Wernher Von Braun's Pioneering Work in Modelling and Testing Liquid-Propellant Rockets

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***Abstract**: This paper presents a view on how Dr. Wernher Von Braun laid the basis for realistic modelling and testing liquid-propellants rockets, by his PhD Thesis – a secret document in 1934, which remained classified until 1960. Understanding that better mathematical modelling is needed if these rockets are to become spaceflight vehicles, he clarified in his thesis essential issues like: maximum achievable rocket speed; Laval nozzle thrust gain; polytropic processes in the combustion chamber and nozzle; influence of equilibrium and dissociation reactions; original measurement systems for rockets test stand; engineering solutions adequate for series production of the combustion chamber – reactive nozzle assembly. The thesis provided a theoretical and experimental basis for a new concept of the rocket, having a lightweight structure; low tanks pressure; high-pressure pumps and injectors; low start speed; rocket stabilization by gyroscopic means or by active jet controls; longer engine burning time; higher jet speed. Numerous tests made even with a fully assembled rocket (the "Aggregate-I"), improved mathematical model accuracy (e.g., the maximum achievable altitude predicted for the "Aggregate-II" rocket was confirmed later in-flight tests).*

Key Words: *Von Braun, liquid-propellant rocket testing, combustion, dissociation, flight stability*

1. THE PRECURSORS

Like many other great and noble enterprises, the flight was at the beginning an idea, a theoretical concept barely taking shape from a dream which generated legends like that of Icarus and of Chinese mandarin Van Ho. However, in the latter case, appeared the concept of flying to the Moon with something that already existed: the rockets. As physics and astronomy showed later, the rocket was the only possible concept to fly to the Moon, in the airless cosmic space.

At the end of the 19th and the beginning of the 20th centuries, several great scientists achieved advances in their fields of expertise which became mathematical steppingstones in the field of rocketry:

- in 1897, Ivan V. Meshcherskiy published his thesis on “Dynamics of a Point of Variable Mass”;
- in 1897, Konstantin E. Tsiolkovsky wrote the rocket propulsion formula which he used later in his book written in 1903: “Exploration of Outer Space by Means of Rocket Devices”;
- in 1912, Robert H. Goddard, not knowing of Tsiolkovsky's 1903 work, independently developed the rocket equation and, unlike Tsiolkovsky, included in his differential equation the effects of gravity and aerodynamic drag;
- in 1913 Robert Esnault-Pelterie, not knowing of Tsiolkovsky's 1903 work, wrote also the rocket equation and calculated the energies required to reach the Moon and nearby planets;
- in 1922, Hermann Oberth proposed a doctoral dissertation on rocket science which was initially rejected as “utopian”. His 92-page work was published in June 1923 as a book which became famous: “The Rocket into Planetary Space” (*Die Rakete zu den Planetenräumen*);
- in 1928, Herman Potočnik (under pseudonym Hermann Noordung) published his book: “The Problem of Space Travel - The Rocket Motor” *(Das Problem der Befahrung des Weltraums - der Raketen-Motor)*;
- in 1929, Hermann Oberth had expanded his dissertation to a 429-page book under the title: “Ways to Spaceflight” *(Wege zur Raumschiffahrt)*.

These great scientists were not always unaware of each other's work; they wrote to each other in some cases, as did Hermann Oberth to K.E. Tziolkovski, who sent him his book of 1903 on “Exploration of Outer Space by Means of Rocket Devices” (‘Issledovanie mirovih prostranstvy reaktivnimi priborami”). In 1923, Hermann Oberth received from Robert H. Goddard his report “A Method of Reaching Extreme Altitudes”. And in 1925, young Wernher Von Braun, who was 13 years old and dreaming of spaceflight even since he was looking at the Moon through his amateur telescope (a gift from his parents) came across the first book of Hermann Oberth and desperately tried to understand the advanced mathematics involved in modelling rockets and spaceflight. That was a turning point in his life, not only because he decided to learn well mathematics and physics, but also decided on his way in life: to build rocket engines and spaceships. Wernher Magnus Maximilian, Freiherr von Braun, was born on 23rd March 1912, in Wirsitz, a town in the Posen Province, then part of the German Empire. He inherited the title of “Freiherr” (equivalent to Baron) from his father, Magnus Freiherr von Braun (1878–1972), a civil servant and conservative politician who served as Minister of Agriculture in the federal government during the Weimar Republic. As a child, young Wernher began his “carrier” in rocketry by mounting a couple of fireworks on a toy car and igniting them in a park in Berlin – a “propulsion test” which granted him the attention of the police [1]. At the beginning of his studies, he was not very interested in mathematics, physics or chemistry – the decision to become a master in these disciplines came after reading Hermann Oberth’s book and only intensified after he personally met his mentor during activities organized by German rocket enthusiasts. As he will write about him in 1964:

“*Hermann Oberth was the first, who when thinking about the possibility of spaceships grabbed a slide-rule and presented mathematically analysed concepts and designs [...] I, myself, owe to him not only the guiding-star of my life but also my first contact with the theoretical and practical aspects of rocketry and space travel. A place of honour should be reserved in the history of science and technology for his ground-breaking contributions in the field of astronautics*.” [2]

2. THE SPACEFLIGHT SOCIETY (VEREIN FÜR RAUMSCHIFFAHRT)

Powder rockets have been around for a long time, at least since the Mongol invasion of 1240, when Europe saw the first such rockets used in combat by the invaders. In time, European armies learned to use themselves the powder rockets, not only for their psychological effect, but also for signal and reconnaissance purposes [3].

Simple in construction and operation, although lacking the precision and firepower of the big guns, the rockets using solid propellants (either powder or more advanced solid compositions) had already achieved a remarkable development at the beginning of 20th century. But for some enthusiastic people, using only solid-propellant rockets was not good enough. Scientists like K. E. Tsiolkovsky, Robert Esnault-Pelterie, Hermann Oberth, and Robert H. Goddard had already concluded that for space flight, to the Moon and beyond, liquid propellants rockets are needed, as they could provide not only the biggest but also an adjustable thrust, along with long burning time and operational flexibility.

After the publication in June 1923 of Hermann Oberth's book "The Rocket into Planetary Space", space travel and rocketry gained popularity in Germany and, in 1927, a group of enthusiastic amateurs founded an association called "Society for Space Travel" (*Verein für Raumschiffahrt).* The "VfR" grew to around 500 members, with prominent members like Hermann Oberth, Johannes Winkler, Max Valier, Willy Ley and Fritz von Opel. The Berlin municipality allowed them to use an abandoned ammunition dump at Reinickendorf as a rocket launching site, which became known as *Raketenflugplatz Berlin*. In 1930, young student Wernher Von Braun joined the association and participated in experiments coordinated by Hermann Oberth [4].

1930: Hermann Oberth (center) and young student Wernher Von Braun (first from right)

The "VfR" launched increasingly powerful rockets of original design from Reinickendorf, until they attracted the interest of the army. After the World War 1, the Treaty of Versailles had forbidden Germany to build advanced weapons like heavy artillery, combat aircraft, battleships, and others.

But the treaty did not say anything about rockets, probably because they were considered of insignificant strategic value.

It was a gap that Germany would explore, and the opportunity for the liquid propellants rocket to take the lead in the weapons race.

In 1932, Capt. Walter Dornberger together with his commander Cap. Ritter von Horstig and Prof. Col. Karl Becker attended a launch at Reinickendorf. Although the launch failed, they prized the work of "VfR" members and especially the energy of the young student Wernher von Braun and issued a contract for a new demonstration launch. In the end, German Army did not allow his plans for this new kind of long-range artillery to be publicly exposed, and therefore all the members of "VfR" were compelled either to join the army secret program or give up any further rocketry research [5].

Prof. Col. Karl Becker suggested to Wernher von Braun to prepare a doctoral dissertation on liquid propellant rockets, in which case he would be allowed to work at the best test facility of German Army artillery, the Kummersdorf Army Armaments Test Center, in the Department for liquid propellant rockets headed by captain engineer Walter DORNBERGER.

Wernher Von Braun agreed and so he has begun working on his PhD Thesis.

3. TESTING ENGINES AND PREPARING A PHD THESIS

Wernher Von Braun research activities at Kummersdorf were to be kept secret, and his PhD Thesis of 1934 remained classified until 1960. Understanding that better mathematical modelling is needed if these rockets are to become spaceflight vehicles, he decided to clarify in his experiments and his thesis essential issues like:

- the real pressures and temperatures in the combustion chamber and nozzle, for which he designed and built original measurement systems for rockets test stand;
- the real, polytropic processes in the combustion chamber and nozzle;
- the influence of the equilibrium and dissociation reactions;
- the thrust gain when using a convergent/ divergent (Laval) reaction nozzle;
- the maximum speed achievable by liquid propellant rockets;
- the engineering solutions adequate for series production of combustion chamber/ reactive nozzle assembly, without which the liquid propellant rockets would have no military significance.

Building upon the findings of Hermann Oberth, Guido von Pirquet, Johannes Winkler, Gerhard Gruschka, Hermann Noordung and others, Von Braun guided his research with a permanent focus on technical feasibility [6].

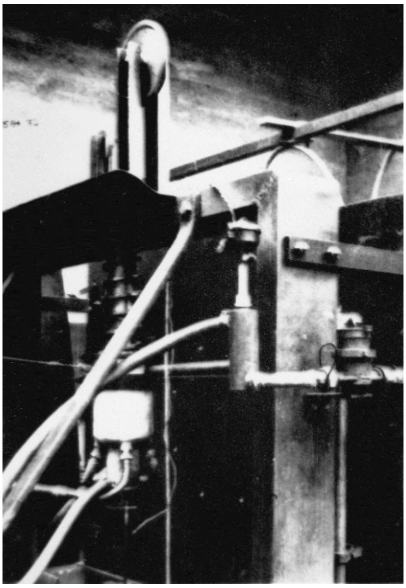
He rightly selected the ethanol to be used as fuel, because it can be mixed with water in any percentage, unlike other fuels, which may have greater caloric power or be less expensive but are restricted to certain mixture ratios. This choice gave him the flexibility to modify the alcohol/water ratio according to his experimental purposes and results.

He also selected a combustion regime with fuel excess, in order to use the unburned alcohol for cooling (also from inside) the walls of the combustion chamber – one of the most critical points of the new, uncharted rocket technology.

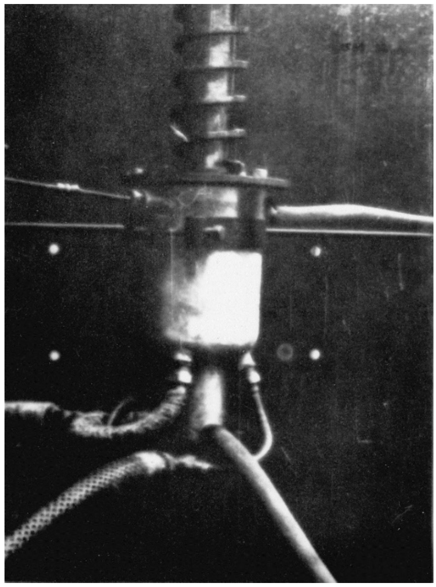
Von Braun was a skilled researcher and created innovative methods and devices to test the combustion chambers performance:

- a system to measure unrestricted thrust, based on free movement upward, against a calibrated spring, of the combustion chamber/ reaction nozzle assembly, coupled to an electromagnetic device to record numerical values;
- pressures in the combustion chamber, nozzle critical section and nozzle exit section were precisely measured and recorded, their gradient allowing von Braun to determine the optimal dimensions of improved models of combustion chambers (he designed and built 4 variants named 1W, 1B, 2B and 2W).

- the pressure in the alcohol and oxygen tanks were closely monitored;
- after an explosion occurred at ignition on one test, Von Braun designed a system by which the ignition would be triggered by the rising pressure itself;
- another dynamometric system was used to measure and record fuel consumption;
- energetic efficiency of the chamber/ reaction nozzle assembly was determined based the measured temperature gradient and the flow rate of cooling water;

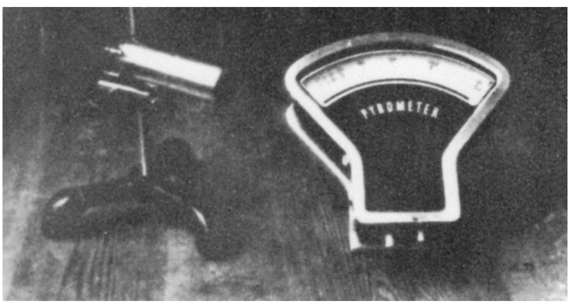


Test stand with thrust holder, calibration device and water cooling device



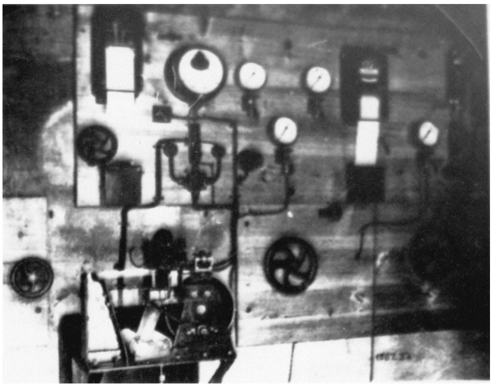
Flange-mounting of a water-cooled combustion chamber on the thrust measuring spring

- temperatures in the nozzle exit section and the combustion chamber itself were not measured by thermoelectric sensors – Von Braun demonstrated they were useless to measure very high (exceeding 1000^{o}K) and very rapidly changing temperatures in the conditions of very short (around 10 to 20 seconds) firing processes. He used instead a radiative pyrometer to measure temperature in the nozzle exit section and an absorption spectrometry method to measure the temperature inside the combustion chamber itself.

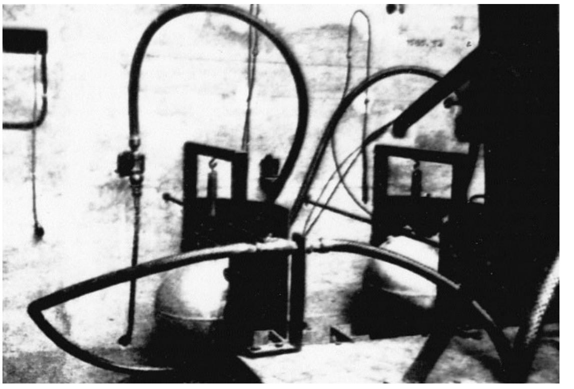


Measurement of the nozzle exit section temperature with a total radiation pyrometer

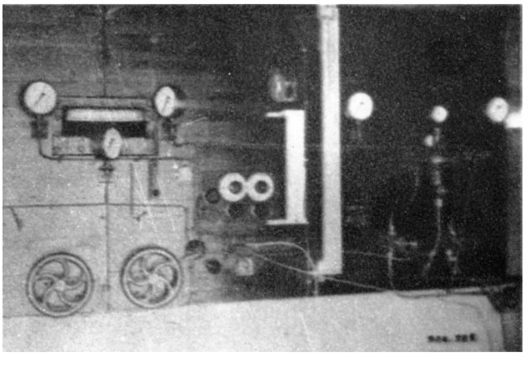
Having tested the best ways to organize various measurements, Von Braun got eventually the first modern rocket firing stand – although by today's standards it may not look like state of the art – but we should remember that the year was 1934!



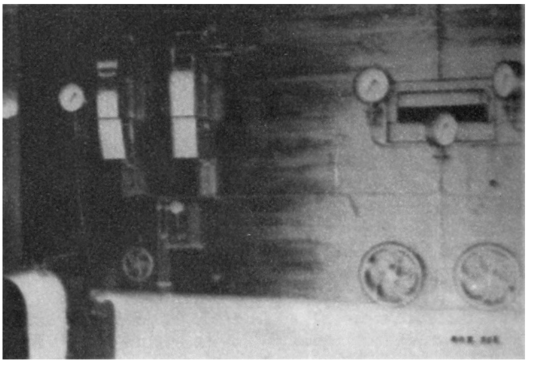
Observation room with thrust recorder, emptying recorder, combustion chamber pressure recorder, pressure reading gauges, cooling water thermometer, ignition device, fuel and oxygen main valves and ventilation taps



Fuel and oxygen tank for test bench operation with additional pressure lines, liquid lines and valves and movable tank suspension for emptying registration



The control panel of the test stand after the conversion. Right side: Additional pressure stand with reducing valves, high-pressure cocks, air vents and pressure gauges. Left side: the control panel with fuel and oxygen main controls and armored observation slot.)



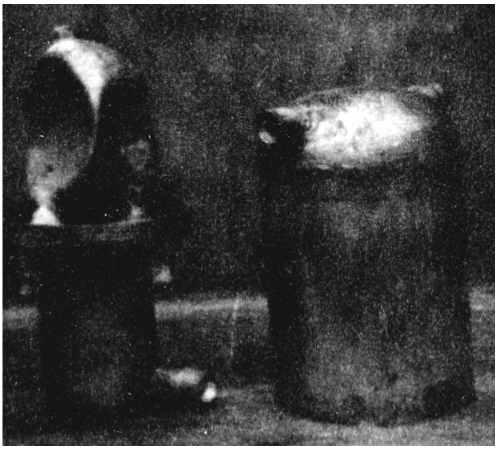
The switchboard of the test bench after the conversion. On the left the writing stand with discharge recorder, thrust recorder, combustion chamber pressure recorder, neck and muzzle pressure reading; the control position on the right.

The diagrams obtained allowed him to draw important conclusions about design and construction of combustion chambers. As he writes:

"The most important task in the construction of the combustion chamber is therefore to make full use of the existing combustion chamber size by means of appropriate and vigorous atomization. To save weight, use light metal as the combustion chamber material. This leads to the requirement to transfer the resistance of the combustion chamber and nozzle walls from the ceramic problem of increasing the heat resistance to the constructive and technological problem of heat dissipation" [6].

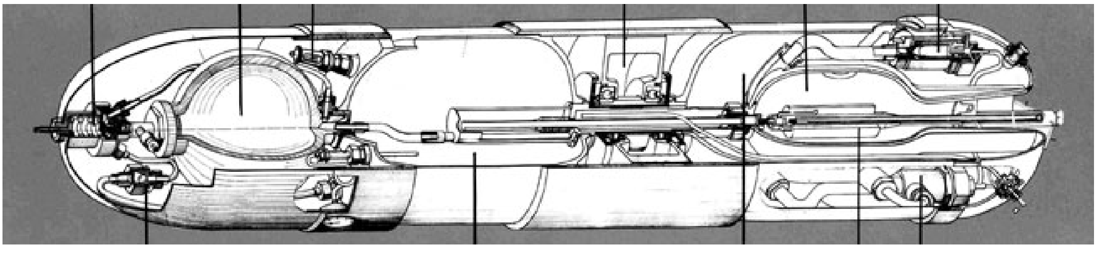
Von Braun made, for the first time, static firing tests on a test bench with a fully assembled rocket, the "Aggregate-I" model, which was not however intended to fly. But for an airworthy rocket like the "Aggregate-II" (two of which flew successfully in the winter of 1934, after Von Braun finished his thesis and got his PhD) cooling with water could not be an option.

Cooling with fuel (the alcohol) was made instead, but this time the outer side of the combustion chamber was subjected to the higher pressure existing in the alcohol tank – and the first model buckled. By reducing the combustion chamber diameter, increasing the wall thickness from 3 to 3.5 mm and by using alloys with higher strength values, the construction of a flyable fuel cooling combustion chamber, **Type 2B**, was finally achieved.



Development of fuel-cooled light metal combustion chamber: **Type 1B** buckled under the cooling water pressure

The **Type 2-B** combustion chamber with automatic fuel cocks, ready for installation on the "Aggregate-II" rocket



The "Aggregate-II" rocket

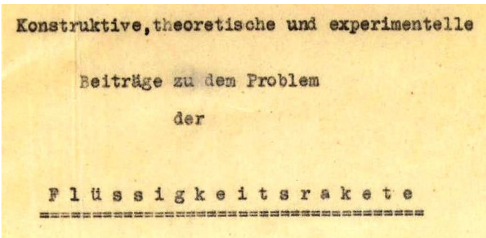
The thesis provided theoretical and experimental basis for a new concept of rocket, having:

- lightweight structure;
- low tanks pressure;
- high pressure pumps and injectors;
- low start speed;
- rocket stabilization by gyroscopic means or by active jet controls;
- longer engine burning time;
- higher jet speed at the nozzle exit section.

Numerous tests made even with a fully assembled rocket (the "Aggregate-I"), improved mathematical model accuracy. The maximum achievable altitude he predicted in his PhD Thesis for the "Aggregate-II" rocket was confirmed later by in-flight tests.

Practical calculation examples, included in his PhD Thesis [1], confirmed mathematical modelling accuracy and in 1934, at the University of Berlin, Wernher Von Braun obtained his doctorate with a classified thesis about "Constructive, theoretical and experimental contributions to the problem of the liquid fuel rocket".

On the diploma was printed only an unclassified title: "ÜBER BRENNVERSUCHE" ("About Testing Combustion").

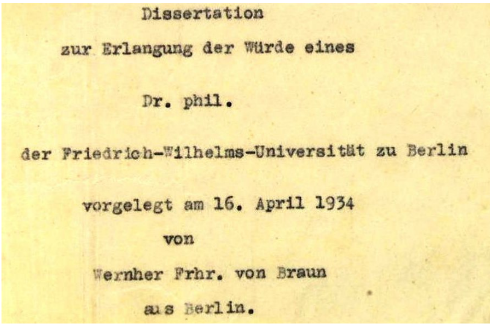


Konstruktive, theoretische und experimentelle

Beiträge zu dem Problem

der

Flüssigkeitsrakete



Dissertation

zur Erlangung der Würde eines

Dr. phil.

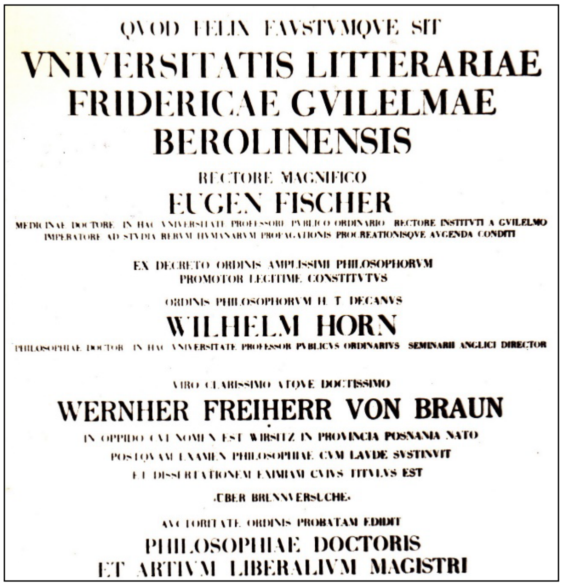
der Friedrich-Wilhelms-Universität zu Berlin

vorgelegt am 16. April 1934

von

Wernher Frhr. von Braun

aus Berlin.



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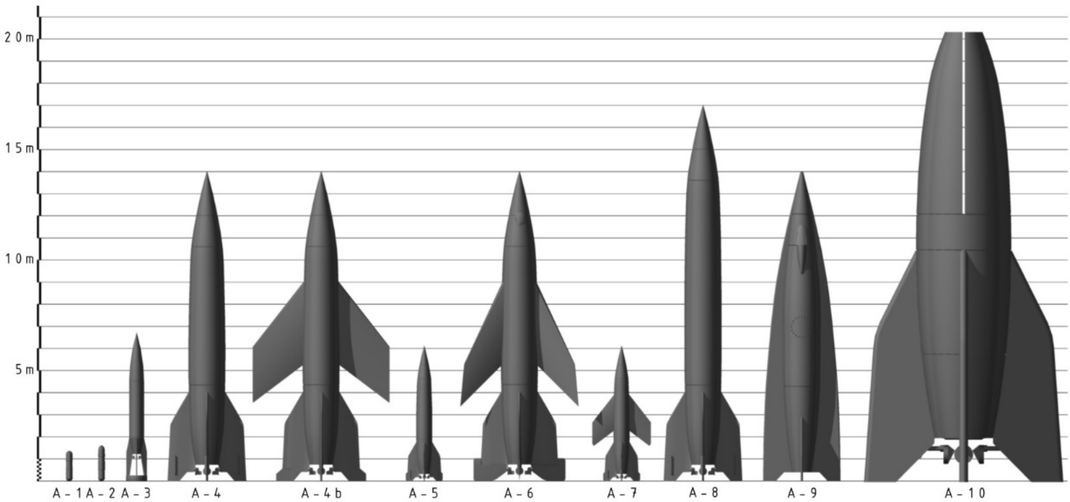
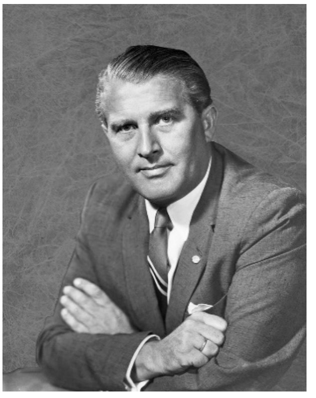
The concept of rocket which took shape from this PhD Thesis was a scientific base for the series of the “Aggregate” series of rockets which includes the first man-made object to fly outside the Earth atmosphere in 1942 (“A-4”, known also as the infamous “V-2”) and also the “A9/A10” complex, which was the basis for the “Redstone” rocket which in January 1958 launched the first USA satellite, the “Explorer-1”.



The “A” rockets series

4. THE SCIENTIFIC LEGACY OF VON BRAUN



Wernher Von Braun (1912–1977)

In the 20th Century, rocket science has developed and diversified so much, that it became difficult for one person to "speak" all its specialized "languages". Specialization was inevitable, but on the other hand, there was an even greater need for leaders capable of multidisciplinary approach with the ability of a "polyglot of sciences". Wernher Von Braun was such a rare man. Dreaming of rockets since childhood, he remained committed to spaceflight all his life. Having made himself advanced researches in the field of liquid fuel rocket engines, he was able to inspire and coordinate research teams made of the best experts in the field, first in Germany, and later in the USA [7].

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