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Red Kite Sounding Rocket Motor Qualification & Application

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Abstract
Red Kite is a commercially available, ITAR-free solid propellant sounding rocket motor in the one-ton propellant class. Bayern-Chemie GmbH was contracted by DLR in 2020 for the development and manufacturing of the Red Kite rocket motor. After initial design and materials selection phases, ground testing of mechanical, pyrotechnical and electrical subsystems was conducted. Following successful qualification at Esrange Space Center, Sweden, in August 2023, serial production was initiated. Motor number one was released for maiden flight from Andøya Space Center, Norway, in November 2023 proving the design with great success. In 2024, two Red Kite Motors were successfully launched from Esrange Space Center as regular first stage motors in the two-stage configurations of the MAPHEUS 14 and MAPHEUS 15 missions. The paper gives a summary of the motor performance, its system component design and the motor qualification program.

1. Introduction

The Red Kite solid propellant rocket motor was developed by Bayern-Chemie in response to a sustained demand from the scientific community for high performance sounding rocket vehicles. It is primarily designed as a powerful booster for military surplus and commercial second stages, but can also be used as a second stage or a sustainer when boosted by either an even larger motor or by another Red Kite as first stage.
Typical payloads will range from 200 to 600 kg [1]. When used in a mission design tailored to microgravity research, typical apogees range between 250 and 300 km, while the needs of the hypersonic community can be met by a suppressed trajectory design, typically providing horizontal flight at Mach numbers between 6 and 9 in the altitude band of 30 to 60 km.
The paper gives insight into the rocket motor design, the motor qualification program and the successful qualification test firings on a static test bench at Esrange Space Center with two serial Red Kite qualification motors.

Up to today, three successful flights have been conducted with Red Kite as a first stage motor:
The maiden flight SOAR (Single Stage Operational Assessment of Red Kite) was successfully launched as single stage configuration from Andøya Space Center in November 2023 and carried the DLR scramjet inlet experiment APEX [2]. In February 2024, the first regular Red Kite launch was conducted from Esrange Space Center as first stage of the two-stage configuration of the MAPHEUS 14 mission [1]. Similarly, the subsequent MAPHEUS 15 mission was successfully launched November 11th, 2024, using again a Red Kite motor as first stage representing the 600th rocket launch from the Esrange Space Center in Sweden [3].

The time-line and the major milestones of the Red Kite rocket motor development program is shown in Table 1.

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Table 1: Major milestones of the Red Kite Motor development and qualification

- Development and qualification phase	01/2020-09/2023
- Static qualification test firings, Esrange Space Center	08/2023
- Beginning of serial production	10/2023
- SOAR mission, first test flight (single stage), Andøya Space Center	11/2023
- MAPHEUS 14 mission, first regular launch (two stages) (Red Kite + Improved Malemute), Esrange Space Center	02/2024
- MAPHEUS 15 mission, second regular launch (two stages) (Red Kite + Improved Malemute), Esrange Space Center	11/2024

2. Motor Characteristics

2.1 Dimensions and Performance

Figure 1 shows a cut drawing of the Red Kite motor. Table 2 summarizes the geometrical and performance characteristics of the motor at nominal conditions (i.e., 10°C soak temperature and vacuum expansion conditions).

Table 2: Red Kite geometry and performance

Caliber	559	mm
Total length	3440	mm
Propellant mass	~910	kg
Total mass	1170	kg
Specific impulse	~2510	m/s
Total impulse	2,3	MNs
Burn time	~13	s
Max. thrust	~240	kN

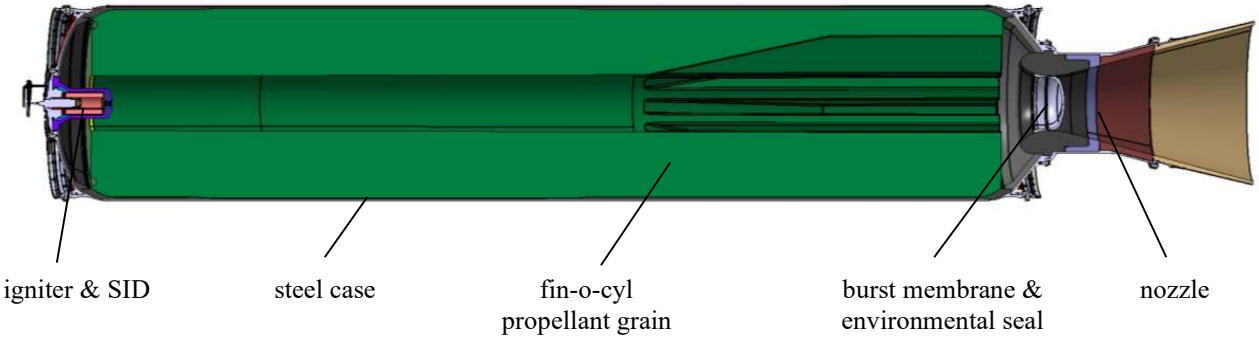


Figure 1: Drawing of the Red Kite motor and its major components

2.2 Red Kite motor components

The pyrogenic igniter is equipped with a Safe & Ignition Device (SID) that makes use of a Low Voltage Exploding Foil Initiator (LV-EFI). In comparison to classical bridge-wire fuses, the EFI technology is insensitive to electro-static discharge environments. It is therefore very safe during handling and operation.
The flow-formed steel case is filled with a 5% Aluminium composite solid propellant. A classical Fin-on-Cylinder (Fin-o-Cyl) propellant grain geometry was chosen in order to provide for the required “staged” thrust evolution.
Figure 2 shows the predicted vacuum thrust profiles within the required soak-temperature range of -20°C to +50°C. The thrust profiles indicate the initial high thrust boost phase in the first half and the reduced thrust level in the second half of the burn.

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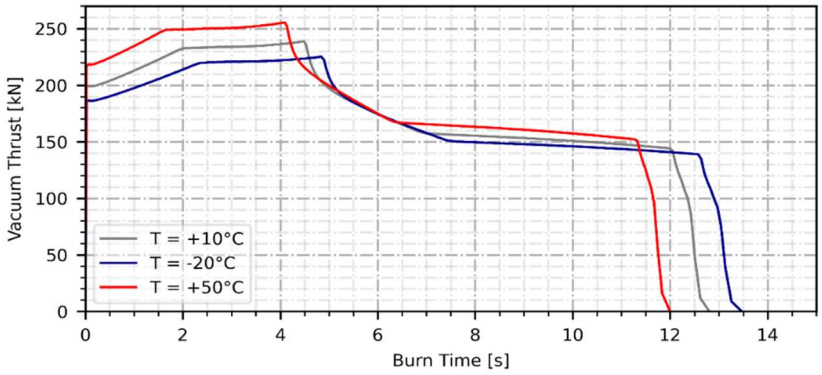


Figure 2: Predicted evolution of the thrust profile within the required soak temperature range of -20°C to +50°C

The Red Kite motor is entirely ITAR-free (International Traffic in Arms Regulations). It follows EAR99 regulations (Export Administration Regulations) and does not make use of Dual Use regulated components and products. It is compliant with REACH regulations and exhibits an operative service life of 10 years with an additional industrial storge time at the manufacturer's site (i.e., at Bayern-Chemie) of 1 year.

3. Motor Qualification

In general, the motor qualification can be divided in two phases: Sub-system pre-qualification and full system qualification. The goal of the sub-system pre-qualification phase is to prove the functionality of individual rocket-motor components in the early stages of the development program in order to reduce risk and to identify possible potentials of improvements ("risks & chances"). Those pre-qualification and functionality tests are often conducted under representative or even more demanding thermal and mechanical conditions.
The full system qualification is conducted in the final phase of the development program. It does not only make proof of the compliance of the complete rocket motor and the correct interplay of all prequalified components, but also qualifies the serial manufacturing process and all related tooling.

3.1 Pre-Qualification of Components

A good example for component testing and according pre-qualification efforts is the development of the solid propellant. Small-scale motor firing tests (see Fig. 3) are used to determine the behaviour of insulation and inhibitor materials, or in case of propellant properties, the burn rate and its dependency on pressure and soak-temperature.
Important artificial (i.e., accelerated) ageing studies are performed at elevated temperatures early in the development program in order to prove the required service life time of the propellant. The aged propellant samples are then used in tensile tests to obtain data for mechanical failure-models of the visco-elastic (or even visco-plastic) behaviour of the propellant grain.

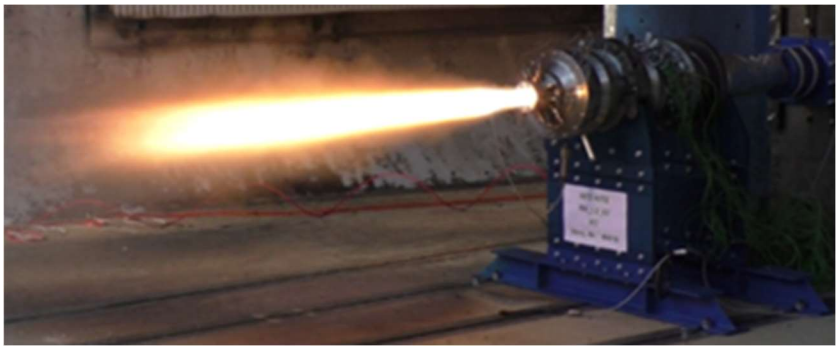


Figure 3: Sub-scale firings of propellant grain samples

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Other pre-qualification efforts during the Red Kite development phase are indicated by the following, three examples:

1. Determination of the motor-case burst pressure (see Fig. 4) in order to establish the safety factor of the case structure against MEOP (maximum expected operating pressure) conditions.

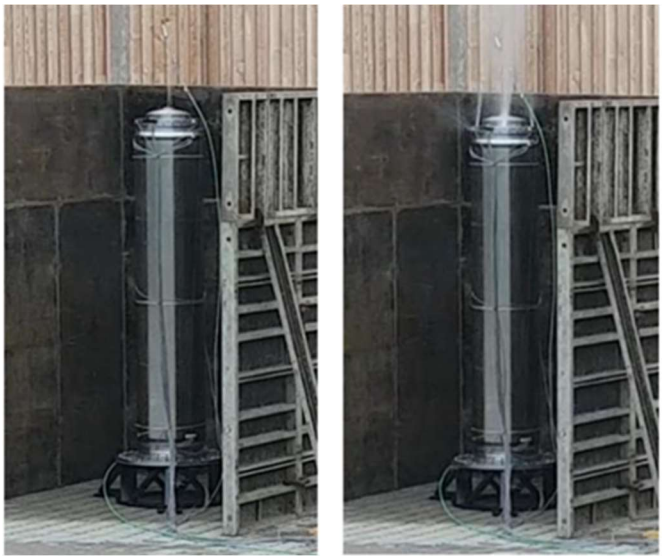


Figure 4: Motor case hydraulic burst test

2. The Red Kite nozzle was successfully pre-qualified by using a modified battleship hardware motor with a propellant mass of 230 kg. The motor was fired at Bayern-Chemie's vertical test stand (see Fig. 5) providing the mass flux, pressure and gas temperature identical to the Red Kite motor, however, only for a few seconds. Therefore, two successive test firings were performed on one nozzle which made it possible to inspect the nozzle in between the two firings by visual means, x-ray and dimensional checks.
   The cool down phase in between the two nozzle-test firings leads to even more critical conditions in terms of thermal deformation of nozzle components and their interfaces such as sealings.



Figure 5: Test firing of the full-scale Red Kite nozzle

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3. The flame expansion of the igniter exhaust plume was investigated to guarantee a reliable heat transfer to the inner surface (bore) of the propellant grain during ignition. In Fig. 6, the bore is marked by the green box, whereas the flow is from left to right.

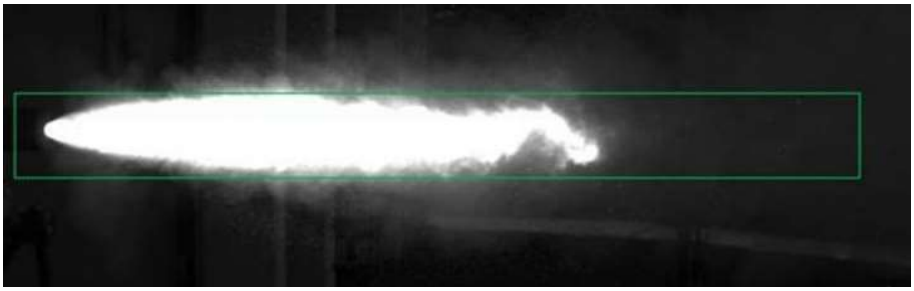


Figure 6: Free-stream firing of the Red Kite igniter

3.2 Qualification of the Red Kite rocket motor

3.2.1 General Remarks

The Red Kite motor qualification was subdivided into two major programs:

1. Qualification of the igniter/SID unit as a stand-alone component, and
2. Qualification of the serial standard Red Kite rocket motor fully assembled with the igniter/SID unit.

The separate qualification of the igniter/SID unit was motivated by the fact that it represents a single shot device. Therefore, Bayern-Chemie wanted to be able to observe the behaviour of that component in the most direct fashion without being obstructed by the integration into the rocket motor.
Figure 7 shows both qualification programs. The motor qualification made use of two fully assembled Red Kite Motors (RKQ-001, RKQ-002). For the separate igniter/SID qualification a total of four units were used (IGN-01 to IGN-04).

Environmental Test Programme Red Kite First Stage Rocket Motor					Qualification Red Kite First Stage Rocket Motor					
					Motor (incl. Nozzle & Igniter/SID)		Igniter/SID Combination			
				Test Hardware	RKQ-001	RKQ-002	IGN-01	IGN-02	IGN-03	IGN-04
				Configuration	live	live	live			
	X-Ray	X-Ray		0°, 90°	RT		RT			
Red Kite Env. Requirements	Thermal Loads	Thermal Cycling	Hot A2 Cycles	10x24h Cycles	33°C ==> 63°C ==> 33°C		33°C ==> 63°C ==> 33°C			
			Cold C2 Cycles	10x24h Cycles	-46°C ==> -37°C ==> -45°C		-46°C ==> -37°C ==> -45°C			
		Thermal Shocks	6h@-20°C, 6h@50°C	10 Cycles			-20°C ==> +50°C ==> -20°C			
	X-Ray	X-Ray		0°, 90°	RT		RT			
	Shocks & Vibrations	Transport Shocks	303 H&T Shocks	±X, ±Y	RT		RT			
		Road Transport Vibration	262 min / Axis	longitudinal + lateral	RT, up to 500 Hz		RT, up to 500 Hz			
		Random Vibration	10 sec / Axis	longitudinal + lateral	RT, up to 600 Hz		RT, up to 2000 Hz			
		Fixed Wing Transport Vibration	C130 Aircraft / 6 Blade Propeller 1h / Axis	longitudinal + lateral	RT, up to 2000 Hz		RT, up to 2000 Hz			
			C130 Aircraft / 6 Blade Propeller 1h/Axis	longitudinal + lateral	RT, up to 2000 Hz		RT, up to 2000 Hz			
	X-Ray	X-Ray		0°, 90°	RT		RT			

Figure 7: Red Kite Motor and Igniter/SID environmental qualification program
(RT – Room Temperature, RKQ – Red Kite Qualification, IGN ¬– Igniter)

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Both qualification programs are very similar with respect to the covered thermal and mechanical load cases. Those load cases are based on military qualification procedures and published in well-known NATO-standards such as the "Standardization Agreements" (STANAG's) [4] and the "Allied Environmental Conditions and Test Publications" (AECTP's) [5].
In order to be able to evaluate and document the state of the Red Kite motors and igniter/SID units during the qualification phase, x-ray imaging was used before, in between and at the end of the environmental test program. The x-ray protocols, among others, also served as formal release documents for the qualification test firings of the Red Kite motors and the igniter/SID units.

3.2.2 Thermal Loads

Diurnal Cycles:
Both, the two Red Kite Motors and the four igniter/SID units underwent 10 high temperature und 10 low temperature Diurnal Cycles. Those Diurnal Cycle tests are important with respect to transport and storage situations, where the rocket motor is stored outside of a controlled and climatized zone.
The high temperature Diurnal Cycles are so called A2 or "Hot-Dry" cycles with temperatures cycling between +30°C at night and +63°C during the day. The A2 cycle is representative of the climatic zone of Woomera, Australia.
The low temperature Diurnal Cycles are so called C2 or "Severe Cold" cycles. The C2 temperatures cycle from -37°C during the day down to -46°C at night. The C2 cycle represents the climatic zones of Esrange, Sweden and Andøya, Norway.

Thermal Shocks:
Thermal Shocks are used to exhibit the propellant grain to maximum thermal strain conditions. They result from thermal deformations induced by strong temperature gradients.
Since the heat conduction coefficients of composite propellants are relatively small (similar to those of thermoset plastics) and the calibre of the Red Kite motor is comparatively large (559 mm), the penetration of the heat wave into or out of the propellant grain takes a very long time (in the order of several days). Therefore, the dynamics of the grain deformation due to induced shock temperature conditions are very slow, which makes that test in combination with such a large rocket motor obsolete.
In contrast to that, the comparatively small diameter igniter/SID units (ca. 100 mm) were exposed to a total of 10 consecutive 12 h temperature shock cycles, i.e., 6 h at the cold-day condition of -20°C and 6 h at the hot-day condition of +50°C. The fast temperature changes were realized by shifting the igniter/SID units between two separate climate chambers, one set to –20°C and the other one to +50°C temperature.

3.2.3 Mechanical Loads

The dynamic test set-up for the Red Kite motor is shown in Fig. 8. Two clamping brackets and four hydrostatic slide bearings were used to position and fix the motor parallel to the ground. In the case of longitudinal loads, the axis of the 100 kN Bayern- Chemie shaker connects horizontally to the head-end of the motor. For loads in the lateral direction, a side-mounted traverse was used to connect the motor via the two clamping brackets to the horizontal axis of the shaker.

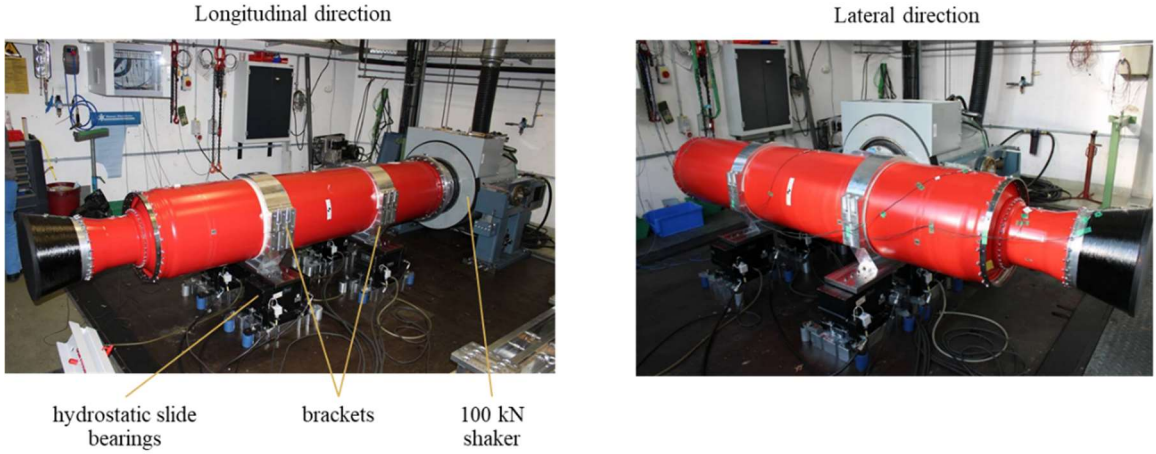


Figure 8: Dynamic test set-up for the Red Kite rocket motor

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Fig. 9 shows the test setup with the four igniter/SID units mounted to the shaker. Here, the shaker axis is positioned in the vertical direction. Due to the common mount on the shaker table, all four igniter/SID units are tested together. The direction of the load can be adjusted easily by turning the igniter/SID units and their mounting brackets into the desired load direction.

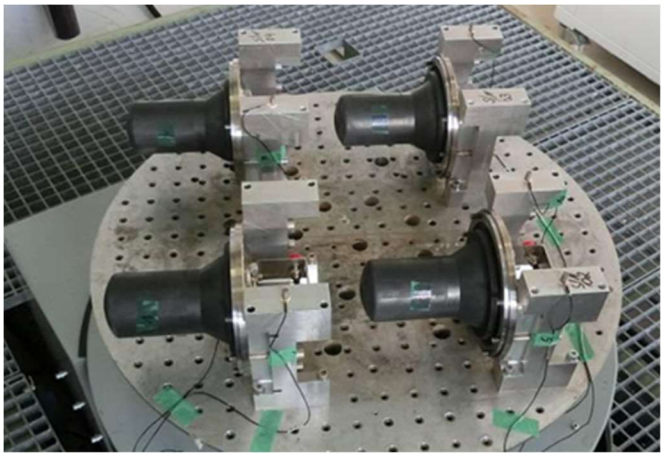


Figure 9: Four igniter/SID units on the shaker table

Transport shocks:
Since the rocket motor and its integrated igniter/SID unit are transported horizontally, transport shocks were applied in the lateral direction only.
Fig. 10 shows the shape of the applied shock, a so called “half-sine shock” with a duration of 11 ms. The number of the shocks to be applied and their peak amplitudes are given in the table in Fig. 10.

Road Transport Vibrations:
Road transport vibrations were applied in the longitudinal and lateral - here designated as “vertical” - direction. The according spectra are shown in Fig. 11. In each axis, the vibrations were exerted for a duration of 262 min which is equivalent to a distance of 7000 km road transport. That distance corresponds to roughly twice the distance between Munich, Germany and Esrange, Sweden.

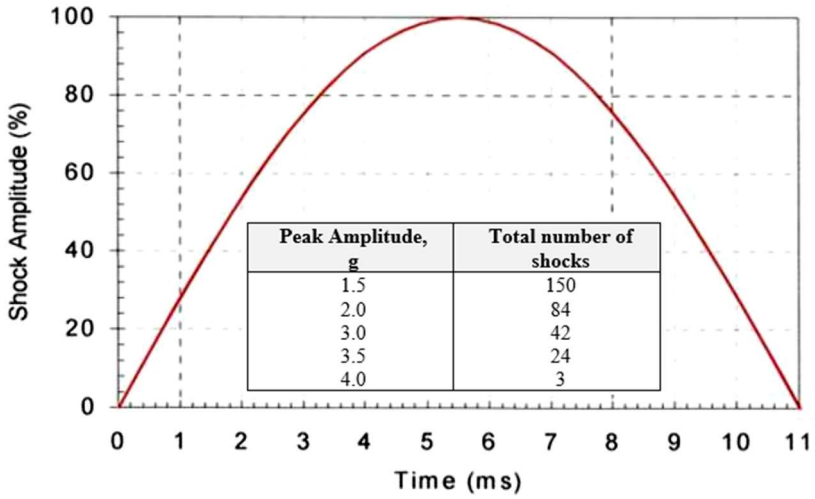


Figure 10: Transport shock conditions

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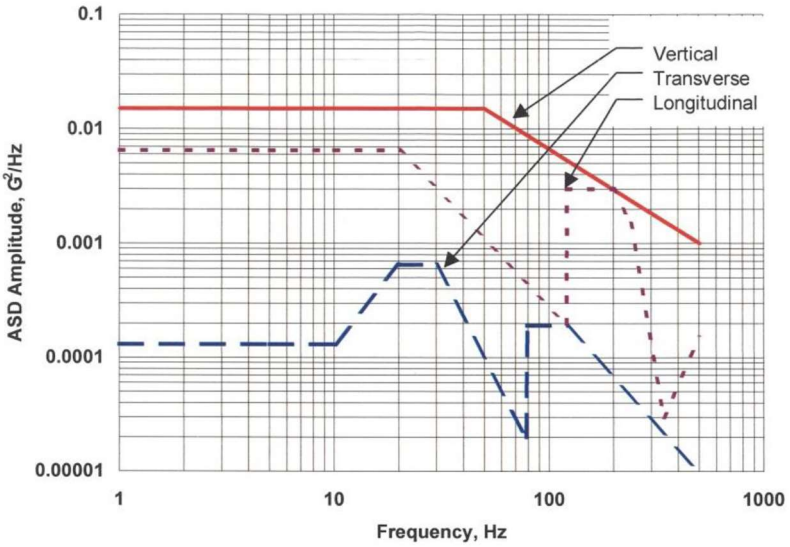


Figure 11. Road transport vibration spectra

Random Vibrations:

Random vibrations are used to simulate the operational loads on the rocket motor and the igniter/SID units, i.e., dynamical loads that result from the launch and flight phases. Those loads are very specific to the rocket motor and its flight trajectories which makes it difficult to use any kind of standardization. Therefore, the requirements for the Red Kite test spectrum were taken from a rather general NASA document [6], where data from tests with Terrier MK70 and Black Brant motors (IX to XIIa) have been published (see Table 3 below).

Unfortunately, due to the large mass of the Red Kite rocket motor the Bayern-Chemie 100 kN shaker was not powerful enough to provide the required 12.7 grms load spectrum. Therefore, and as indicated in Table 1, only a reduced spectrum with an overall energy of 5.34 grms was realized. In contrast to that, the four igniter/SID units were exhibited to the full vibrational spectrum. In both cases, the loads were applied in the longitudinal and lateral direction.

Table 3: Red Kite random vibration spectrum

	Requirement	**Actual**
Duration	10 s	12 s
Spectrum	20 Hz: 0.01 g²/Hz	20 Hz: 0.010 g²/Hz
	1000 Hz: 0.10 g²/Hz	600 Hz: 0.076 g²/Hz
	2000 Hz: 0.10 g²/Hz	
Load	12.7 grms	5.34 grms

Fixed wing transport vibration:

Finally, the Red Kite qualification motors and the four igniter/SID units were tested in combination with fixed wing transport vibrations. The spectra of the Hercules C130 aircraft with four- and six-bladed propellers were used in both, the longitudinal and lateral directions. A test duration of 1 h was chosen, which is equivalent to a transportation flight time of 20 h.

Fig. 12 shows in (a) the lateral load spectrum with 1.76 grms of the four-bladed propeller version and in (b) that of the six-bladed propeller version with 3.97 grms. In both spectra, the propeller frequencies and their decaying harmonics a very well indicated by the discrete amplitude peaks. The spectra for the longitudinal fixed wing transport vibrations are less energetic than the lateral spectra and are therefore not shown here.

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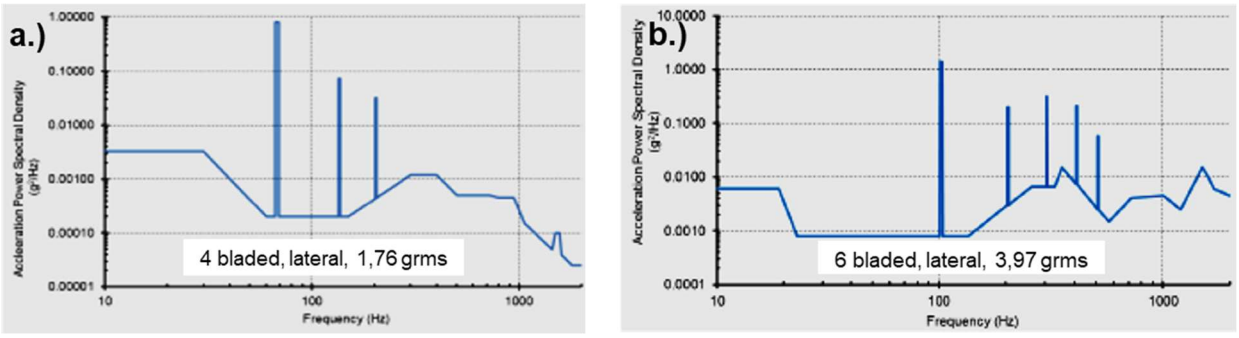


Figure 12: Hercules C130 fixed wing transport vibrations: a) 4-bladed propeller, b) 6-bladed propeller

3.3 Qualification Test Firings

After the successful completion of the described environmental qualification test program, the four igniter/SID units and the two Red Kite qualification motors were fired on static test benches.

3.3.1 Igniter/SID units

The initiation of the igniter/SID units was realized by using the ignition flight controller and its electrical interface to the EFI-equipped SID from DLR Mobile Rocket Base.
Therefore, not only the flight hardware (controller, cabling, connectors, SID and igniter) was qualified by the igniter/SID test firings, but also the motor initiation sequence itself.
Two units each were fired at the minimum and maximum soak temperature levels of -20°C and +50°C, respectively.
The firings of the igniter/SID units were all successful. The results were compliant with requirements such as minimum mass-flux, maximum pressure and also the timing of the sequence of events.
Since the focus of the paper is more on the performance of the Red Kite qualification motors, the test firing results of the igniter/SID units are not further reported here.

3.3.2 Red Kite qualification motors

In accordance and cooperation with DLR Mobile Rocket Base, the qualification test firings were performed on the HTS-1 test stand at Esrange, Sweden.
Fig. 13 shows one of the two qualification motors mounted to the HTS-1 test stand. Its head end uses a thrust frame to connect to a wall mounted load cell that measures the motor's thrust.



Figure 13. Red Kite motor mounted to the HTS-1 test stand at Esrange, Sweden.

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An elaborate set of (partially redundant) sensors was used to monitor the qualification test firings:

- thrust
- motor pressure
- temperatures
- strains
- vibrations
- spectroscopic measurements

As in the case of the igniter/SID units, the qualification test firings were conducted with the Red Kite motors having been soaked to the minimum and maximum temperature levels of -20° and +50°C.

Figs. 14a and 14b show the measured pressure and thrust evolutions in comparison to the predictions of internal ballistics computations.
The pressure evolution in Fig. 14a indicates the well-known effect of the sensitivity of the propellant burn-rate on the soak temperature level, i.e., with increasing motor soak temperature the burn rate and the delivered mass flux do increase. Since the throat area remains (nearly) unaffected by soak temperature changes, the increased mass flux causes higher motor pressure levels and, as the thrust evolution in Fig. 14b shows, also higher thrust levels.
The comparison with the results of the internal ballistics calculations shows that the measured pressure and thrust evolutions are slightly higher than predicted. This also leads to a reduced burn time at both soak temperature levels. It is interesting to note that the burn time reduction appears to be stronger at the lower soak temperature level by at least a factor of two.
The reason for the resulting differences between measurement and prediction lies in the fact, that the temperature induced deformation of the propellant grain was not respected for in the internal ballistics computations. This rather trivial issue has been resolved by including the effects of the grain deformation in future internal ballistics predictions.

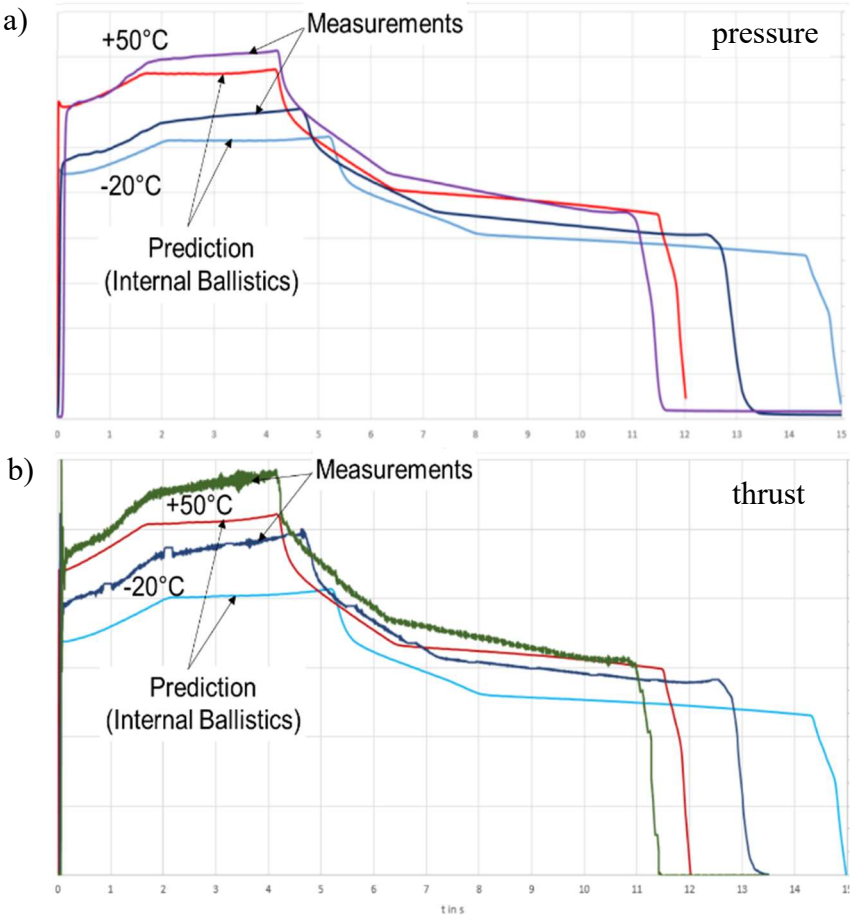


Figure 14: Results of the Red Kite motor qualification test firings: a) pressure evolution, b) thrust evolution

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4. Conclusion

The Red Kite solid rocket motor was developed and successfully qualified over a period of 3 years and 8 months which led to the start of the serial production in 10/2023.

The motor qualification program and static test firings at Esrange Space Center showed:

1. The pressure and thrust data are in good agreement with predictions of internal ballistics calculations.

2. Firing data at -20° soak temperature was used to correct for the temperature related deformations of the case-bonded propellant grain. The correction improved the prediction of the Red Kite motor performance characteristics.

3. The thrust data indicate a very good performance level with vacuum specific impulses between 2589 and 2623 m/s.

4. The pressure data contain no sign of any significant pressure oscillation.

5. The erosion of the nozzle throat is small and below 3% of the throat diameter.

6. Temperature measurements on the outer skin of the motor case indicate very good performance of the internal thermal insulation. Two minutes after ignition, the measured skin temperatures remained below 70°C.

Up to now, three successful missions were performed using the Red Kite solid propellant rocket motor:
The initial launch in a single-stage configuration (SOAR, 11/2023, from Andøya Space Center) and two launches in a two-stage configuration (MAPHEUS 14, 02/2024 and MAPHEUS 15, 11/2024, both from Esrange Space Center).

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