OTRAG – A Low Cost Rocket
(U2, September 2014)

“Faster - better - cheaper”! This is the slogan since Herman Oberth declared in his book “A Rocket into Planetary Space”: *Under certain economic conditions, the construction of such machines (*rockets*) may even become profitable. Such conditions might arise within a few decades (1923).*
Since then, many have tried, almost all of them could not beat the cost issue – even with the most ingenious ideas.
One of the pioneers in this field was the German engineer Lutz Kayser, founder of the rocket company “Orbital Tansport und Raketen AG” (OTRAG). Whether he was a financial genius (he invented an early version of “crowd funding”), an inspiring technician - or both, but got caught in the politics of the cold war – who knows? There is a lot of (contradicting) information on the internet and everybody can make up his own mind.

This article concentrates on the technical facts of OTRAG – which in my opinion, as the Editor of SpaceOps News, could have “made it” under different circumstances – I think Lutz Kayser was as charismatic as nowadays Elon Musk is.

The following technical description is an English translation and partial edition of portions extracted from Bernd Leitenberger’s German article “OTRAG –Rakete”
http://www.bernd-leitenberger.de/otrag.shtml

	**A Brief History** Lutz Kayser (born 1939) was interested in rockets as a teenager already. In 1954 he started and finished graduating as a M.S in aerospace technology at the Stuttgart University under Eugen Saenger and later became a member of the Society for Space Research (GfW).

1954
Lutz Kayser was as a high school sudent the founder of a student association of space enthusiasts (Arbeitsgemeinschaft fuer Raketentechnik und Raumfahrt at the University of Stuttgart), which experimented on the premises of his father’s company (Suedzucker AG) with rockets. Together with university students he built a 5-foot test stand for rocket engine tests and the group was technically advised by Irene Saenger-Bredt, the wife of Eugen Saenger. Saenger designed the first liquid propellant rocket engine in Germany after WWII. The Baden-Wuerttemberg Ministry of economics gave research grants to develop low-cost rocket propulsion concepts and asked Kayser to bring Wolfgang Pilz to Stuttgart. He had developed the French Veronique rocket in Vernon, France. Pilz and Kayser selected the site for the DLR rocket test site in Lampoldshausen.

1963
Still a graduate student Kayser was awarded a consultancy contract by GfW for the failure investigation of the ELDO (European Launcher Development Organization) EUROPA II

satellite launcher.
Together with Professor Argyris, the originator of the Finite Element Structure Analysis (FEM), Kayser analyzed that the rough cutoff of the second stage destroys the common bulkhead of the German third stage. After 9 launch failures in a row the Europa II project was cancelled.

1971
In summer of 1971, the Federal Research Ministry of Germany (BMFT) awarded four contracts to German aerospace companies to develop designs for a low cost Europa III B rocket (which later became the Ariane rocket) as successor of the Europa II rocket. The new rocket should be cheaper to operate and had to undercut the 2 billion DM development costs of Europa II.
Besides the established companies ERNO, Dornier and MAN, a start-up company, "Technologieforschung GmbH" entered the contest. This company was founded by Lutz Kayser in 1971. Each of the winning contractors, including Technologieforschung, was awarded with study money of 250,000 DM.
The proposal of Technologieforschung GmbH represented a radical new concept: a "Buendelrakete" (cluster rocket). The concept of the rocket was conceived by J. Winkler, between 1928-1930 and was taken up by Armin Dadieu and Wolfgang Pilz during the Peenemuende-days.
Kayser's rocket proposal consisted of 6 clustered modules with 36 units each, as the first stage. Each module was equipped with 36 engines i.e., one per unit, which would work with simple fuels such as Diesel, kerosene and nitric acid. The second stage then consisted of a single module of 36 engines. The two stages would be nested into each other like a Russian doll (see also chapter "Staging" below). Control of pitch and yaw motions could simply be done by reducing the thrust of one of the outer engine units.
Figure 1 shows some possible configurations, the available Coralie stage from Europa I and II developments was proposed to be used as upper stage.
This arrangement would, according to the Technologieforschung not only reduce the Europa II development cost of 2,000 Mio DM, but slice it down to 500 Mio DM.
This was the first concept as proposed by Lutz Kayser.
On top of the initial 250,000 DM study money Lutz Kayser received additional funding from the Federal Ministry of Research (BMFT) adding up to a total of 4 Mio DM for improving the concept and to develop an engine and for a joint contract with DLR Lampoldshausen.

1974
Unfortunately for Kayser's activities Germany participated in the development of the European Ariane rocket funded by the newly established European Space Agency (ESA) and its member states in 1974. As a consequence the Europa III B approach was discontinued. But during this time initial testing of the engine was already in progress and Kayser continued his activities and as reaction to BMFT's withdrawal Lutz Kayser founded the "Orbital Transport und Raketen AG" (OTRAG) on 17th Oct 1974, with Kurt Debus as chairman of the supervisory board. The headquarters of the new company was located at Neu Isenburg. They first used the test stands at Lampoldshausen being built for European launcher test program by DFVLR (which later became the German Space Agency - DLR). But later, as a private company OTRAG had to find a place for its own test- and launch facilities.

1975/76

In 1975/76 negotiations with government officials of Zaire took place which finally led to the conclusion of a leasing contract for a huge remote terrain in the east of Zaire where an aircraft landing strip and a launch facility could be established. For supplying the new site OTRAG founded a subsidiary company, the “OTRAG RAS” (Range Air Service) using “second hand” Argosy airplanes for resupply, shuttling between Munich and the airstrip in Zaire.

1979
After three test launches President Mobutu of Zaire cancelled the originally “indefinitely” lease contract under pressure from Chancellor Schmidt promising Mobutu another 100 Million D-Mark development aid. OTRAG had to move out of Zaire. Another test site was found in Tawiwa, 600 km south of Tripoli in Libya upon the personal invitation of Muhammar Gaddafi to use the Sahara.

1981
The first launch from Libya took place on 3rd March 1981. Libyan military presence was reported. Some 14 launches were reported by Kayser, but they were not verifiable because the public was excluded.
By end of 1981 reports were published announcing that OTRAG has halted its activities because of internal conflicts, Kayser refused to develop a two stage version of his rocket. In the aftermath of this conflict the Libyan military confiscated the entire 50 Million Dollar inventory (Test facilities and manufacturing machines) in 1982. OTRAG left the county, however launches continued to be carried out under Libyan military control.

1982
Dr. Debus retired as board speaker succeeded by Kayser and Frank Wukasch became the Chief Executive. OTRAG continued in Germany and Frank Wukasch tried to clean up the distorted relations with German politicians offering OTRAG’s services for sounding rocket experiments. In spite of these efforts Chancellor Schmidt, under political pressure from Breshniev (Soviet President) and d'Estaing (French President), continued his opposition against OTRAG and Kayser's technology, and had the German Financial Court to look into OTRAG’s financial situation. The Financial Court decided that “OTRAG had no intention to make profits” and as a consequence of this decision OTRAG’s financing society was disintegrated.

1983
With no new money and little public support Frank Wukasch managed one last launch from Esrange in Kiruna (Norway) in 1983 (see separate report from Sven Grahn, SSC: “OTRAG at Esrange”), after this not entirely successful launch OTRAG was dissolved completely in 1986 by its shareholders under Financial Court orders.

The Concept
Lutz Kayser wanted to bring down launch vehicle cost according to the following principles:

• Reduce costs by using commercially available technologies: the tanks were made of steel tubes used for pipelines, the motors for the engine valves initially were VW windshield wiper motors produced by Bosch (later replaced by more powerful motors).
• Lower development costs by bundling many simple and robust identical engines/tank units,

instead of developing more expensive specialized larger engines.
• Reduce production costs using a simple design suited for mass production (series principle).
• Reduce operations costs through the use of low-cost fuels.

Lutz Kayser claimed 31 inventions and patents during the development of the rocket. In 2005 still 20 of the patents were registered in his name.

The Modules
The basic principle was to arrange multiple single, very simple engines and tanks of variable length into modules.
A minimal **module** consisted of **4** clustered **tank units** mounted on **4 engines**. Kayser defined this technology "Common Rocket Propulsion Modules" abbreviated CPMR or "Common Rocket Propulsion Units (CRPU). A specific name for the entire rocket assembly was never coined, however the media called it the "OTRAG rocket" or more notoriously “Billigrakete” (low-cost rocket). Possible configurations of cluster combinations are shown in Fig. 1.
During the 20 year development period various iterative design changes resulted in 36, 4 and finally one rocket engine per module.

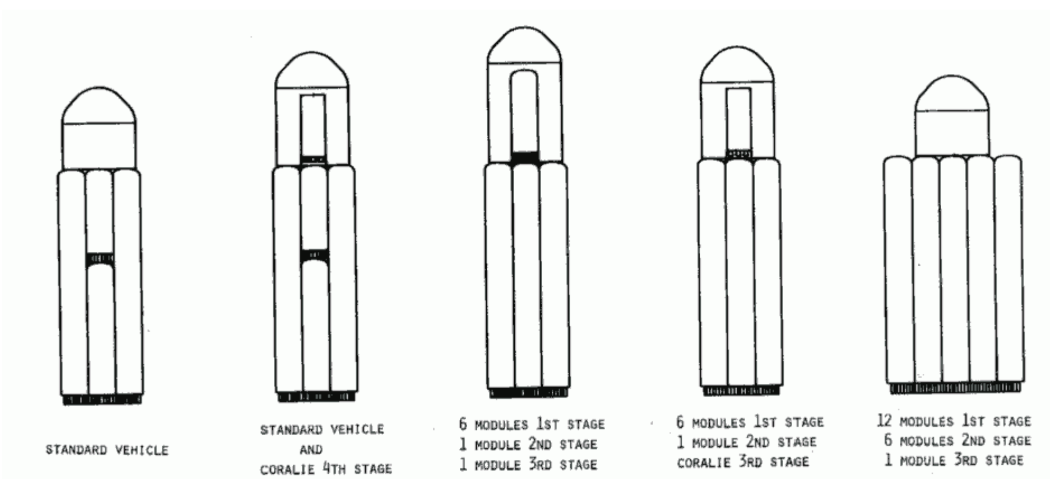
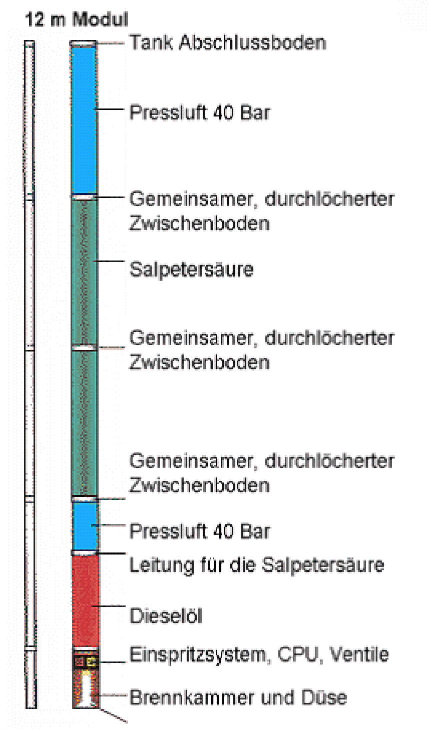


Figure 1: Possible rocket configurations (black bars indicate engine assemblies)

The Tanks
The tanks were manufactured in a special rolling process which was developed together with Krupp. The low carbon stainless steel had a stress limit of 232,000 PSI [1600 N / mm^2]. The welded tube interconnections needed to be made by spiral-welding process. Later it turned out that tubes produced by the regular cold drawing process were better suited.
Each tube is 10.63 in [27 cm] thick and 9.84 ft [3 m] long. It consisted of 0.020” [0.5mm] thick, low-carbon stainless steel. A specialized machine could produce 10 tanks a day largely automatically.
This indicates that it was tried to optimize the tank thickness and pressure for best performance. The best performance/cost relation was achieved with tank pressure of 40 bar.
At each tank joint was an intermediate bulkhead of 4.4 lbs [2 kg] mass. The connection between the SS tanks and the Al- bulkheads was by shear screws with O-ring seals.
A 9.8 ft [3 m] tube (unit) had a weight of about 26.5 lb [12 kg] including the M10 bolt connections.
Up to 8 of these 3 m- tubes could be joined together on top of each other with bayonet

brackets and formed a tank of 80 ft [24 m] in length and of 10.6 in [27 cm] diameter. For test purposes tanks of smaller lengths were used. An example of a 12 m module is shown in Fig. 2.



12 m Module: single tank/engine unit (see also Annex)
(for other module lengths, equivalent ratios apply)

Tanks (3x 3m tanks)
- upper lid
- compressed air (40 bar), blue
- intermediate lid at 9 m (perforated)
- nitric acid oxidizer (approx. 2/3 mix ratio), green
- intermediate lid at 6 m (perforated)
- intermediate lid at 3 m (NOT perforated)
- compressed air (40 bar), blue
- feeding line for nitric acid through the fuel tank
- diesel fuel (approx. 1/3 mix ratio), red

Engine
- injector, CPU, valves
- combustion chamber and nozzle, brown

Figure 2: Basic tank/engine module (CRPU)

Each 3 m tank segment had a tank bottom which was perforated so the tanks could be filled continuously. The fuel tanks are only partially filled, the rest is filled with compressed air at up to 580 PSI [40 bar] initial pressure, which provides for the fuel transport. Due to the emptying of the tanks, the pressure then dropped to 218 PSI [15 bar] at the end of the burn phase. This blowdown feed system is the cheapest and most reliable.
As low-cost fuel HDA (high density acid, 50%N_2O_4, 50 % HNO_3) / diesel oil (or kerosene) was found to be optimal due to its high performance and high density (1.66 g/cm3). This combination is far less expensive than the usual combination of hydrazine / nitrogen tetroxide. Other combinations such as the use of liquid oxygen were not viable because of the high evaporation rate, low density, and non-hypergolocity.
Also other combinations such as red fuming (68%) nitric acid as oxidizer and other hydrocarbons (kerosene, JP-1) were tested. The injection head of the engine proved to be very robust to different oxidizers and fuels.
The refueling process was unusual and took place as follows after thousands of optimization tests.
1. Loading of compressed air to 40 bar plus 5 bar contingency pressure.
2. Opening of the fuel valve releases air pressure through the engines and decreases the pressure to 15 bar. This was a positive check of the valves and the injection head removing any possible blockages.
3. Simultaneous pressure fueling with oxidizer and fuel up to 40 bar pressure.

The whole procedure could be done within 3 minutes in parallel and automatically for all modules with separate fueling systems.
During the thrust period the pressure decreased gradually to 15 bar. The valves in the tanks were adjusted in a way that the resistance for the fuel was higher than for the oxidizer achieving a uniform fuel flow and maintaining the desired volume ratio of oxidizer to fuel.
Since the engine remains at it original weight, the empty/full mass ratio increases with increasing length of the modules.
A length of 24 m (3x 8m modules on top of each other) was considered to be optimal. Further increases in length would increase the gravity losses. The generated thrust theoretically would allow a maximum extension of up to 40 meters.
For a 24 m version the empty/full mass ratio 0.15 was quoted in 1980, about twice as high as for conventional rockets. The data received in 2005 from Kayser were much better:
0.1 for a 24 m version and 0.15 for a 18 m version and 0.18 for a 12 m version.
In the 24 m version a module containing 1130 kg HDA and 220 kg diesel oil, i.e., a total of 1350 kg propellant at a launch mass of 1500 kg.

The Engine

Like the tanks, each engine is 27 cm wide but has a length of only 1 m: 60 cm for the combustion chamber and nozzle and 40 cm for housing the valves, battery and injector. The engine is fixed and could not be swiveled. It was not actively cooled, but used an ablative cooling resin and asbestos and later chopped carbon fibers. The only moving parts were the valves which regulated the fuel flow. The ball valves were standard valves as used by the chemical industry (ARGUS) and were driven by a DC electric motor used by the automotive industry. First it was 50 watt Bosch motor operating windshield wipers, but it was not powerful enough, so finally 100-120 watt motors were used.
Particularly difficult was the development of the radial injection ring(s) for the fuel. This ring-injection technique was developed by Lutz Kayser during his studies at the Stuttgart University and was based on Wolfgang Pilz’s work in France.
Each engine had an average thrust of 25 kN. However, this could be varied over a wide range and the thrust decreased during the thrust period.
The engine had one feed line for the oxidizer and one for the fuel from the associated tank unit.
This design allowed the engine to be attached firmly with screws. The mass of the engine was 65 kg at the start. According to Kayser a reduction in mass of up to 50 kg was possible due to ablation of the inner lining of the combustion chamber.
The engine design had been tested and verified by DFVLR. The concept and the intellectual property rights were claimed by Lutz Kayser, who transferred them to his new company OTRAG. It is the result of a 20 year iterative design – manufacturing – test cycle with altogether more than 4000 static tests with 50,000 sec duration.
This is the only known rocket engine in the world with guaranteed combustion stability and 99% c*-efficiency and manufacturing cost below US$ 2,000 burning HDA/Diesel.

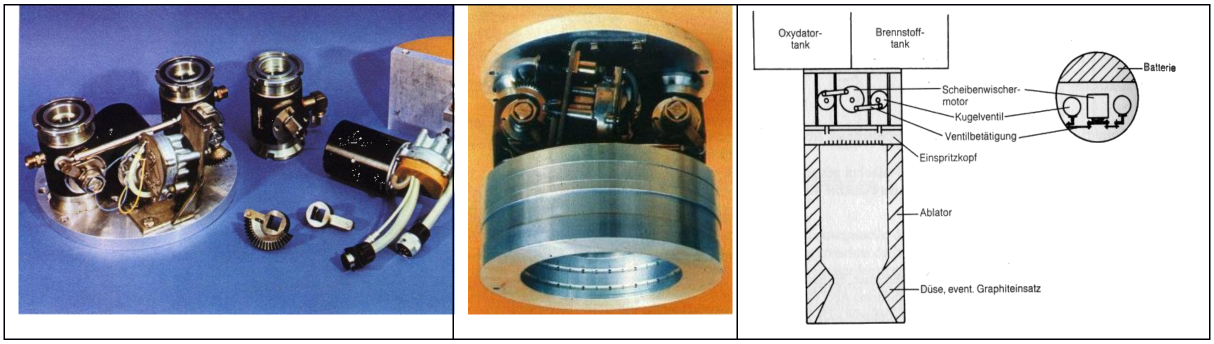


Figure 3: (from left) Valves with (VW-) wiper motor, Injector ring, Combustion chamber and control (old version, 1969)

Unlike in other engines the fuel was not injected downwards from the head of the engine but is injected radially from the outside (see Fig. 3, middle). The injection is performed through 3 rings with 144 holes, which should allow a particularly good mix of fuel and oxidizer. This radial approach also prevented the fuel to reach the combustion chamber wall before igniting, resulting in a very high combustion efficiency. (keeping the combustion front inside the ablator).
The nozzle throat was initially a simple graphite ring and later purely ablator. Determined by its opening, the thrust could be adjusted in a very wide range. The engine thrust therefore could be varied in a range between 5-50 kN. A nozzle throat area of 80 mm was used in the tests with 6 or 12 m long modules. This throat provides a thrust of 25 kN which linearly decreases in-flight to 15 kN due to the decrease of the combustion chamber pressure from 30 bar to 10 bar.
For modules longer than 24 m the aperture could have a diameter of 100 mm, producing a thrust of 35 kN at the beginning, decreasing to 15 kN at the end of the thrust period.
Since the tank pressure decreases with the depletion of the tanks, the combustion chamber pressure drops during operation from 30 to 10 bar. This yields a decreasing total thrust during burn time and a welcome limitation of thrust acceleration during accent of the launcher of 3 g.

The burn time was depending on the degree of tank fillings, the thrust duration was between 20 to 150 seconds. For the 24 m tank version a burn time of 150 sec, for the 15m version a burn time 120 sec was quoted.
The specific impulse for the 24 m version was 260 sec at 1 bar external pressure and 290 in a vacuum as quoted by Kayser.

The image (Fig. 3, right) illustrates the simple and robust design of the engine. First, there were no moving parts, no pumps or gas generators and no swiveling. The combustion chamber has no regenerative cooling or double walling. The production process of the nozzle was very simple: the nozzle was a conical opening in the block of ablation material. The whole engine consisted of a block of ablation material and asbestos embedded in a matrix of phenolic resin with the milled contours of the combustion chamber and the nozzle.

Ignition took place by a hypergolic slug of (50% furfuryl alcohol in 50% hydrazine) stored at the bottom of each diesel oil tank. The mixture is hypergolic with HDA, thus igniting on contact. The ignition takes place within 10 ms and ignited the diesel oil. Re-ignition was not required and neither ignition under microgravity conditions (in this case the furanol would mix with the fuel).

Fuel flow to the engine was controlled via a valve with a planetary gear that regulates the fuel flow in 3 positions. (close, half flow, full low). The half flow rate corresponds to a thrust of 40% nominal. The launcher would be tilted to one side by lowering the flow to the engine on this side thus reducing the thrust and changing the total thrust vector.
In the aerodynamic phase, tube fins (short pipes) rather than regular fins were used to stabilize the rocket. This concept was tested in DFVLR's wind tunnels.
Each engine contained a simple microcontroller, which could only determine whether an engine is working or not. It was a simple ASIC (Application Specific IC) from Motorola, with a nickel cadmium battery and two Darlington transistors potted in a polyurethane block.
In case of an engine malfunction (loss of thrust), the valve was closed and a message passed to the central computer on top of the rocket to stabilize the entire rocket by shutting down he corresponding opposite engine also in order to maintain a symmetrical thrust. This control scheme has been tested and verified by computer simulations.

Staging
Standard is a 3-stage-to-orbit configuration, which is the textbook optimum for middle-energetic propellants.
As mentioned before, a tank and an engine formed a basic unit. Kayser called this arrangement a "Common Rocket Propulsion Unit", abbreviated CRPU or "Common Rocket Propulsion Module" (CRPM). Launch vehicles for payloads from 1,000 kg to 100,000 kg can be assembled from identical mass produced CRPM.
The length of the CRPM could be varied by the number of 3 to 5 m tank segments. The flight tests were carried out with modules ranging from 6 - 12 m in length. A length of 30 m (10 stacked tank segments) was conceivable. An ideal length was considered to be between 12 m and 24 m because of the required volume ratio of oxidizer to fuel of 3:1. In this case the fuel tank could either be one or two 3 m segments. For intermediate sizes, it was not possible to exploit the full capacity of a tank. The structurally strong interconnection between the CRPM is done by specially designed patented brackets.
Lift-off was reasonably uncomplicated: the main control computer located in the top stage received a 40% thrust confirmation from each of the engines. Once confirmed that all engines have ignited the controller waits for .5 sec before commanding the engines to 100% thrust. Within 0.5 seconds the rocket would lift off without the use of expensive hold-down clamps.

Pitch and yaw motions were controlled by the main computer by throttling the thrust or shutting down individual engines.
One disadvantage of this approach was that the switched off of engines retained larger quantities of fuel in their tanks, which could not be used by the other engines, thus increasing the empty weight considerably. Therefore a high reliability of 10^{-6} is required.
Roll control was first considered to be achieved by off-setting the engines of the outermost ring by 10 degrees to the thrust axis. A reduction of the thrust of one engine then causes a rolling momentum of the whole rocket. Later the installation of an additional cold-gas system was considered depending on the actual roll control requirement of a precisely assembled cluster.

The separation of the various stages was done by rubber wheels rolling along the tanks of the lower stage allowing the next "inner" stage to slide out of the cluster upon ignition (see also Fig. 4). The separation of two stages took only approx. 2 seconds.
Since first the furfuryl alcohol must flow into the combustion chamber, the stage was ignited "hot", i.e., the follow-on stage was ignited, while the lower one still was in operation. Staging

therefore was not initiated when the fuel was exhausted but when the rocket had reached a predetermined speed.
The central computer on the last stage would have a gyroscopic system to measure the accelerations. This was used to calculate the speed and location of the rocket. Control was carried out by a conventional program guiding the rocket to a predetermined target trajectory. The engine controls were actuated by a 600 channel radio transmitter / receiver.
The first and second stage would be operated until the fuel was exhausted. According to Kayser this was possible to an accuracy of 0.1%.
The third stage was switched off when the desired final speed was achieved. This was possible with an accuracy of 0.01 seconds, securing an accurate injection of the payload.

Payload

The nested parallel clustering of hundreds of CRPM does allow a transportation cost in LEO down to a few thousand Dollars per kilogram at the highest reliability. But the biggest advantage for future satellite designers is a payload diameter of 10 m for 10,000 kg and 20 m for 50,000 kg. In Kayser's opinion one of the worst detriments of present day launchers is their limited payload diameter

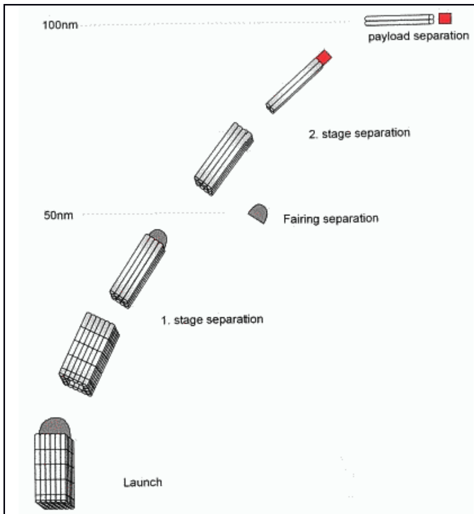
 	**Staging** - Payload separation (red) - 3rd stage ignition and stage "roll"- out (separation) - Protective fairing jettison - The 2nd stage "rolls" out of the surrounding 1st stage - At 99.9% fuel depletion the 2nd stage is ignited - Lift off (1st stage ignition)

Figure 4: Staging and separation

This article was extracted from Bernd Leitenberger's article "OTRAG – Rakete" and translated to English with Bernd's friendly permission. Details can be found in the original German article within the book "Ariane 1-4: Technik und Einsatzgeschichte der europäischen Erfolgsrakete".
The above article was updated and authorized by Lutz Kayser in September 2014 (Version u2).

Summary of documented OTRAG Launches

Nr.	Date	Launch Site	3m-Segments per	Engines	Results/ Purpose

			Engine		
1Z	17.May.1977	Shaba (Zaire)	2	4	20 km altitude
2Z	20.May.1978	Shaba (Zaire)	4	4	Night launch, 30 km altitude
3Z	05.Jun.1978	Shaba (Zaire)	4	4	Failure, rocket deviates
1L	01.Mar.1981	Tawiwa (Libya)	4	4	Failure, rocket turns after 21 sec.
2L	07.Jun.1981	Tawiwa (Libya)	4	4	High speed acceleration test, 20 % fuel
3L	17.Sep.1981	Tawiwa (Libya)	4	1	Roll test
4L	01.Oct.1981	Tawiwa (Libya)	?	1	Complete fuel exhaustion test
5L	24.Oct.1981	Tawiwa (Libya)	?	1	Oxidizer exhaustion test (rough)
6L	19.Nov.1981	Tawiwa (Libya)	?	1	Diesel oil exhaustion test (soft)
7L	12.Dec.1981	Tawiwa (Libya)	?	1	Test with onboard TV camera
8L	02.Jun.1982	Tawiwa (Libya)	?	1	Low-thrust test (10 kN)
9L	24.Jun.1982	Tawiwa (Libya)	?	1	Self-destruction test
10L	02.Sep.1982	Tawiwa (Libya)	?	1	Roll-control test
11L	11.Sep.1982	Tawiwa (Libya)	?	1	Stage- separation simulation
12L	10.Nov.1982	Tawiwa (Libya)	2	1	60 degrees launch
13L	16.Nov.1982	Tawiwa (Libya)	?	1	Concentrated nitric acid as Oxidizer
14L	09.Dec.1982	Tawiwa (Libya)	?	1	JP-4 as fuel
1K	01.Sep.1983	Kiruna (Sweden)	2	1	Successful (?), but destructive high vibrations due to payload cover lid loss

Annex

According to the “Technologieforschung Experimental Report” (Contract Nr. RV 12-V9/73-MK) which had to be supplied to the BMFT/GfW as final report several tank configurations were investigated, tested and/or simulated. The report is dated December 1973, i.e., before OTRAG was established.

The shown tank configuration above seems to be only representative – the author of this article could not research more details about the actual tank configurations actually used during the actual field-tests listed above. (Seven Grahn’s report ”OTRAG at Esrange” suggests a coaxial tank version for this flight).

For the sake of completeness the configurations suggested by Technologieforschung are briefly mentioned in this annex.

- A trade-off of the tank configurations “stacked” or “side by side” was made in favor of the “coaxial” solution (see Figure A-1)
- An alternative was to have one coaxial-tank for more engines with a joint feeding plane (see Figure A-2)
- The trade-off between adiabatic and/or hot gas feed-back pressurization was decided in favor of the adiabatic method (however the hot gas feed-back method was tested to the extent to be fully usable also). The two methods are illustrated in Figure A-3).

Communications with Lutz Kayser in 2014 confirmed that the final chosen configuration corresponds with that shown in Fig. 2 of the main article above (Fig.2: Basic tank/engine module (CRPU)), a stacked fuel/oxidizer tank configuration. The oxidizer was transported to the motor with a 6 cm steel tube, led through the fuel tank, withstanding the 40 bar pressure to avoid buckling (Lutz Kayser, e-mail 13. Sept 2014).

Figure A-1: Coaxial tank configuration with direct engine feed via distribution plates.

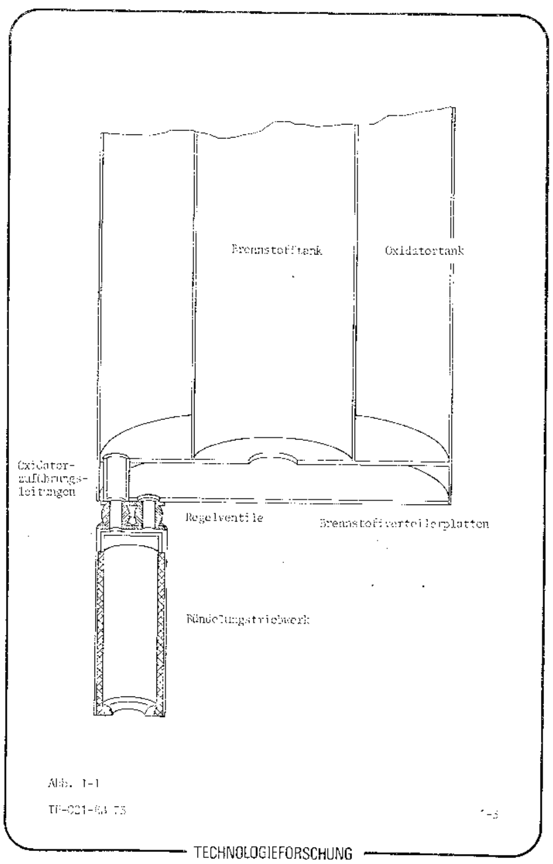
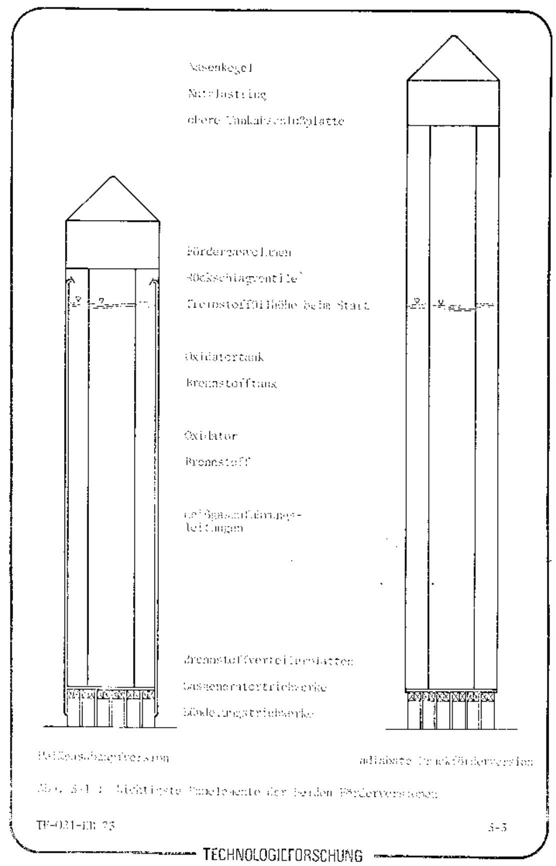


Figure A-3: Feeding systems: hot gas feed-back (left), adiabatic pressure feeding (right)
Hot gas feed-back from the nozzle to the top of the tank (secured via non-return valve)



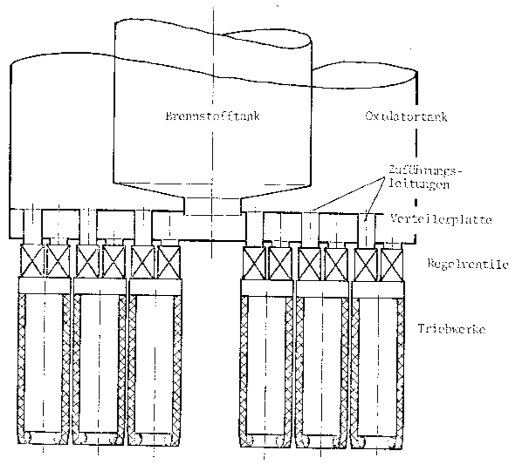


Figure A-2: Single coaxial tank for multiple engines.

fuel tank (inside) oxidizer tank (outside)

feeding lines

joint distribution plate

fuel/oxidizer regulation valves

engines

September 2014_u1, Joachim J. Kehr, Editor SpaceOps News