Development and Projected Performance of the Red Kite© Sounding Rocket Motor

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and

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1 NOMENCLATURE

BB	Black Brant (Rocket Motor)
DCTA	Departamento de Ciência e Tecnologia Aeroespacial
DLR	German Aerospace Center
EFI	Exploding Foil Initiator
ESRANGE	European Space and Sounding Rocket Range
HAWK	Surface to Air Missile System
IM	Improved Malemute (Rocket Motor)
IO	Improved Orion (Rocket Motor)
ITAR	International Traffic in Arms Regulations
MORABA	Mobile Rocket Base
NATO	North Atlantic Treaty Organization
PATRIOT	Surface to Air Missile System
RK	Red Kite (Rocket Motor)
SID	Safe and Ignition Device
STANAG	NATO Standardization Agreement
TT&C	Telemetry, Tracking and Control

2 ABSTRACT

Averaging about ten launches per year, DLR Mobile Rocket Base (MORABA) has been supporting rocket borne research for more than five decades. Major fields of experimentation include atmospheric physics, microgravity-based research in material physics and biology as well as hypersonic flight research and technology development. Over the last decade, a sustained demand has evolved for sounding rocket vehicles with the capacity to deliver payloads in the order of 400 kg gross mass into trajectories with apogees beyond 250 km or extended dwell time in the hypersonic regime. To leverage cost efficient and reliable military

surplus motors such as the Improved Malemute for use in this regime, DLR has contracted Bayern-Chemie GmbH for a joint development and delivery of a suitable solid propellant motor to be used as a first stage. Currently in project phase C, the definition of the motor performance, materials and design are completed and manufacturing of first components has begun. The paper gives an overview of the motor performance and safety characteristics, applications of the motor in vehicle combinations with their projected performances and a schedule of tasks until qualification flight.

3 INTRODUCTION

Pursuing its mission statement to support rocket borne science experiments from all over the world, MORABA has launched more than 100 rockets in the past ten years and more than 500 since its foundation in 1965. Initially focused on experiments in atmospheric physics and astronomy applications, the spectrum has widened to microgravity research in material physics, biology, and space technology. Most recently, a sustained and increasing demand to support research regarding re-entry and highspeed atmospheric flight has emerged.

We have responded this demand by adapting our vehicle hardware and simulation capabilities accordingly, with main efforts to cope with the elevated thermal and mechanical load environment inherent to high Mach and low apogee trajectories. Herein, the VSB-30 sounding rocket vehicle has many times proven its great performance and further potential. The VSB-30 is a two-stage solid propellant sounding rocket that was developed by the Brazilian DCTA with support by DLR MORABA in our longstanding partnership [7]. Since its inauguration flight in 2004, MORABA has launched more than twenty VSB-30 with 100% success rate. With a performance capacity in excess of 400 kg payload to a 250 km apogee, the vehicle is now in service for all our research fields and manufacturing of the motor stages is charged to capacity. At the same time, MORABA has acquired military surplus propulsion units of the PATRIOT missile defense system and conducted a number of successful single and two stage flights from 2016 onwards. The vehicles proved valuable and their application to higher performance environment attractive, but necessitated the acquisition of a powerful booster stage.

It was under these circumstances that a Phase A study was conducted together with the German solid propulsion systems manufacturer Bayern-Chemie GmbH in 2017 [6] to define the characteristics of such a motor. DLR management approved the concept and work plan and Bayern-Chemie GmbH was contracted in the beginning of 2020 for the joint development and subsequent delivery of 30 units. The project and the motor stage were dubbed after the European bird of prey "Red Kite".

Figure 1: Red Kite© motor with logo

4 MAJOR DESIGN REQUIREMENTS

The major requirements that drove the design were:

I. Performance of > 400 kg to 250 km apogee on an up and over trajectory when used in two stage configuration or with military surplus second stage.
II. Compatibility with existing launchers.
III. Compatibility with existing interstage, adapter and fin assembly hardware.
IV. Compatibility with ESRANGE Space Center's impact dispersion requirements (for both single and multi-stage application).
V. ITAR free design to limit export complexity for operations in and outside the European Union.
VI. Design with focus on ease of handling, cost efficiency and development risk.

Compatibility with existing hardware (III) and launchers (II) fixed the motor diameter to 559 mm (22 inches) and allows for interchangeability and stacking with VSB-30 motor stages. Hardware can hence be produced in larger numbers at lower cost per unit. Motor interchangeability reduces schedule risks originating from the motor procurement.

Since the payload capacity of a multi-stage vehicle is comparably insensitive to structural mass of the booster (depending on configuration, a saving of around 50 kg booster mass only translates into roughly a 9 kg increased payload capacity), extreme lightweight design, elaborate manufacturing techniques and materials were excluded from the development to ensure short development duration and a competitive pricing of the Red Kite (VI).

Amongst the test and rocket ranges visited by MORABA, ESRANGE Space Center became the design driving range due to its comparably small impact area (120 km x 75 km) and strict impact dispersion requirements (IV).

5 MOTOR DESCRIPTION

5.1 Dimensions

The following figure presents a cut view of the motor illustrating the main dimensions as well as the internal flow path and grain geometry.

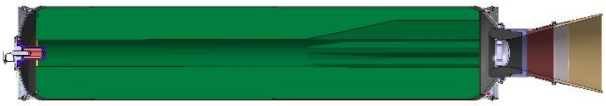

Figure 2: Half-section through the Red Kite©

5.2 Thrust Profile and Performance Characteristics

The requirement to comply with ESRANGE's acceptable impact point dispersion (< 20 km circular radius 1-sigma for flight proven vehicles, [1]) necessitates a regressive thrust profile. The underlying reason is that high initial acceleration mitigates the perturbing effects of wind, measurement inaccuracies and vehicle asymmetries on the trajectory. As the maximum thrust level also drives the dry mass of casing and insulation, a viable compromise was found by iteration.

The iteration loops covered all aspects from grain design to simulated two stage vehicle trajectories and were also used to derive the grain net mass and required total impulse delivered.

Table 1 illustrates the results of the process. With a net explosive mass of 914 kg and a burn duration of 13.1 s, the Red Kite merges into MORABA's rocket motor portfolio as one of the larger and more aggressive units and can be used to boost any of our sustainer motors.

Parameter	Units	Value
Gross Mass	[kg]	1176
Propellant Mass	[kg]	914
Structural Coefficient	[%]	22.2
Main Diameter	[mm]	559
Length (Front Flange to Nozzle Exit)	[m]	3.440
Specific Impulse	[m/s]	2505
Total Impulse (Vacuum)	[MNs]	2.30
Burn Duration	[s]	13.1
Maximum Thrust (Vacuum)	[kN]	226

Table 1: Red Kite Dimension and Performance Parameters

Figure 3 displays the thrust profile projected which was realized by a fin-over-cylinder grain geometry as displayed in figure 2. The fin fraction was put in the aft section of the propellant grain to move the motor center of gravity forward and thereby gain aerodynamic stability margin for any future vehicle that utilizes the motor.

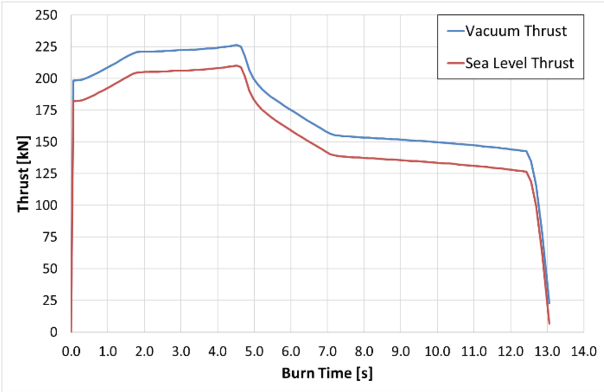

Figure 3: Red Kite Vacuum and Sea Level Thrust Profile

5.3 Ignition System and Range Safety

Experience of Bayern-Chemie GmbH with the use of Exploding Foil Initiator (EFI) devices in smaller rocket motors suggested their application in the Red Kite motor. As opposed to the commonly employed bridge wire initiators, an EFI offers intrinsic safety due to its insensitivity to stray electric currents, electrostatic discharge and electromagnetic radiation. Therefore, the two-fault tolerance of an ignition device demanded by Rocket Test Ranges [3] and design standards (ECSS: [10], NATO: [9]) could be met by a tailored electronic Safe and Ignition Device (SID). Thereby the complexity, cost and added mass of a manually or electrically operated Safe and Arm Device that physically interrupts the explosive train could be avoided. To the authors' knowledge, Red Kite is the first sounding rocket motor that will be equipped with such a device.

5.3.1 Exploding Foil Initiator

An Exploding Foil Initiator consists of an explosive charge that is physically separated from a thin metallic foil by a conduit (called barrel) and a set of cover foils, see figure 4.

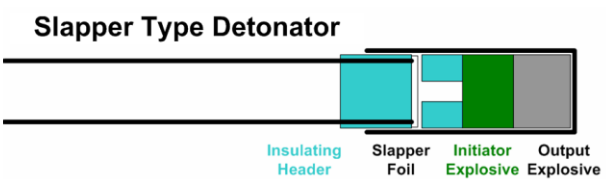

Figure 4: Schematic of an Exploding Foil Initiator [12]

Reception of a strong current pulse leads the metallic foil to explode in a plasma cloud, punching the cover foils through the barrel at high velocity (in the order of km/s) to initiate detonation of the explosive charge upon impact. For proper ignition, a particularly strong and sudden pulse is required (in the order of 1000 A/msec slew rate), otherwise the foil bridge will not create a plasma cloud of sufficient pressure and volume. This pulse characteristic is obtained by discharging a high-capacity capacitor and substantiates the intrinsic safety of the device, since this pulse characteristic can inconceivably be reached without intent by e.g. stray electric currents, electrostatic discharge or electromagnetic radiation.

Further, the high velocity of the cover foil flyer allows to employ an insensitive secondary explosive as the explosive charge, contributing a further cornerstone to the overall system safety.

The capacitor charging is initiated by a low voltage arm signal [12]. Full charge is obtained after about 100ms. A subsequently provided firing signal will trigger sudden discharge of the capacitor over the EFI and initiation of the pyrotechnic chain.

The EFI primary charge is a detonating low volatile explosive and transmits its explosive energy into a boron potassium nitrate ($BPNO_3$) transfer charge consisting of small pellets, which in turn activates the pyrogenic igniter charge (composite propellant), see Figure 5.

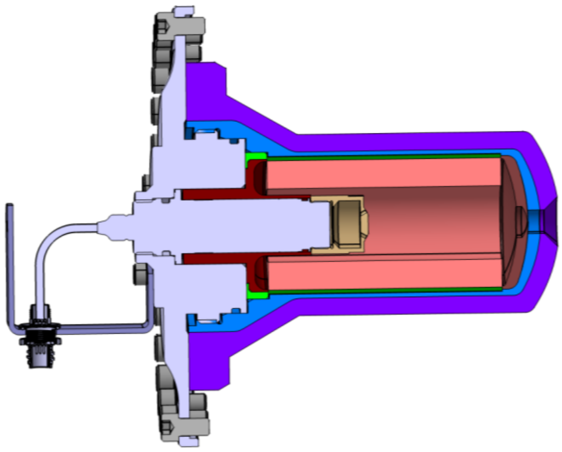

Figure 5: Cross section of the Red Kite Igniter Assembly

The igniter initiates selfsustained burn of the motor propellant grain. The motor case is closed by a pressure seal in the nozzle throat that bursts upon reaching 30 bar.

5.4 Classification and Export Control

To facilitate deployment of the Red Kite motor on Ranges all over the world, emphasis was put on ease of transport, export control and dangerous goods regulations. In particular:

- The motor does not contain components subject to ITAR (but is of course subject to the European Union list of Dual Use items).
- The motor does not contain Asbestos.
- The motor is rated for transport by ship, air and land in a designated cradle over long distances with dangerous goods classification 1.2C.

6 PROJECTED VEHICLES AND FLIGHT PERFORMANCE

This section presents the projected performance of vehicles based on the Red Kite motor offering unique performance and attractive launch cost. Figure 6 displays these vehicles with a generic payload mounted.

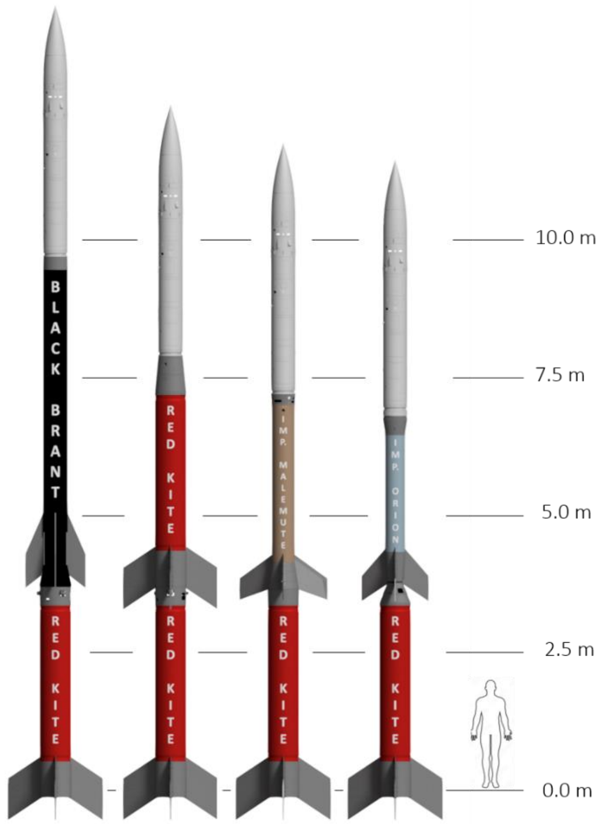

Figure 6: Red Kite motor in projected vehicle configurations with typical payload. From left to right:

- *Red Kite – Black Brant (RK-BB)*
- *Red Kite – Red Kite (RK-RK)*
- *Red Kite – Improved Malemute (RK-IM)*
- *Red Kite – Improved Orion (RK-IO)*

MORABA and Esrange Space Center hold stocks of military surplus motors. The Improved Orion and the Improved Malemute (which are based on the HAWK and PATRIOT Missile Defense Systems) qualify as very cost efficient second stages. Both stages are relatively light weight which leads to high velocity gains during the early flight phase and low impact point dispersion estimates, even when omitting spin induction motors. This reduces the system complexity and costs further.

The Red Kite will also be qualified for operation as a second stage. In two stage combination with itself, the Red Kite provides strong performance and can accommodate for payloads up to a diameter of 22".

MORABA also operates the Black Brant Mk4 rocket motor which provides a total impulse of 2.5 MNs over its

30s action time. With Red Kite as a booster, the Black Brant provides very high performance for heavy payloads or especially long trajectories.

6.1 Apogee Performance

The following graph compares the apogee performance of these vehicles as a function of their payload mass, assuming a typical ballistic up-and-over trajectory with short impact ground range (ca. 70km). This type of trajectory maximizes exo-atmospheric dwell time and hence is extensively used in microgravity research, where long and undisturbed weightlessness is the key requirement.

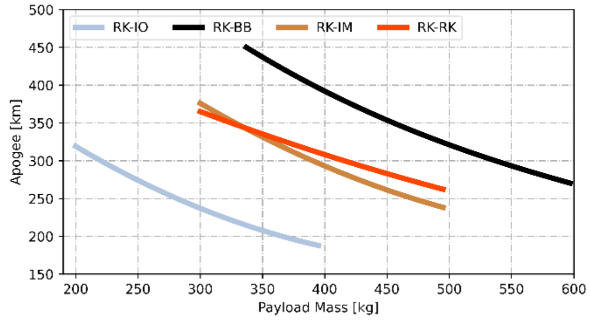

Figure 7: Apogee performance of projected vehicles. "Payload Mass" refers to all mass above forward motor flange

Albeit the Improved Malemute is a distinctly less powerful motor stage than the Red Kite, the RK-IM outperforms the RK-RK for total payload masses below 360 kg. Here, the mass ratios of first and second vehicle stages are closer to the theoretical optimum and overcompensate the lower impulse delivered by the Improved Malemute. Heavier payloads however benefit from using the Red Kite or the Black Brant as a second stage.

6.2 Hypersonics Testing

Each of these vehicles also offers great potential when used as a hypersonics test carrier. The following graphs illustrate that by giving some example trajectories assuming typical payloads and a target apogee of 60 km.

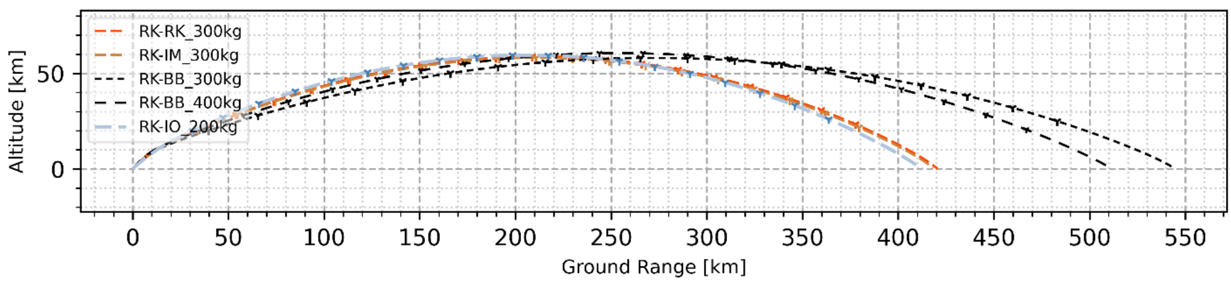

Figure 8: Example hypersonic test trajectories. Cylindrical payload shapes were assumed with total payload masses of 200 kg, 300 kg and 500 kg (including all systems above second stage front flange). Ballistic flight path and captive flight (i.e. payload stays attached to launch vehicle) is assumed until splash down. Ticks indicate 10 s time intervals.

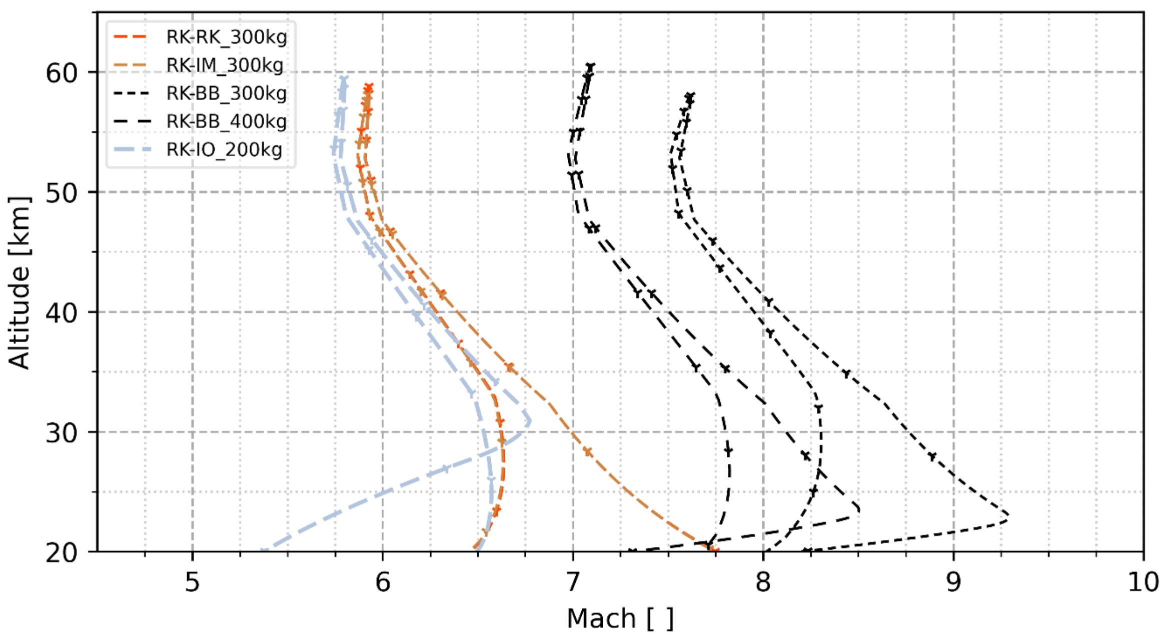

Figure 9: Illustration of dwell time in the hypersonics regime. Ticks indicate 10 s time intervals. Cycle direction is counter-clockwise.

To obtain this kind of trajectories, the vehicles are rail launched at elevations between 55° to 65° (depending on vehicle and payload). The Red Kite booster will be drag separated after burnout. A subsequent coast phase of 10 to 20 s duration is performed to exploit gravity turn and further flatten the trajectory before igniting the second stage.

This class of trajectories subjects the vehicles to a demanding environment regarding the aerodynamic loads, aerodynamic heating and TT&C coverage. MORABA has gained considerable flight experience in the field over the past fifteen years and aims development effort to harden systems for even more demanding flight trajectories.

7 PROJECT SCHEDULE AND AVAILABILITY OF VEHICLES

Currently (06/2022) in the Critical Design Phase, the project awaits its Critical Design Review by September 2022. Critical subsystems and technologies have already passed subscale testing. Several test firings of the pyrogenic igniter have been completed satisfactorily. A first full scale envelope of the motor case was manufactured and has undergone a successful burst test. Qualification firings of two full scale motors are planned to follow early 2023. Provided no major issues are found, production of the first batch of flight units is authorized and first flight expected in summer 2023.

8 ACKNOWLEDGEMENTS

The need for the procurement of this commercial first stage motor to the scientific community found support by DLR programmatic management and its managing director. Amongst others, the support and advocacy of Roland Pleger, Susann Groß and Hansjörg Dittus has made the project possible.

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