technology from experimental to light weight hardware)
- EURAAM (transfer from light weight to flight weight hardware)

These programs were looking at system aspects and various components of a missile, but the TDR work was clearly the core topic.

The motor concept for the 180mm missile, like AMPT, featured an asymmetrical geometry with two lateral air intakes positioned in the lower quadrant of the fuselage. AMRAAM launcher compatibility requirement induced the shape and position of the three hangers and a umbilical plug and cable duct to be incorporated in the gasgenerator case. The design concept also featured a nozzleless integrated booster and ejecta free air intake covers and port covers.

Major progress was achieved for the air intakes. A rectangular multi shock compression air intake was defined to provide both, optimum performance over a wide flight Mach number regime between 2 and 3.5 and aerodynamic lift in BTT operation. Already within the first programme phase (under the designation A3M) an air intake with closable capture area was designed and tested in the vertical wind tunnel of the DLR Cologne. At launch, the intake ramp is positioned upwards closing the air intake and protecting the sharp leading edges. At transition, the ramp is unlocked and retracted into its operational position by a combined translating and turning motion, actuated by springs and a gear. Fig.21 shows the design principle and the fullscale windtunnel model in closed and open configuration.



**Figure 21: Air intake closure – functional principle and fullscale windtunnel model in closed and open configuration**

The sustainer propellant formulation was further improved with regard to burn rate characteristics. Now, a mass flow turn down ratio in excess of 10:1 within a pressure bracket between 1 and 100 bar (at constant soak temperature) could be achieved. The formulation incorporates about 35% of Boron and features a volumetric heating value of about 51MJ/l.

A new class of smoke reduced (class BC, STANAG 6016) HTPB composite propellants was tailored to the needs of the application for a nozzleless booster. These propellants have to combine a very high burn rate (>35mm/s) with a low burn rate pressure exponent. High strain capability is needed for the propellant to cope with the high mechanical loads induced to the tubular grain during cooldown. The achievement of good mechanical properties is especially challenging for high burn rate propellants. The first boosters, tested in experimental hardware demonstrated a specific impulse well above 2000 m/s at SL conditions. A rapid tail off verified most favourable sliver characteristics.

Bonding the booster to the ramcombustor insulation was another development challenge. The application of the silicon rubber RC-insulation was changed from the earlier spin wrapping process to pump casting with a mandrel to achieve precise and reproducible wall thickness. A migration barrier and a thin layer of HTPB liner are added to complete the multi layer bonding system.

The aim of the second phase, called DEM (Demonstrator programme) was technology transfer from experimental to light weight / near flightweight hardware including:

- pressure vessel structure (gasgenerator and ramcombustor) based on high strength steel

- sections of of machined forgings (RC front and rear section, gasgenerator front closure, front hanger and umbilical section and gasgenerator rear interface) and flow turned tube sections (wall thickness 2mm) connected by circumferential welding
- an “Ortman Key” tangential interlock used to connect the loaded gas generator case with the integrated ramcombustor. The interstage, housing the control valve was clamped between shoulders of the gasgenerator and ramcombustor structure, when the Ortman Key was inserted
- an interstage with a fully integrated control valve including the electrical actuator and gear; aluminium support structure with insulated steel end plates facing the gasgenerator and ramcombustor (Fig.22)
- hinged consumable aluminium port covers opened by pyrotechnic bolts
- a ceramic C/SiC sustain nozzle to withstand booster loads and endure sustain operation



**Figure 22: DEM interstage/control valve assembly**

In the final EURAAM programme phase, an improved flightweight design was combined with a higher strength (1500 MPa) structural material for the pressure vessels allowing to reduce case wall thickness to 1.5 mm. Fig.23 shows the EURAAM motor mounted with a forebody structure which was also built as part of the program.



**Figure 23: EURAAM missile with flightweight TDR motor**

The EURAAM motor was successfully demonstrated in direct connect sustain tests as well as full sequence tests (Boost, transition, sustain) as shown by the photographs of Fig.24.

An ejector test set up was also designed and established in this programme, to enable successful demonstration of spontaneous auto ignition and afterwards a stable ramcombustion at high altitude flight conditions, where the ramcombustor pressure is well below 1 bar. The setup consists of a coaxial ejector nozzle (driven by cold air) around the ramcombustor exit plane and a subsequent ejector/diffuser pipe. The rig as shown by Fig.25 allows the simulation of ramcombustor operating conditions up to about 30 km of altitude.

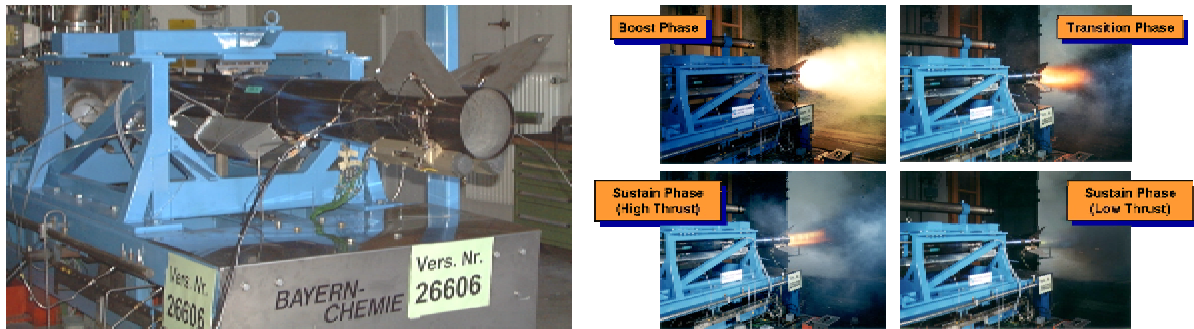


Figure 24: EURAAM motor test, full operational sequence; 1999

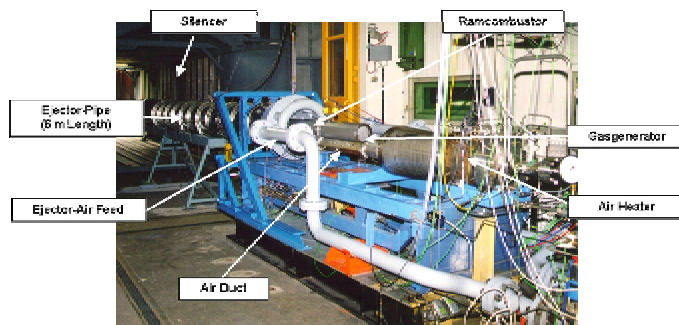


Figure 25: High altitude simulation test rig

## VI. Meteor

Less than one year after successful completion of the EURAAM program, fullscale development of the propulsion subsystem (PSS) for the Meteor beyond visual range air to air missile started in September 2000 based on a precontract 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 is subdivided into a prototype phase leading to the first flight demonstration in fall 2005 and development and qualification of the operational missile-PSS until 2010.

The Meteor PSS concept is widely derived from the EURAAM motor, but has a reduced diameter of 178mm to allow full compatibility with AMRAAM launcher interfaces.

The development standard motor evolved in two stages denominated M1 and M2. The motor design incorporates:

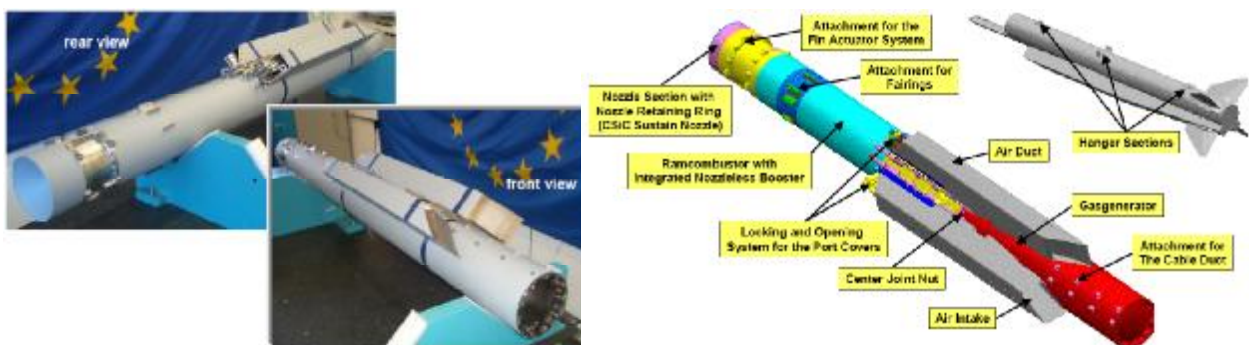
- motor case made of high strength stainless steel
- flow formed tubular sections combined (welded) with integral machined sections like front interface, front hanger/umbilical plug section, middle hanger/ramcombustor air-inlet port section, rear hanger section and ramcombustor nozzle/fin actuator section
- 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

Experience gained with manufacture and testing of the M1 std. motor led to evolutionary design improvement for the M2 std. motor with regard to manufacturability, assembly and functionality, e.g.:

- replacing the Ortman key center joint by a lightweight buttress thread
- structural enforcement of the center hanger section by a more optimal employment of the interstage structure
- improved air intake attachment to the motor case
- improved boost grain geometry and propellant properties

Fig.26 shows the assembled M2 motor together with a CAD view of the subassemblies



**Figure 26: Meteor M2 development standard motor, front and rear view and CAD view of subassemblies**

Characteristics of both the booster and the gasgenerator propellant could be further improved and the manufacturing process was refined and industrialized:

- Gasgenerator turn down ratio could be extended beyond 12:1
- A unique industrial facility was established for the preprocessing of Boron powder into beads incorporating ingredients for combustion enhancement (Bayern-Chemie proprietary process) as shown by Fig. 27
- Burn rate and mechanical properties (operational temperature  $-54^{\circ}\text{C}$  -  $+71^{\circ}\text{C}$ ) of the booster propellant could be further improved



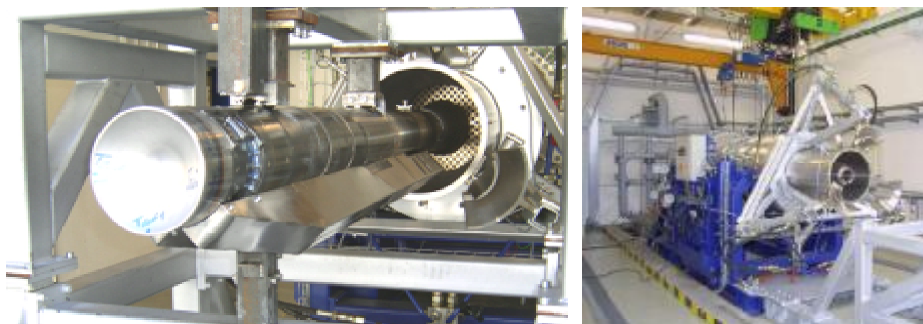
**Figure 27: Boron preprocessing facility established for Meteor gasgenerator propellant production**

A new test center for airbreathing motors (called 'Ramjet City') was put into operation in Aschau to support the Meteor development. It incorporates test boxes for cp testing and freejet testing of the ramjet motors as well as a box for booster testing. The test building is shown by Fig. 28.



**Figure 28: New test building for airbreathing motors at Aschau**

For the Meteor programme, a so called Quasi Free Jet test rig was set up to allow for functional motor testing and aeroheating close to real flight conditions. The motor is mounted on the center plug of an annular windtunnel nozzle (diam. 500 mm). The nozzle configuration can be adapted for Mach numbers 1.9, 2.1 and 2.3 by exchanging the shaped center plug. The windtunnel nozzle is fed by appr. 150 kg/s of air heated to the relevant stagnation temperature by hydrogen vitiators. Fig. 29 shows the the Quasi Free Jet test facility and the mounted M2 motor .

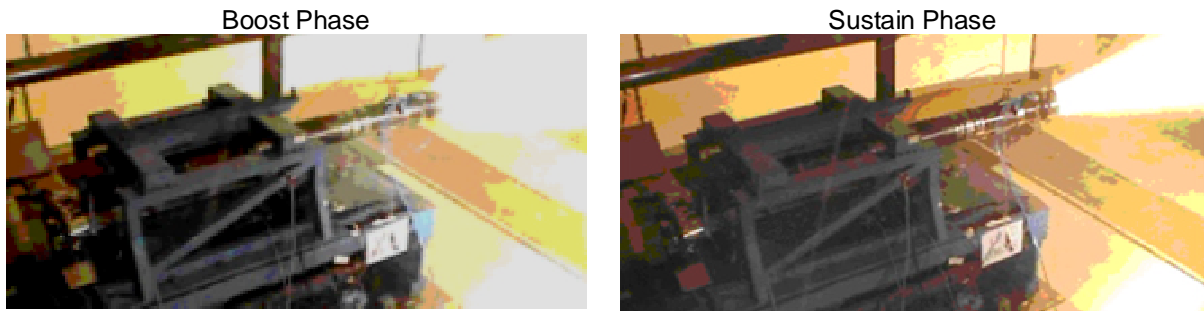


**Figure 29: left -Meteor M2 development standard motor on the Quasi Freejet test rig, right – QFJ test rig**

Validation of the M2 development standard motor in ground tests was finished by 2006. Boost and sustain operation and performance has been proven in numerous tests. Full sequence tests in direct connect (Fig.30) and Quasi Free Jet have shown the safe and reliable functionality of the PSS. As a last step in ground testing, a fullscale missile with live motor was tested under different flight conditions, including incidence and sideslip angles, in a large windtunnel of the French ONERA in Modane.

Functional and performance testing was complemented by structural and environmental testing to ensure flightworthiness of the PSS. This included sled testing of the boost motor to validate structural integrity during acceleration. This testing (Fig. 31) was done at the German WDT 91 military proving ground at Meppen.

Air carriage tests on Gripen, Eurofighter/Typhoon and Rafale (including operation on aircraft carrier) were performed for further validation of missile and motor structural integrity.



**Figure 30: Full operational sequence testing of the Meteor M2 development standard motor in cp test; 2005**



**Figure 31: Sled test of the boost motor; 2005**

Flight testing of Meteor has started in 2006. Testing is currently done from the Swedish Gripen fighter aircraft. The Vidsele test range in Sweden and a UK MoD range at the British Hebrides were used to perform Meteor flight tests. Six flights have been performed successfully at various operating conditions, including

- subsonic launch (M 0.9) at lower altitude (5500m)
- high altitude (13000 m) supersonic launch
- extended free flight with speeds in excess of Mach 3
- extensive manoeuvres.

Figure 32 shows one of the Meteor development standard motors delivered for flight testing, while Figure 32 shows pictures of Meteor launch and early boost phase after aircraft separation.



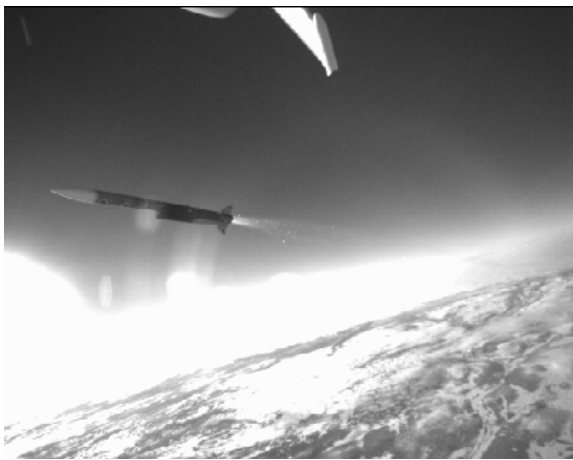
**Figure 31: Meteor M2 development standard motor as delivered for flight testing**

In the last test performed in March 2008, Meteor successfully intercepted a target drone. Figure 33 shows a picture taken from a high speed camera onboard the target drone at the intercept situation.

Besides reliable functionality of the Meteor TDR engine, the flight tests confirmed performance predictions of the propulsion system giving outstanding capabilities to the Meteor Beyond Visual range missile system.



**Figure 32: Meteor flight testing, launch and early boost phase (photos courtesy of MBDA Missile-Systems)**



**Figure 33: Meteor flight testing, intercept of target drone (photo courtesy of MBDA Missile-Systems)**

In 2007, the design of the PP (pre production) standard motor was completed, which will undergo qualification, leading to start of production in 2010. The PP standard hardware is further improved in functionality and performance, taking into account results from the extensive evaluation of the M2 design standard and will be compliant to the demanding requirements without restrictions.. First PP standard hardware is currently getting available for testing.

## **VII. Summary**

Continuous technology build up and development work has been carried out on the topic of the Throttleable Ducted Rocket with high energy Boron propellants in Germany over nearly 40 years. The propulsion system has found its way into an operational system and it has proven its maturity and outstanding performance.

Other missions, besides the air-to air application can take advantage of the superior performance of the TDR with reduced development risk and effort. Existing technical solutions can be directly applied or scaled also for missiles with greater diameter than Meteor.

This technological success story is based on three generations of gifted and dedicated engineers as well as determined sponsoring of a promising but complex technology by the German authorities and industry. The author want to express his thanks and high appreciation for having been able to work with such an enthusiastic team for almost 30 years.

## References

- [1] H.-L. Besser, R. Strecker; 'Overview of Boron Ducted Rocket Development during the last two Decades'; Combustion of Boron-Based Solid Propellants and Fuels (Ed. K.K. Kuo, R. Pein); CRC Press Inc, 1993
- [2] H.-L. Besser, H.-L. Weinreich; 'Technical Status and Application of the Variable Flow Ducted Rocket'; AGARD-CP-600, Paper C23, Dec. 1997
- [3] H.-L. Besser , H.-L. Weinreich; 'The Ducted Rocket Propulsion System for Meteor and its Background in German Airbreathing Motor Technology'; ISABE 2005, Munich, Paper 1149
- [4] H.-L. Besser , H.-L. Weinreich, Guido Kurth, Göran Klose; ' The Throttleable Ducted Rocket, a booster for the kinematic Performance of future tactical Missiles'; NATO-RTO/AVT 135/RSY, Symposium on 'Innovative missile Systems', Amsterdam, May 2006
- [5] Paul Spremberg; 'Entwicklungsgeschichte des Staustahltriebwerks'; Krauskopf-Flugwelt Verlag, Mainz , 1963
- [6] W. Trommsdorff; 'High-Velocity Free Flying Ram-Jet Units (TR-Missiles), Research Work at the German Army Ordnance Office 1936 – 1945'; AGARDograph 20, 1957