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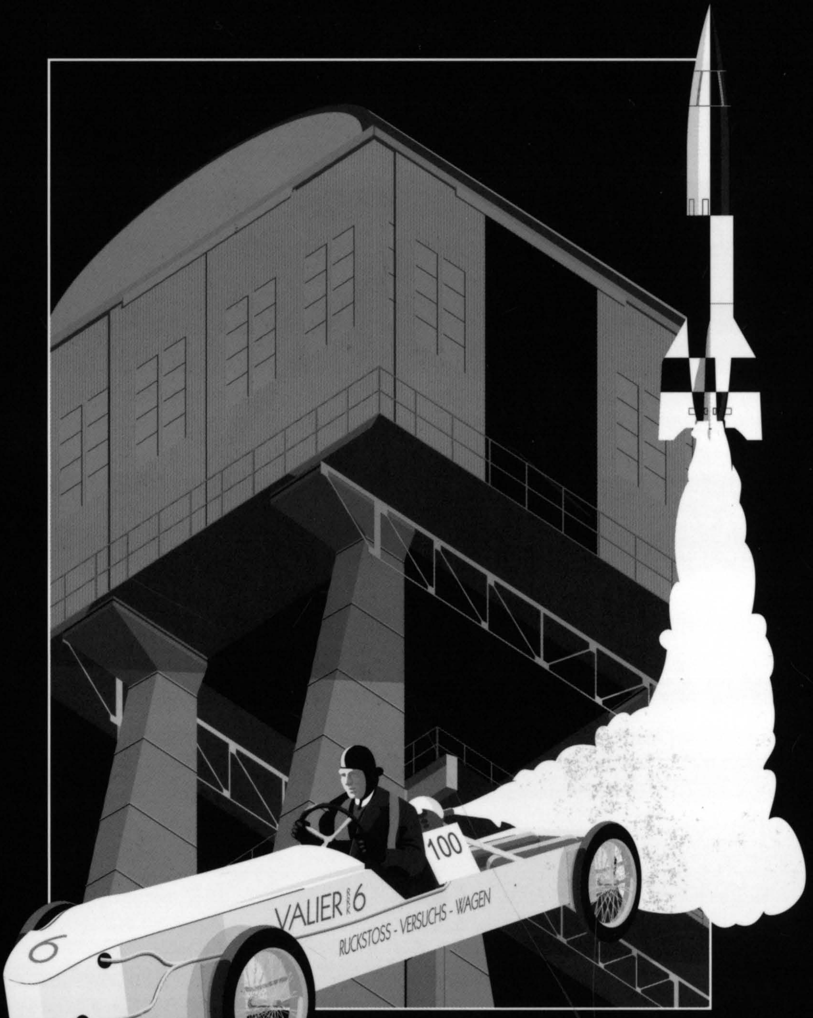
ROCKET DEVELOPMENT WITH LIQUID PROPELLANTS



A BRIEF TECHNICAL OVERVIEW BY

W H J RIEDEL

TRANSLATED FROM THE ORIGINAL BY

DR J C KELLY

TECHNICAL SERIES NO7

ROLLS-ROYCE HERITAGE TRUST

ROCKET DEVELOPMENT WITH LIQUID PROPELLANTS

From the early days with Max Valier
to the A4 (V2) long-range rocket

(1930 to 1942)

A brief technical overview by
W H J Riedel
Written at Westcott near Aylesbury
July 1950

Translated from the original by
Dr J C Kelly

TECHNICAL SERIES No7

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INTRODUCTION

The Riedel papers cover one of the most evolutionary periods of European liquid propellant rocket engine development. Their unequivocal authenticity lies in the fact that they were written, almost as an autobiography, by a key engineer as he had seen it, on a year-by-year basis.

The papers were completed in 1950, during the author's time at the Rocket Propulsion Establishment at Westcott, near Aylesbury. He wrote it, largely as a tribute to his mentor, Max Valier, a respected rocket pioneer.

Because it was Riedel's native tongue, the papers were largely written in German. It is believed that the British Interplanetary Society were approached, late in 1951, with a view to translating and publishing the documents, but at that time it was felt that the costs of both translation and reproduction of the many illustrations exceeded the available resources.

The document eventually found its way to the archives of the Imperial War Museum, though by this time a number of key illustrations had disappeared. There the documents rested until noted by Mr P R Stokes, a researcher in rocket history, in about the year 2000.

In the passage of the fifty years since they were written, the world has seen the exploration of space (near Earth, Lunar and Planetary) on a scale previously only foreseen by the 'dreamers' of the various rocket communities. Even Britain took until 1971 to launch its first, all-British launched satellite, called Prospero, using the Black Arrow rocket vehicle, much of whose technology can be traced to German liquid propellant engine developments. Recent history has, therefore, significantly increased the value of a comprehensive document such as Riedel's. Given these early results, many present day systems can be traced to German projects – V-2 technology can be found in British, American and Russian rocket engines. (This in no way diminishes the stalwart efforts made in the UK by Professor Lubbock and his team).

The 'rediscovery' of the papers was brought to the attention of the Rolls-Royce Heritage Trust at the time when some publication covering UK engine developments was already being considered. The Trust, therefore, having assessed the approximate content of the text and illustrations, arranged to have it translated into English so that a detailed assessment of its value and content could be made by persons who had actually worked on the UK rocket programmes.

This study showed the Riedel papers to be absolutely fundamental to consolidating the exact history of this crucial period (1930 to 1942/3) and thus a decision was taken to take the necessary steps leading to a possible publication of this work. This meant a critical review of the basic very comprehensive translation, followed by an in-depth study of the many technical parameters and values quoted.

It also fell to me, as technical coordinator to attempt to reproduce the missing illustrations, using both research material and knowledge of how 'we' did these things in the UK. The synthesized diagrams are, therefore, presented as 'Coordinator's impressions'. In one case, research has still failed to produce the finest of details described on a thrust chamber ignition device; this omission is noted in the text. Footnotes are also added, which it is hoped improve the understanding of certain points arising.

In order to show Riedel's vast range of experience, some of the key events in his life are presented as an appendix. The list, compiled by Peter Stokes, is extensive and serves to illustrate the range of projects in which Riedel was involved, thus reinforcing the value of the papers as a profound reference.

Whilst the papers end 'historically' in 1943, Riedel eventually came to England in 1946 to continue working on rocket engines at the Rocket Propulsion Establishment at Westcott. Little is known of his life after 1950, except that he became a British citizen in 1957 and died in 1968. We can only try to place on record his story of the evolution of liquid propellant rocket engines technology as we know it today. He was obviously a deeply-committed engineer but also had a flair for sketching technical apparatus. To this end, all of his pencil sketches of rocket engine systems and test facilities are reproduced untouched in this publication. It is rare to find such exactitude in engineering sketches, many of his constitute artwork in their own right.

It has been a great honour for me to coordinate this publication technically, ably assisted by Peter Stokes, an engineer for the de Havilland rocket work. I must also thank Dr John Kelly, a retired Rolls-Royce engineer and German translator, for his highly professional work in what to him was a new subject discipline. The translation is an accurate, authentic recording of the original text and illustrations.

Riedel dedicated his work to Max Valier. We can only support his efforts by publishing an English version of his work as a Rolls-Royce Heritage Trust book.

J L Scott-Scott
Technical Coordinator, January 2005

FOREWORD

About 20 years ago in Germany the public first became aware of a number of experimental groups who were testing liquid propellant rockets. Some years previously it was solid propellant rockets that were being demonstrated. One remembers the Sander-Opel-Valier tests with land vehicles in which solid propellant rockets were used as the propulsion system. In this monograph I will describe the development of liquid propellant rockets from the earliest days with Max Valier up to the long-range rocket, the V2. I was engaged in this development from its beginnings and up to the final days of the V2, and in this monograph I have given myself the task of recording the path followed in historical sequence. After the long years of secrecy I felt that it was necessary that this subject should be written about from an authoritative viewpoint, since following the developmental path taken from the initial to the final chapters provides a fascinating and important overview of rocket design. It is now 20 years since Max Valier, a pioneer of rocket development, was forced to lay down his life for his ideas. This one fact in particular has obliged me to write this monograph in memory of Max Valier. Today we know that his thoughts, ideas and records of the direction for future development were not incorrect. In retrospect we can see that he foresaw much that has already found practical application today.

In the years around 1930 there were basically two groups active in the field of liquid propellant rockets. The one group, familiar through the names of Prof Oberth, Klaus Riedel, von Braun, Nebel, etc worked on the rocket launch site in Berlin-Tegel. The author Willi Ley, who also belonged to this group, has become well known through the publication of various books on rocketry in which the activities of this group have already been described.

The other group, associated with the familiar names of Max Valier and Dr Heylandt, worked on the Heylandt company's site in Berlin-Britz. I emerged from this group, and subsequently in collaboration with Dr von Braun I took part in the ongoing development of liquid propellant rockets through to completion of V2 development at the Army Establishment at Peenemünde.

I will describe the development path taken by this latter group. It is not my intention to publish a scientific work, but rather I will attempt to give a technical overview in a summarised form. Many of the drawings are more or less retrieved from memory since records were not permitted to be kept for reasons of security. Other documents are no longer available and in part have been lost as a result of the war.

In memory of Max Valier I have shown a picture of him that was taken in his last year, shortly before his death. Max was a true pioneer of rocket development. He dedicated himself to the development of the rockets with a huge amount of effort and energy and tireless enthusiasm. His practical and technical talents and his determination to engage people both in writing and verbally in support of his ideas produced practical results in a short time in the early days of development. His civilised and courteous character was impeccable, with the result that he received the greatest empathy and respect from all quarters. Prematurely, on the 17 May 1930, he was torn away from a promising life as a result of a tragic accident in the course of a rocket test. In this manner a young, precious personality in whom many hopes had been placed, a true pioneer in rocket development, was taken from us. At this point I would like to reproduce an extract from the foreword of his book Rocket Travel that was published on 10 November 1929. In this piece one can recognise his completely unselfish attitude to the problems of rocket development.

> *The phrase "fast travel using rocket propulsion" will then no longer be made up of empty words, and also the "venture into space" may then come to pass. For the world it will basically be unimportant which of the individual researchers makes the decisive discoveries. For the researchers themselves however it is a hard battle in which each must dedicate all the means at his disposal, including his own life. And this each will do willingly, since each knows that only through the exertion of all his energies and in fair and open competition will this greatest of technical problems be mastered.*

The book *Rocket Travel* closes with the words:

'ONLY ABILITY WILL FULFIL THE DREAM'.

As one who was Max Valier's closest colleague I am now writing this monograph in memory of him and in gratitude and recognition of his contribution. And when at some point a history of rocket development is written I hope that no-one will forget the researcher and rocket pioneer – Max Valier.

Walter Riedel, 1950

-5a-

Versuchsfahrt mit CO_2
am 22.12.29. auf der Avus in Berlin.

R.002.

Bild 0

Ai.
1.7.32.

Fig 0: Test drive with CO_2 on 22.12.29 on the Avus in Berlin

CHAPTER ONE

Development projects involving liquid-propellant rockets at the Heylandt Company in Berlin-Britz (1930-1933)

In his book Rocket-Powered Travel Max Valier described the last testing activities with solid-propellant rockets in collaboration with von Opel and Sander. We still remember the vehicles propelled by solid-propellant rockets and individual test runs - in particular Fritz von Opel's test run on the Avus. In 1929 collaboration between Valier and Opel became no longer viable, since Opel used these experiments to exploit them as propaganda for his own name and that of the company. Valier was no longer able to apply his own thoughts and plans towards his prime objectives, and therefore withdrew from the partnership. At that time he also came to the conclusion that the energy content of the powder set a limit for the development of solid-propellant rockets that was lower than that for liquid-propellant rockets, and that it was now the right time to turn to the development of the latter.

It is well known that the so-called 'fuels' are hydrocarbon compounds in certain compositions and that these when ignited burn in reaction with oxygen to form carbon dioxide (CO_2) and water vapour (H_2O), neglecting dissociation. This reaction produces combustion gases that can exit from a combustion chamber with a de-Laval nozzle attached at high exit velocities (1800-2500 m/sec). The thrust from a combustion chamber in which fuel burns with oxygen or an oxygen carrier (eg HNO_3) and exits through a de-Laval nozzle, is in very general terms given by:

$$S = \left(\frac{G_t . c}{g} \right)$$

where S = the thrust produced in kg, G_t = the mass flow rate of exiting gas in kg/sec, g = the acceleration due to gravity in m/sec^2 and c = the exit velocity in m/sec. The best combustion reaction agent is pure oxygen. It is not practical to use this in a gaseous state, since it would have to be stored in strong steel bottles operating under high pressure, with the result that the empty weight of the rocket would become too large. Instead the oxygen must be utilised in a liquid state.

On the basis of these deliberations Max Valier decided with good reason that he had to seek collaboration with a specialist who was very familiar with the production and handling of liquid oxygen. The most obvious course of action was to turn to the well-known specialist Dr Heylandt. In the Britz district of Berlin the latter had a factory that manufactured all the equipment necessary for the production and transport of liquid oxygen. At the end of 1929 negotiations were concluded in which Dr Heylandt agreed to support Max Valier in the development of liquid-propellant rockets using liquid fuels and liquid oxygen. At that time I had a position as Test and Development Engineer with the Heylandt Company with the aim of putting into practice Dr Heylandt's new patents concerning equipment for the practical and safe transport of liquid oxygen. In addition to this activity I was assigned in 1929 by the company to begin design and development work with Max Valier, and from that time to the present I have been actively involved in the development of liquid-propellant rockets. However, before reporting on the practical design and development activities, I must describe the strategy to be adopted as put forward by Max Valier. His was in complete contrast to that of the other design and development group at the rocket launch site in Berlin-Tegel. In their work this latter group headed straight for the ultimate objective and built a rocket vehicle for flight that became known by the name 'Mirak'. In contrast Valier wanted to develop a propulsion system in which all the individual components, working as an assembly, would provide measurable evidence of good performance. This concept undoubtedly provided the advantage of incremental development and the opportunity to go public sooner to report on the latest developments. At the same time this would arouse and promote the interest of the public in these activities. A rocket unit from the test stand could be installed into a land vehicle or an aircraft much more easily and be demonstrated to the public in this state, without having to worry about the configuration and weight necessary for a rocket vehicle designed for flight. In this manner the practical was combined with the virtuous. At that time rocket development lay in the hands of idealists who did not have funding at their disposal and who therefore had to earn the money for further development by means of publicity and demonstrations. Max Valier also had to resort to such measures, despite the fact that he was linked with an industrialist. Dr Heylandt certainly had provided some financial support, but for the future the funding had to come from demonstrations and lectures. Since Max Valier had previously promoted demonstrations using rocket-powered land vehicles, this route was to be pursued further. There was however a danger of bringing the work into disrepute, since most of the public assumed that the project was concerned with a new form of land vehicle propulsion, which was not the case. Setting aside the different views in the two camps concerning the direction of development, and whether the one or the other was correct, I will now describe the course taken in design and development with Max Valier.

One day towards the end of 1929 the rocket car with which Max Valier had conducted his earlier tests with solid propellants made its appearance in Berlin-Britz. It was a long wooden chest with two axles, a proper steering wheel and a foot brake. The most valuable items were the tyres! While we were looking at the vehicle with quiet smiles, Max Valier was full of pride. This was easy to understand! In this small, makeshift vehicle he had gained the first successes in his career. For him this small vehicle was worth more than the most expensive and stylish Mercedes.

It was now decided to rebuild this vehicle somewhat and to fit it out with a carbon dioxide propulsion system. This system had nothing to do with the development of a liquid-propellant rocket. What was in mind was to set up a demonstration for the press in which this car would be driven using the carbon dioxide propulsion system. In the view of the organisers this was a way of bringing it again to public attention and of demonstrating the thrust principle to the public once again using simple practical means. At the same time this would steer the attention of interested parties towards the merger of interests between Max Valier and Dr Heylandt and would announce the fact that this collaboration introduced a new era of rocket engine development using liquid propellants.

With reference to the carbon dioxide propulsion system it should be mentioned that industrial storage of carbon dioxide is normally in steel bottles. In these steel bottles it is held in a liquid state under the critical pressure of ~ 50 atm. If heat is applied from an external source to the steel bottle, the liquid carbon dioxide converts to a gaseous state with a simultaneous increase in the pressure. This is the physical process that was used for the propulsion system to be demonstrated.

The driver's seat that was originally positioned almost over the front axle was moved into the centre of the vehicle. This provided space to accommodate four carbon dioxide bottles. Behind the driver's seat two further bottles were accommodated. The six steel bottles were connected via main isolating valves and a common manifold system to a plenum chamber. The plenum chamber was a near-spherical tank with strong walls that at one end featured the exhaust nozzle and at the other end the guide for the Pelton pin[1]. The Pelton pin was used to regulate or close off the throat area of the nozzle. It was connected via a cable to the foot pedal that was located next to the brake pedal. By moving the foot pedal the exhaust mass flow rate could be regulated simply through the axial movement of the Pelton pin.

On 22 December 1929 the demonstration of the car took place on the 'Avus' in front of the press representatives. Before the car could be started the pressure in the bottles had to be increased so that the carbon dioxide was converted from the liquid to the gaseous state. A public house located nearby provided hot water that was poured into a large tank in which the steel bottles had been placed. When the pressure had increased to ~ 100 atm the bottles were transferred to the car, connected to the manifolds and the main valves opened. The car was ready for the off. Actuation of the foot pedal opened up the exit nozzle and the car began to move.

Figures 0-2 show the photographs from this demonstration. In Figure 0 Max Valier can be seen in the demonstration car after the start. The location and configuration of the steel bottles can clearly be seen; also the manifolds that are still covered with rime ice caused by the expansion of the carbon dioxide gas flowing through them. Figure 1 shows the car during the run. Here one can see the carbon dioxide exhaust stream. The speed achieved was low and the run time was only a few minutes. Figure 2 shows the plenum chamber with the exhaust nozzle. At the head of the chamber can be seen the connection to the manifold and the cable for actuation of the Pelton pin.

The actual design and development of combustion chambers for the liquid propellants began in January 1930. The blowtorch that had often played a role in the past in demonstrations of thrust provided the starting point for the design. The normal combustion head of the blowtorch was modified accordingly and the normal injection system was used in its entirety. The first design can be seen in Figure 3. Two ducts 's' were introduced into the combustion head '0'. These were fed from one manifold 'L'. The normal atomiser device a remained in its place. For the combustion tests ethyl alcohol was mixed with water. Gaseous oxygen was used from steel bottles. The ethyl alcohol was fed through the atomiser device 'a' and the gaseous oxygen passed through the manifold 'L' and the two small ducts 's' into the combustion chamber. The first tests produced a flame without any significant thrust. As a result the device was modified as can be seen in Figure 4. The combustor head now contained an exhaust nozzle 'd'. The ethyl alcohol passed through a duct 'l_1', heating coil 'S' and 'l_2' into the atomiser 'a'. This configuration was somewhat more effective, but was in no way satisfactory since a large volume of unburned material still

[1] *A Pelton pin is a conically-shaped valve head that is normally used in water turbines to vary the jet flow area.*

exhausted from the nozzle. This was understandable since the propellants were injected in the same direction as the exhausting combustion gases. It was anticipated that the effectiveness would be significantly higher if the ethyl alcohol were to be injected in a direction counter to the main flow. Figure 5 shows how this thinking was put into practice. A small injection pipe 'st' projecting into the combustion chamber featured a small spray head 'k_0' in which were located a number of small spray holes. The ethyl alcohol was now injected through these holes counter to the oxygen gas flow incoming from the chamber 'K'. The level of success was in accordance with expectations and was very satisfactory. Encouraged by this success a new combustion chamber was immediately built and this can be seen in Figure 6. This combustion chamber failed to achieve any practical significance however, since it represented too big a step forward at the time, and setbacks were fated to appear. Nevertheless the combustion chamber did burn. A number of photographs, Figures 7-9, show the overall view of the combustion chamber. In Figures 10-11 the combustion chamber can be seen whilst burning.

Using this experience we built another combustion chamber after two further months of experimentation. This unit can be seen in Figure 12. The chamber '0' was made from a conventional steel tube. At one end was attached the exit nozzle 'd' and at the other end the spray injection system for the propellants. The oxygen was supplied from the plenum chamber 'K' through a number of small holes in the disk 's' into the combustion chamber. A baffle 'w' reduced the velocity of the oxygen gas flow by forming vortex fields behind the disk. Figure 12 shows the arrangement when operating with gaseous oxygen, while Figure 13 shows the same device when using liquid oxygen. The complete experimental set-up for tests of the combustion chamber unit can be seen in Figures 14 and 15, which are self-explanatory. Figures 16-18 show the combustion chamber unit while combustion was taking place. These tests were carried out in the test laboratory of the Heylandt company, and from Figures 16-18 it can be recognised that the tests were carried out in a rather naïve and careless manner with little regard for the possible dangers! Figure 16 shows this in particular. In this photograph we can see Max Valier placing one weight after another on to the balance scales as the thrust increases!

In general terms the tests were carried out as follows. After ethyl alcohol had been poured into the tank, the latter was pressurised and small quantities of the propellants were fed into the combustion chamber by opening both the ethyl alcohol valve and the reducing valve in the oxygen circuit. Using the flame of a conventional blowtorch the propellant mixture was now ignited at the exit plane of the nozzle, so that a small flame was formed in the combustion chamber. By opening the propellant valves further the combustion chamber pressure and hence the thrust could be increased. The latter could be measured by placing weights on the balance scales. When one thinks about the many safety regulations that govern rocket tests today, one can only wonder at the matter of fact and carefree manner in which the tests were carried out in the early days.

The accompanying list (Fig 18A) shows the test records for the period from 4 March 1930 to 1 April 1930. The records show the most important test results that were achieved at that time. The combustion chamber pressure was on average 1-4 atm, the thrust achieved was between 2 and 20 kg and the combustion duration was between 10 and 20 minutes, using gaseous oxygen.

On 26 March 1930 liquid oxygen was used for the first time and was always used thereafter.

Figures 19-22 show the tests in which the combustion chamber unit was mounted on the test car with combustion taking place. Max Valier can be seen once again in Figure 22. Figures 23 and 24 supplement the set of photographs. The combustion chamber unit can be seen, still with the blowtorch injection system and this can be compared with Figure 4. Figure 24 clearly shows the stem with the small spray injection head and Figure 25 once again shows the spray injection system. Here the liquid oxygen was sprayed through small tubes into the combustion chamber. The small tubes were configured so that the liquid oxygen impinged on to the edge of the disk, breaking up the jets and converting the liquid oxygen into droplet form.

Rebuild of the rocket car with a liquid propellant system began in April 1930 and the car was re-designated 'Rak 7'. The carbon dioxide bottles were replaced by the ethyl alcohol and liquid oxygen tanks together with a steel bottle for the nitrogen used as the high-pressure gas to drive the propellants into the combustion chamber.

Figure 26 shows a schematic of the pipework and valves for the test car's ethyl alcohol-liquid oxygen propulsion system.

The thrust was 20-30 kg.

The drive time duration, dependent on the amounts filled into the tanks, was 8-10 minutes.

On 17 and 19 April 1930 the car was successfully demonstrated to the press at the Heylandt company site in Berlin-Britz. This date is one to be remembered since it has a particular historical significance. It was on this day that a rocket propulsion system with liquid propellants was demonstrated for the first

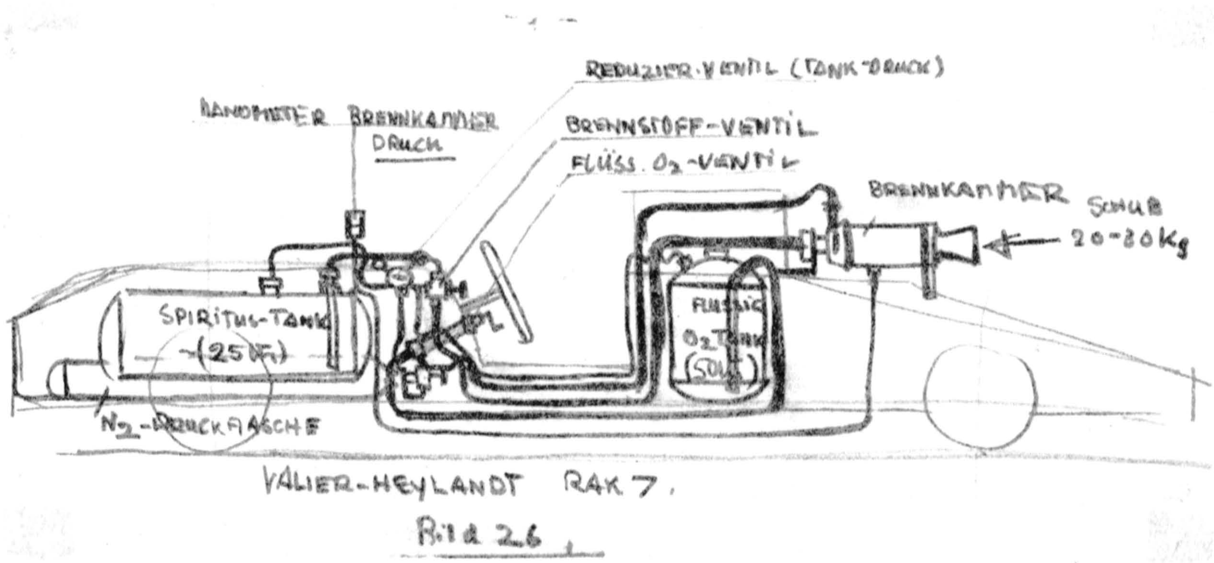

Fig 26: Valier-Heylandt RAK 7

Brennkammer	combustion chamber
Brennstoffventil	fuel valve
flüssig O_2-Tank (50 ltr)	liquid O_2 tank (50 litres)
flüss. O_2-Ventil	liquid O_2 valve
Manometer Brennkammerdruck	combustion chamber pressure gauge
N_2 Druckflasche	N_2 driver gas bottle
Reduzierventil (Tankdruck)	tank pressure reducing valve
Schub 20-30 kg	thrust 20-30 kg
Spiritus-Tank (25 ltr)	ethyl alcohol tank (25 litres)

time, and as such it can be judged to be the start of all subsequent rocket development using propellants of this kind. After four months of design and development activity, starting with the blowtorch tests, the first rocket propulsion system had been developed and publicly displayed. As I have already stated at the start of this monograph, this kind of propulsion system was never intended for practical application in a land vehicle. Nevertheless, these first demonstrations provided the evidence that liquid propellants could be burned to produce a thrust that could propel vehicles. With reference to the short development time it should also be added that the design, development and testing activities had to be carried out after normal working hours, since normal work could not be disturbed. On the other hand well-equipped workshop facilities were made available, staffed exclusively by coppersmiths. As is well known, coppersmiths are craftsmen who are very comprehensively trained and able to turn their hand to almost any kind of task. These highly qualified craftsmen made it possible to manufacture a rocket propulsion system in a short space of time and to demonstrate it in public. The following set of pictures, Figure 26a, comprises a number of photographs taken in the course of the press demonstration. Unfortunately I do not have any further photos in my possession that show the vehicle during its run. In the first two pictures Max Valier can be seen in the car while it is being filled with liquid oxygen. The large tank near the car is a storage tank for liquid oxygen as used by the company for commercial purposes. In the next row the car is shown in side view. On this side of the car one can see the liquid oxygen valve and the pipework to the combustion chamber as well as the combustion chamber itself. The next picture shows Dr Heylandt (with hat in hand) as do the two lower pictures.

Figure 27 shows Max Valier and Dr Heylandt near 'Rak 7' as the liquid oxygen is being tanked aboard.

During this successful period Max Valier was able to gain the interest of Deterding, the well-known General Manager of the Shell Company, in his investigations. Deterding wanted to have a financial stake in the work and at the time there were plans to develop a rocket propulsion system for an aircraft that would fly across the Channel. For Deterding this was a publicity project and Max Valier was able to acquire money to pursue his developments more widely. At about this time a physicist and a chemist who had been contracted by Deterding to assess the performance of the existing combustion chamber appeared on the scene. A test lasting 20 minutes was performed for these gentlemen, during which they themselves took the consumption measurements. These measurements reconfirmed the existing performance data for the combustion chamber. Ongoing development was now linked with just the one condition that Shell Oil (paraffin) had to be used instead of the ethyl alcohol that had been used up to that point. Ethyl alcohol is a fuel that can be mixed in any proportion with water. The maximum combustion temperature for the optimum ratio of ethyl alcohol to liquid oxygen is 500 Kelvin degrees lower than for a combination of paraffin and liquid oxygen. This meant that by mixing water with the ethyl alcohol it was possible to lower the combustion temperature further according to choice. In the tests that had been carried out a mixture of 60 to 75% ethyl alcohol with 40 to 25% water was generally used. In addition combustion was performed with excess fuel so that the chamber could be run without wall cooling. The combustion chamber pressure lay between 5 and 10 atm. While ethyl alcohol can thus be mixed with water in any ratio without any problems, this is not so for paraffin. If water is poured into paraffin and shaken vigorously an emulsion is formed for a short time in which the paraffin and the water apparently mix, but only to separate out again shortly afterwards. To maintain the integrity of the combustion chamber walls, every effort must be made to hold the combustion temperature of the gases within defined limits. The problem was solved by passing the paraffin through a so-called emulsifying chamber before it entered the combustion chamber. In the emulsifying chamber paraffin was mixed with water in a certain ratio and the resulting emulsion was fed through the fuel injection spray unit into the combustion chamber. It also proved possible to provide the combustion chamber with a cooling jacket. The combustion chamber as now used was as seen in Figs 28a and b. In Fig 28a a water-cooling jacket is fitted, and in 28b this cooling jacket has been removed.

The old thrust measurement equipment shown in Fig 14 was now replaced with the new equipment that can be seen in Fig 28. The thrust was transferred via a lever ratio arrangement to measurement balance scales.

After a number of preliminary trials further tests were carried out with this configuration using paraffin as the fuel on 17 May 1930. These tests were Max Valier's undoing. On Saturday the 17 May 1930 testing began in the early afternoon. The first two tests were successful and good combustion behaviour was observed. In the course of the third test, however, thrust transients occurred with the result that the traverse gear and the balance beam were bent. The liquid oxygen tank had been emptied by the tests so several hours were required before everything could once again be ready for a new test. In view of the thrust transients that had occurred during the last burn and their unknown cause, coupled with the fact that a long period of time would have to elapse before the facility was once again ready I recommended to Valier that we should stop testing for the day. However, Max was so encouraged by the successes of the first two tests, that he was determined to carry out further testing. The combustion chamber was therefore reassembled and all preparations made to begin a new test. Whereas in the previous tests an exhaust nozzle with a 28 mm throat diameter was fitted, it was decided to use a 40 mm throat diameter for this test. At about 9 o'clock in the evening all was ready. The combustion chamber was ignited and in accordance with the old familiar procedure the combustion chamber pressure was brought up to a level of 7 atm by regulating the manual valves for the propellants and the water. The combustion chamber had just reached this pressure when a violent explosion occurred. I immediately shut off all the propellant valves and ran across to Max Valier who was on the point of collapse. I was just able to catch hold of him. Blood was flowing out of his mouth and from his chest. His last words were: *"I am dying".* I laid him on the floor. While the oxygen production plant machinist and my colleague Arthur Rudolph, who was also taking part in the tests, took care of him, I tried to get hold of a car to transport Valier to the hospital located nearby. It was Saturday evening and there was no-one still present on site who could help me out with a car. I had to try my luck off site and after about 10 minutes I was able to make contact with the fire brigade, who immediately despatched an ambulance to the scene of the accident. When I returned to the scene of the accident ten minutes later, Max Valier had already passed way. Unhappily a tiny splinter had penetrated the artery to the lungs so that he had bled to death in just a short time. Miraculously both my colleague and myself escaped with just shock.

Figs 29 and 29A show the scene as it was at the time of the accident. On the right-hand side of the drawing can be seen the test rig again and on the left-hand side the positions of each of those involved. At the back on the bank stood a methane tank, and in front of it was the liquid oxygen tank. Arthur Rudolph was in a crouching position in front of the latter, operating the pressure rise valve controlling tank pressure. 1.5 m from the bank was a small metal panel, behind which I myself operated the propellant valves for the combustion chamber. The panel was only high enough to cover about half of me. The rocket test stand was set up 2 m from this wall. During the test Max Valier was 2 m from the rocket test stand reading off the thrust from the measurement balance scales. Up to that point in time this was the usual method for carrying out rocketry tests and taking observations. We never thought that we were in any immediate danger. Today it seems extremely negligent that we carried out those tests without any real protective measures.

During an inspection on the day after the accident, hundreds of small pieces of the combustion chamber were found. Just below the roof of the methane tank that stood behind those taking part in the test a large number of impacts were detected. It was as if a burst of machine gun fire had been released. The pieces of shattered combustion chamber had roared just over our heads and it was a miracle that both of us had remained unscathed.

The probable cause of the explosion can be explained as follows. The emulsion of paraffin and water passed through the atomiser and into the combustion chamber. While the propellants were being adjusted up to the maximum combustion chamber pressure a proportion of the emulsion was burnt, but the remainder did not take part in the combustion process. This remainder mixed with liquid O_2, and since liquid oxygen has a very low temperature, the emulsion, together with the injected oxygen, was free to convert into a jelly-like mass in which the oxygen was trapped. This mass deposited itself on the internal wall of the combustion chamber. Shortly before the moment of the explosion part of this mass separated from the wall and fell into the combustion zone. Since the jelly-like mass represented a highly explosive chemical mixture, an explosive form of combustion process immediately took place, generating a detonation that led to the destruction of the chamber.

In this manner the work that had begun so promisingly in this group came to a standstill for the first time. This tragic accident caused a feeling of depression that paralysed any further activity for quite a long time. This was all the more so because one of the best and most successful of men had lost his life in the course of the work.

After an interval of about one year Dr Heylandt decided to restart the work. Through his connection with Max Valier, Dr Heylandt's name had become associated with rocket development and those members of the public who were interested in rocket development expected that the testing would be pursued further. Dr Heylandt was a man who was very interested in all new technological developments. In fact he was also ambitious to create new technological products, and this was one reason why he decided to restart the work. But there was also another reason that was crucial. Dr Heylandt had invested 20 to 30,000 Marks in the work during the collaboration with Max Valier. It was, therefore, his intention to retrieve the sum that had been invested through demonstrations if at all possible. The decision was therefore taken to put more money into the development and construction of a larger rocket car and to display the new car in the context of flight demonstrations. The income would in this way retrieve part of the money invested in the work.

At the beginning of 1931 a start was made with the development of a rocket propulsion system for a rocket car. All the rocket-related equipment was built on to a chassis of a conventional NAG car that was designed to take a load of approximately 2000 kg. The following data provides the weight distribution between the individual components:

1	Combustion chamber		20 kg
2	Instruments		25 kg
3	Body (light metal)		50 kg
4	2 people		150 kg
5	Framework, wheels, steering, axels etc		660 kg
			905 kg
6	O_2 tank		325 kg
7	Fuel tank		145 kg
			470 kg
8	Propellant weights		
	(a) fuel (C_2H_5OH + 25% H_2O)	300 lites	270 kg
	(b) liquid oxygen	322 litres	365 kg
			635 kg

Resulting in an approxiamate total weight of 2010 kg

For the desired travel speed v ≈ 150 km/h, taking into account air and rolling resistance, this required a power output of

$$N_e \approx 90 \text{ HP}$$

And hence a thrust[(2)] of $\underline{P \approx 165 \text{ kg}}$

The system diagram is shown in Fig 30, from which the most important features can be picked out. The propellant system consists of a spherically shaped thick walled brass O_2 tank with thin brass insert (to reduce the filling losses when filling up with liquid O_2), the cylindrical fuel tank, the small spherically shaped tank for the N_2 ancillary tank, the combustion chamber and the valves. For the approximate dimensions of the combustion chamber see Fig 31. For spray injection a system was used in which the liquid oxygen flowed out of a plenum chamber through a slit to form a conical sheet. The fuel flowed out of the small head in the opposing direction so that, as Fig 31 shows, the liquids met, were atomised and burned. Ignition of the propellants was produced by means of a conventional spark plug. Fig 32 shows the electrical diagram for the rocket car's ignition and lighting systems.

It should be mentioned that a particular feature of the propulsion system was the use of a barrier liquid, namely liquid nitrogen, between the liquid oxygen and fuel tanks. The N_2 ancillary tank was also used to generate a rise in pressure to drive out the propellants. The pressure in the propellant tanks was an average of ~ 12–15 atm. As before, foot-operated propellant valves were fitted. The foot pedal sat on a common shaft with two cams that moved the tappets of the valve faces. The cams were set so that when the foot was first depressed the oxygen valve was opened (advance) and the fuel valve was opened somewhat later. The manual valves that can be seen in the system diagram fulfilled pre-set functions, being adjusted to produce full thrust at maximum cross-sectional area for the required mixing ratio.

A brief description of the operation of the propulsion system now follows. After filling up with fuel, liquid nitrogen and liquid oxygen the tanks were sealed and we then waited until the pressure in the system had risen to ~ 12 – 15 atm as a result of heat transfer from the ambient conditions. The liquid nitrogen ancillary tank prevented the liquid oxygen from coming into direct contact with the fuel. The rising pressure in the oxygen tank was fed through a connecting pipe on to the liquid surface of the nitrogen ancillary tank. This pressure drove liquid nitrogen through an off-take pipe, which via a nitrogen vaporiser and the adjacent pipe coil connected with the gas space of the fuel tank. Thus the pressure in the fuel tank was exactly the same as that in the liquid oxygen tank. The maximum flow areas of the manual fuel valves had already been adjusted from previous static tests. The system was ready. By pressing the button in the Bosch ignition circuit, see Fig 32, the spark plug received current from the 6–10 volt battery via the trembler coil that created the ignition sparks. By gentle actuation of the foot pedal with the left foot (the foot pedal corresponding exactly in position and configuration to the accelerator pedal in a normal car) the propellants were driven into the combustion chamber, ignited and combustion initiated. The foot pedal could now be depressed further until the maximum thrust or maximum pressure in the combustion chamber was achieved. With the aid of this equipment the thrust, and with it the driving speed, could be controlled. On the dashboard gauges displayed tank pressure and combustion chamber pressure. To hold the propellant pressures in the whole system constant while the propellants were being fed to the combustion chamber, another pressurising valve was fitted. Through this valve liquid nitrogen was extracted from the nitrogen ancillary tank, vaporised in a specially fitted nitrogen vaporiser and fed to the liquid oxygen tank. With this equipment the propellant supply pressure could be held nearly constant over the period of combustion.

Fig 33 shows the car in the workshop of the Heylandt company in Berlin-Britz. In the foreground is the cylindrical fuel tank, close behind it the small spherical nitrogen tank and further behind the large spherical liquid oxygen tank. The wooden framework for the car's bodywork is also in place. The combustion chamber and the configuration of the rear of the car can be seen in Fig 34. Fig 35a shows the complete car with full bodywork. The fuel tank is being filled with fuel. Fig 35b shows the car on a test drive on the site of the Heylandt company in Berlin-Britz. One can see the dashboard with the gauges in front of the two drivers and at the rear the exhaust jet. In Fig 35c the car is being towed to the Tempelhof Field in Berlin for a test drive. Fig 36a shows the car after a drive on the Tempelhof Field and Fig 36b shows the car near a Junkers 52 together with the transport lorry fitted with a 500 m3 liquid oxygen tank. Unfortunately, I do not have in my possession any pictures relating to the successful rocket run

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[2] *To produce this thrust, assuming an exhaust velocity c ≈ (165 x 9.81)/1 ≈ 1600 m/sec, the approximate propellant consumption was calculated as σ = (9.81x165/1600) 1 kg/sec. With a capacity of 635 kg this provided a run time of t ≈ 10 minutes. The mixing ratio of the propellants is given by M = O_2/Fuel = 365/270 ≈ 1.35.*

that took place alongside the flying demonstrations.

Development and construction had required scarcely six months. The propulsion system as envisaged moved straight from the drawing board to the workshop and into the car. It had only a short trial in the car. Apart from minor adjustments the development and trial had succeeded at the first attempt.

On the Tempelhof Field various demonstrations were carried out in the late summer of 1931 as part of flying events. These were all successful and to some extent recovered the development money that had been consumed.

Here I should mention some other matters connected with the work pursued on these technical problems.

The results achieved in this field were accorded full recognition by a large number of technically educated people. Alongside them, however, there was a group who had no understanding of the path that we adopted for the development activity. Sadly this lack of understanding came from a circle whose names are still well known today in rocketry. Some of these have never been able to achieve anything of practical worth in the field. At the time there was talk of 'rocket car fuss and commotion' without those concerned bothering to inform themselves of the terms of reference with which this work had originated. I have already clarified these at the beginning of this chapter and it was perfectly clear that this propulsion system could never be used as a propulsion system for normal cars, as was often erroneously presented in the press. At this time this was the second complete rocket propulsion system using liquid propellants to provide evidence of the individual components working together. This system could also be demonstrated in public and showed that it was not only possible to generate thrust by the combustion of liquid propellants, but also that the propellants could be ignited without danger and the thrust controlled. This was further development along the path that Max Valier had always recommended, although he had often been treated with hostility on the matter in an unjustified manner. Even today one can read such things in the general literature on rocketry. In any event the current course of development was recognised as correct by the Heylandt group. Before a rocket propulsion system can be used in a missile the complete propulsion system must be designed, understood and mastered to a much greater extent. It is unimportant whether this propulsion system has been tested out on a static or a moving test rig (the rocket car).

As will be recognised later, the basic system principles of this rocket car were used in the later development of the A3 at Peenemünde, something that at that point in time could not be envisaged. In conclusion it must be said once again that this is another justification of Max Valier's vision. Quite apart from this there is the fact that today[3], after 20 years, rocket propulsion systems have in fact been used and are still being used for the propulsion of aircraft, before a moon rocket or space rocket has left the earth.

At the end of 1931 the Army Weapons Department in Germany became interested in rocket development, and from 1932 onwards design contracts were awarded to the groups working on rockets. From this point in time no independent activities or publications associated with rocket development were allowed in Germany.

The first contract we obtained concerned the study of nozzles and nozzle shapes using high-pressure air. The aim was to research those conditions favourable for the thrust produced by a nozzle in operation. In actual fact It was not totally clear to us why it was necessary to carry out this study since it was well-known from the thermodynamics of fluids that the nozzle dimensions for generation of favourable thrust could be defined in accordance with familiar laws. The contract was perhaps just a bridging contract with the intention of returning the group to the real rocket development work later. For the tests two high-pressure air compressors were made available with a combined intake capacity of 750 m^3 per hour. Special equipment was used to condition the air by removing carbon dioxide and moisture. Fig 37 shows the test and measurement equipment for the tests with air exhaust nozzles. On one side of a balance beam was fitted a cylindrical pipe of 47 mm diameter. The end of the pipe was configured as a knife-edge that made contact with the balance beam. The nozzle that was to be tested was bolted on to the head of the pipe. The throat of the nozzle had a diameter of 10 mm. The exit diameter of the nozzle was 80 mm and the length approximately 390 mm. Downstream of the throat measurement ports (M 1-8) were installed at intervals of 23 to 25 mm, to measure static pressures as the air flowed through the nozzle. These pressure measurement ports were connected via small taps to a liquid column manometer. The pressures in the pipe (MI) and in the throat (MII) were measured using gauges. The measurement pitot (MIV) was inserted in the supply pipe from the air plenum chamber. This enabled the mass flow rate to be determined from the pressure difference. The thrust generated by the air exhaust was determined by placing weights on the other side

[3] *ie circa 1950*

of the balance beam. Fig 38 shows some photographs of the test rig layout.

The results from the study are presented in Fig 39. For the nozzles with various lengths and nozzle angles studied the finding was that the highest thrust occurred in the nozzle when correctly matched to the design expansion ratio, as defined by the inlet and outlet cross-sectional areas. In this diagram can also be seen the thrust characteristic for excess nozzle lengths, likewise the pressure characteristic over the nozzle length. In summary this investigation delivered nothing new. As I have said, all these facts were well known. The single important new piece of knowledge established was that the divergence angle of the nozzle has an influence on the optimum configuration for the nozzle. It was already observed in these tests that with a larger nozzle angle the thrust increased. Only much later (at Peenemünde) were systematic studies performed to determine the best nozzle angle for nozzles with hot exhaust gases. An average divergence angle of 30° proved to be best practice.

In the middle of 1932 Dr Heylandt decided to authorise systematic studies on combustion chambers to determine their performance characteristics. For this purpose measurements of various parameters were necessary, such as thrust, tank pressure, propellant consumption, mixing ratio, combustion chamber pressure, static pressure at nozzle throat and nozzle exit, and, if possible, gas temperatures.

As is well-known, the exhaust velocity 'c' (m/sec) can be determined from the measurement of thrust 'S' (kg) and propellant consumption 'G_T' (kg/sec):

$$c = (S.g)/G_T \quad \text{(m/sec)}$$

The specific consumption 'σ' in g/sec per 1 kg thrust is given by[4]:

$$\sigma = (G_T.10^{-3})/S \quad \text{(g/(sec.kg))}$$

and the thrust 'R' in kg that can be produced per kg/sec of propellant consumption is proportional to the reciprocal of 'σ':[5]

Thus $R = (S/G_T)$ ((kg/kg).sec), or also $R = c/g$

From thermodynamic analysis it is possible to determine the theoretical values for the combinations of propellants so that these values can be compared with those measured.

If the theoretical exit velocity is denoted by c_{theor} and that obtained in practice by c, the quotient:

$$(c/c_{theor}) = \varphi = 1$$

would provide the highest possible utilisation of the thermodynamic heat release with complete combustion of the propellants. In the case of exhaust of hot gases through nozzles with supersonic velocity the friction factor cannot be neglected and the loss on average is 5%. The factor φ can thus be estimated to be 0.95. This means that with optimum atomisation and combustion of the propellants a value $\varphi \approx 0.95$ should be achieved and invoked as a measure of performance. The further the factor φ deviates from this value, therefore, the worse must be the quality of combustion and also the atomisation of the propellants. The size of the combustion chamber volume also plays a role here and must be taken into account accordingly.

Based on the measurement requirements a combustion chamber and measurement equipment was produced with a system diagram as shown in Figs 40a-c. Since the question of money was once again playing a significant role, an attempt had to be made to do reasonable justice to the technical requirements with the simplest means.

As can be discerned from Fig 40c, the test rig for the combustion chamber thrust measurements comprised a simple block of wood B with a small angle iron frame 'r'. The combustion chamber '0' was attached to a small trolley that ran on the angle iron frame. The thrust was transferred to a balance beam by means of a cable 'S' that ran over the pulley 'R'. The thrust measurement device 'm' was a water ball such as is used as a toy by adults and children at the seaside. On the bottom and top of the water ball were brass universal ball joints to transfer the forces to be measured. The ball was filled with water and was connected through a pipe to a u-shaped bent glass pipe, which was also filled with water. The thrust was read off this water column (measurement station MV) at defined time intervals.

In the operating station, see Fig 40b, the propellant tanks were mounted on decimal weighing scales that enabled the propellant consumption per unit time to be determined. The driver gas for the propellant supply was taken from a large high-pressure air bottle 'Pr' and fed through a pair of reducing valves 'D.Br' and 'D.O2' to the tanks. Also located in the operating station were the manual propellant valves 'V.O2' and 'V.Br' and the ignition equipment consisting of the battery 'AK', interrupter unit 'U' and the switch 'Sch'.

[4] *Riedel appears to have made an error in this equation, which should read:*
$\sigma = (G_T.10^{+3})/(S)$ *(g/(sec.kg))*

[5] *Note that this 'R', used as (kg thrust/(kg/sec)) later became an international measure of performance referred to as 'specific impulse'.*

Included in the measurement instrumentation were:

M I	pressure port for nozzle exit plane pressure	(Hg column)
M II	pressure port for nozzle exit plane pressure	(gauge)
M III	combustion chamber pressure	(gauge)
M IV	gas temperature measurement station	(thermocouple)
M V	thrust measurement	(H_2O column)
M VI	oxygen mass measurement	(scales)
M VII	fuel mass measurement	(scales)
M Br	fuel tank pressure	(gauge)
M O_2	oxygen tank Pressure	(gauge)

Fig 40a shows the combustion chamber. The liquid oxygen entered via 'N' into the oxygen plenum 'F' and then flowed through a perforated disk into the combustion chamber. The fuel was fed via 'O' into the combustion chamber's cooling jacket, flowed through the jacket and was then directed via the pipe 'M' to the atomiser stem 'H'. Through the small head 'I' the fuel is sprayed as before into the chamber through small holes against the direction of flow of the oxygen. The main dimensions of the combustion chamber and nozzle were approximately as follows:

Combustion chamber:	Nozzle:
$D_i \approx 50\ \phi$	
$D_2 \approx 53\ \phi$	$d_m \approx 14\phi$
$D_3 \approx 64\ \phi$	$d_a \approx 22\ \phi$
$L_1 \approx 220$	$L \approx 33$
$L_2 \approx 70$	divergence angle $\approx 12°$

Material steel

Combustion chamber pressure $p_i \approx 10$ atm

Average thrust $\approx$ 20 kg

Fig 41a shows photographs of the actual combustion rig with the thrust measurement device as shown in Fig 40c. Fig 41b and c show the operating station in accordance with the system schematic 40b, and Fig 41d shows the combustion chamber in plan view.

The combustion rig was located in front of a methane shed. In the methane shed itself were located the operating station and the measurement station. The combustion chamber could be observed through a viewing slit while combustion was taking place.

The accompanying lists of test values show the tests undertaken with the combustion chamber from 16 September 1932 to 7 December 1932. In Fig 42-44 there is a set of thrust diagrams that are plotted from the test values. Any further information can be extracted from these.

The tests were observed by staff officers of the Army Weapons Department, amongst whom was General Dr Dornberger, later the leader and commandant of the Army Test Facility at Peenemünde. As a result of these tests we were awarded a further development contract by the Army Weapons Department. The contract required:

> *Development of a 20 kg x 100 sec thrust unit with a maximum specific consumption σ = 7 gr/sec per kg thrust. Thrust to remain constant over the combustion period. Completely automatic operation of the propulsion system except for manual operation of the ignition and propellant valves. Manufacture of the system to be exclusively in light alloy.*

This contract meant that money was again available for the work. In addition to carrying out many tests this allowed us to build a better test rig, to improve the thrust measurement device and to use an automatic twin-pen recorder to measure thrust and combustion chamber pressure, and record these measurements against time.

The layout of the test rig and the operating station can be seen in Figs 45a and b. Compared with the very simple test rig previously described it can be seen that the combustion chamber was no longer mounted horizontally, but vertically, with the exhaust jet directed downwards. The combustion chamber was attached to a plate that is configured as a piston with guide. Around this guiding device sat a strong spring that was used for measurement of the thrust generated. Above the piston guide was fitted a set of pulleys that formed part of a system to determine via a steel wire and calibration weights the spring force per cm. Over the other set of pulleys ran a wire that was connected to the hook of the Askania twin pen recorder. Combustion chamber, piston guide, spring and pulleys were all attached to a traverse that sat on a tall iron frame. The exhaust gases, directed downwards, flowed into a conically tapering iron funnel. A concrete deflection chute fitted in the floor directed the exhaust gases through a venting shaft into the ambient air. Measurement of propellant consumption took place as in the old configuration by means of decimal weighing scales and the operating station had the same layout as before. The only modification was that fast-acting valves, controlled by a manual lever, were installed into the propellant lines ahead of the manual control valves.

This testing layout was put together in a dedicated shed with the following ground plan:

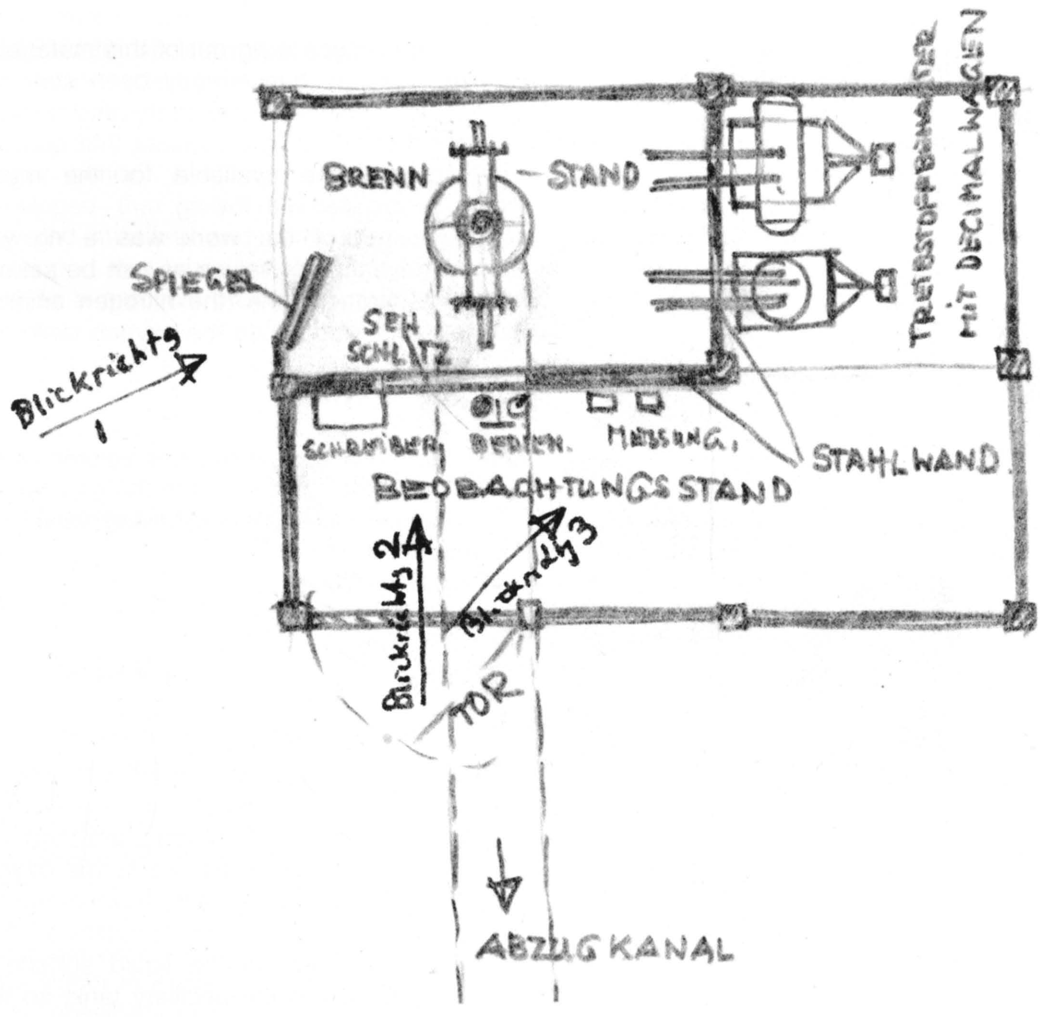

Fig 45C: This testing configuration was assembled in a dedicated facility with the following ground plan:

Abzugkanal	exhaust channel
Bedien.	operating station
Beobachtungsstand	observation cell
Blickrichtg.	direction of view
Brennstand	combustion test stand
Messung.	measurement equipment
Sehschlitz	viewing slit
Spiegel	mirror
Stahlwand	steel wall
Tor	door
Treibstoffbehälter mit Decimal-Wagen	propellant tanks with decimal scales

Figs 46a and b show photographs of the testing layout as viewed from direction 1, in Fig 46c as viewed from direction 2, and in Fig 46d as viewed from direction 3. In Figs 46a and 46b one can see the vertical thrust frame, and suspended in it the combustion chamber and with it the thrust spring. The inlet to the extractor funnel for exhaust jet removal of the combustion gases can also be seen. In the foreground of the photo one can see the rear face of the observation mirror.

In Fig 46c one can see the manually controlled propellant valves, the viewing slit and nearby the twin-pen recorder. In Fig 46d one can see the fast-acting valves controlled by manual levers, nearby the manometer for the nozzle exit pressure measurement station and the other gauges.

This was the layout used to carry out the tests with combustion chambers that were manufactured in light alloy in accordance with Army Weapons Department requirements. The injection systems were modified with respect to the number and alignment of holes until the specific consumption 'σ' of 7 gr/sec per kg thrust was achieved with confidence and in fact was reduced further.

To fulfil the Army Weapons Department contract requirement to produce a completely automatically working facility, it was necessary to replace the manually regulated propellant valves with something that could be controlled in some manner. A pneumatically-controlled propellant valve provided the solution, as shown in Fig 47. A conventional valve face 'a' is sealed against the propellant volume 'd' by a spring 'f', creating the control volume 'c'. A small screw 'b' provides adjustment of the maximum valve lift. The control volume 'c' is connected by means of a three-way tap 'Dr' through the line 'l' with the gas volume of the propellant tanks 'g'. While the pressure is rising in the propellant tanks the valve remains closed, the sealing force for the valve seat being generated by appropriate selection of the valve seat areas and the effective spring face area. The valve is rendered functional by switching the three-way tap into the position in which line 'l' is closed and the control volume 'c' is connected to the atmosphere, so that the pressure in volume 'c' drops and the valve opens. In place of the three-way tap an electrically controlled valve can also be used. These valves were built into a system that can be seen in Fig 48.

The self-acting regulator and O_2 vaporiser built into the system in Fig 48 was not used, and the driver gas to expel the propellants was still taken from a high-pressure air bottle. For this rig all parts were manufactured in light alloy. Here I should also mention that the lighter alloy 'Elektron' was used as the material for the combustion chamber instead of 'Hydronalium', and that these combustion chambers were successfully fired. For reasons of corrosion, however, the use of the Elektron material was not pursued. The light alloy 'Hydronalium' (an alloy of Al, Mg, Mn and Si) subsequently used for the rig, was being introduced at this time by I G Farben as a corrosion-resistant light alloy. The techniques for working with the material, particularly welding, were not very well known and it was therefore very difficult to form this material into the components required for the rig (combustion chamber, propellant tanks, valves and lines). Nevertheless, it was a remarkable success to produce a rig out of this material at that time and, as has already been stated at another point in the monograph, this success can only be attributed to the fact that qualified coppersmiths were available for the metal-working associated with the rig.

The upshot of the work was a rig with automatic systems of valves as can be seen in Fig 49. A nitrogen tank (the nitrogen ancillary tank) was installed inside the oxygen tank. Into the ancillary tank extended a pipe that was connected to the gas volume of the fuel tank. Small holes were introduced into the neck of the N_2 ancillary tank so that the gas volume of the ancillary tank was connected to the gas volume of the oxygen tank. A pressurising valve was fitted to the bottom of the oxygen tank, and this controlled the vaporisation of the oxygen in an O_2 vaporiser. The fuel supply line passed through the oxygen vaporiser so that the heat of the fuel could be transferred to the liquid oxygen, thereby generating the required gas pressure.

When the fuel tank was filled with alcohol, the O_2 tank with liquid oxygen and the nitrogen ancillary tank with liquid nitrogen, and the tanks were then sealed, the pressure in the oxygen tank increased as a result of heat transferred to the tank from the ambient conditions. This pressure also acted on the liquid surface of the liquid nitrogen in the ancillary tank, so that liquid nitrogen was fed through the pipe located in the ancillary tank into the gas volume of the fuel tank. The liquid nitrogen vaporised on the liquid surface of the fuel. By means of these devices the pressure was held equal in the two propellant tanks. In addition the liquid N_2 formed a barrier between the O_2 and the fuel, preventing any coming together of the inflammable propellants.

When the correct supply pressure had been achieved in the tanks the ignition system was switched on and a short time later the three-way tap was set to the vent position. The propellant valves opened, as did the pressurising valve, which supplied an amount of liquid oxygen, as determined by a spring, into the O_2 vaporiser such that the pressure in the tanks remained nearly constant. It should be particularly noted that this system eliminated the use of gaseous nitrogen from steel bottles for holding constant the propellant supply pressures, which in terms of weight was a great advantage.

With this propulsion system the problem as set in the Army Weapons Department contract was fulfilled in all respects. In its final configuration the combustion chamber produced a 'σ' of less than 7 gr/sec per kg and on average 'σ' equalled 6.5 gr/sec per kg.

Although the system did not possess a configuration that could be accommodated in a rocket vehicle, and neither was the thrust designed for such an application, nevertheless the work had produced a self-contained automatic system with a combustion chamber that could operate at constant thrust over a longer period. A design process had been developed that could be applied to rocket-powered missiles, and components had been developed that when combined together could provide a practical propulsion system for such missiles. In a later chapter it will be recognised that this design process, together with its components, was that used in the A 3 (the rocket vehicle used for the testing of control systems).

The achievements of the three years of rocket development from 1930 to 1933 by the group in Berlin-Britz, with a one-year interruption following the death of Max Valier in 1930, can be summarised as follows:

Propellant selection:

The best propellant combination was 75% ethyl alcohol with 25% water and liquid oxygen.

(Tests with benzene and paraffin encountered difficulties in the control of gas temperatures and maintenance of the integrity of the combustion chamber walls. Combustion temperatures when using benzene or paraffin were about 25% - 30% higher in Kelvin degrees. There was little or no possibility of mixing these fuels with the water to lower the combustion gas temperature).

Propellant mixing ratio:

$$M = O_2/C_2H_5OH \approx 1$$

(Values were determined empirically. Alterations to the ratio within the limits $M \approx 0.8$ to 1.2 produced no significant changes in performance data).

Combustion chamber performance data:

Fig 50 has been introduced to provide an understanding and overview of the performance data of combustion chambers. This diagram highlights specific consumption 'σ' (gr/sec.kg) and specific thrust 'R' (kg.sec/kg). (It should be recognised that the term specific thrust was already well-known at that time and used as an assessment parameter). The diagram also shows thermal efficiency[6] for various mixtures of alcohol and water as a function of exhaust gas velocity.

The area of achieved performance data is shown hatched in the diagram. The theoretically achievable values are shown against the vertical line with corresponding comments. Taking into account the frictional losses of the gases in the nozzle that amount to ~ 5%, the velocity that can practically be achieved with complete combustion is given by:

$$c_{prakt.} = 0.95.c_{theor.}$$

The average performance values achieved in the combustion chamber tests were as follows:

Average combustion chamber pressure
$p_i \sim 10$ atm (theoretical)

Exhaust velocity achieved
$c_m \sim 1200\text{-}1500$ m/sec (2060)

Corresponding specific thrust
$R_m \sim 122\text{-}153$ kg/kg/sec (210)

Corresponding specific consumption
$\sigma_m \sim 8\text{-}6.5$ gr/sec.kg (4.55)

Thermal efficiency
$\eta_{therm} \sim 0.12\text{-}0.19$ (0.35)

Burn times
$_m \sim 10$ min

Fuel-cooled combustion chambers

Combustion chamber materials:

Steel and light alloys (Hydronalium and Elektron).

Projects completed:

1. Development of a rocket unit as shown in Fig 27 using alcohol and liquid oxygen, designed for the propulsion of a rocket car with constant thrust S of between 20 and 30 kg and ~ 10 minutes burn time. Use of conventional materials. Gaseous nitrogen from steel bottles used as driver gas. Electrical ignition by means of spark plug.

2. Development of a rocket unit as shown in Fig 30 using alcohol and liquid oxygen, designed for the propulsion of a rocket car

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[6] *This is now better understood as 'theoretical performance'*

with variable thrust S of between 150 and 200 kg for a 10 minutes burn time. Use of a liquid nitrogen ancillary tank and generation of a constant driver pressure by the vaporisation of liquid nitrogen. Foot-operated propellant regulation valves. Electrical ignition by means of spark plug.

3. Studies of nozzles and nozzle profile shapes as shown in Fig 37 using compressed air with the aim of researching optimum conditions for thrust generated during nozzle operation.

4. Studies on combustion chambers as shown in Fig 40 and 41 with an established injection system. These studies were to achieve optimum exhaust velocities using simple measurement techniques appropriate to the amount of funding awarded.

5. Studies on combustion chambers as shown in Fig 45 and 46 on an improved test rig recording the characteristics of combustion chamber pressure and thrust using a twin-pen recorder. Use of manually-operated fast-acting valves.

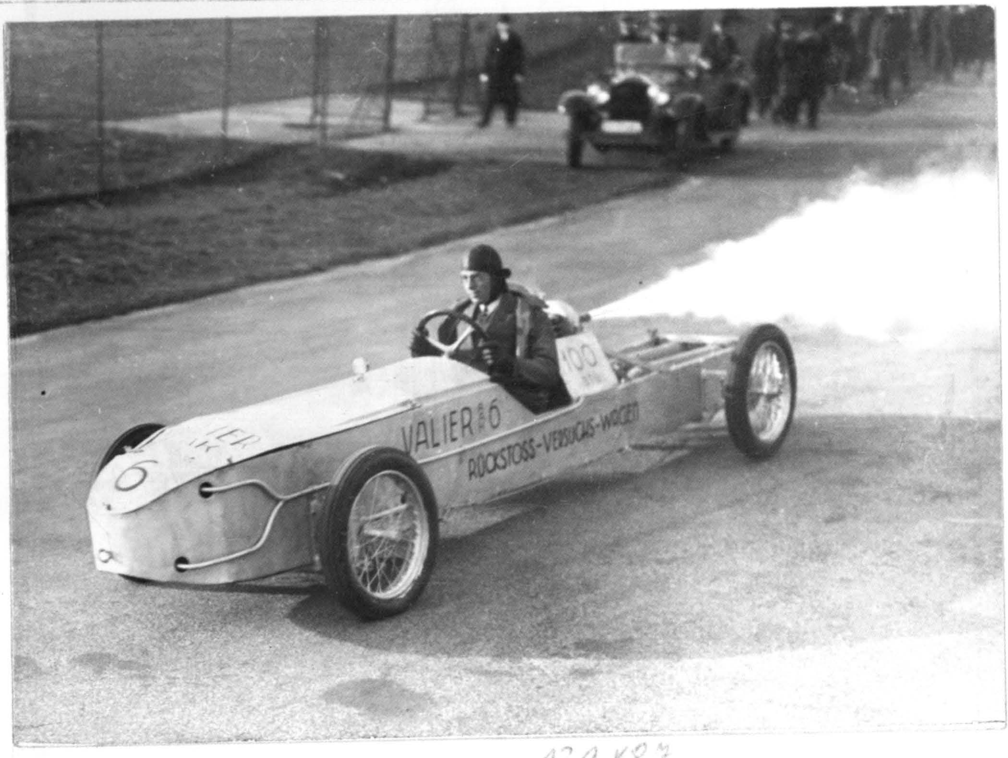
6. Development of a 20 kg thrust x 100 sec burn time rocket unit in accordance with the Army Weapons Department contract. Maximum specific consumption to be 'σ' ≈ 7 gr/sec.kg with a constant thrust characteristic. Fully automatic operation of the facility apart from manual switching of ignition and propellant valves. Discontinuation of the use of high-pressure nitrogen gas bottles. Driver gas generation from the vaporisation of liquid O_2. Use of alloy (corrosion-resistant Hydronalium). The first configuration of the facility is shown in Fig 48. Use of pneumatically controlled valves as shown in Fig 47. For final system to fulfil the requirements of the contract see Fig 49.

This concludes my overview of the rocket development work carried out by the group at the Heylandt company in Berlin-Britz. The fundamental knowledge that was generated and the experience gained represented a valuable contribution to the later development work carried out at the development establishments.

As a result of the work carried out at Heylandt I was moved across in January 1934 by the Army Weapons Department to continue my work with the well-known Professor Dr von Braun in Kummersdorf on the development of long-range rocket-powered guided missile using liquid propellants.

Versuchsfahrt mit CO_2
am 22.12.29 auf der Avus in Berlin.

R.003.



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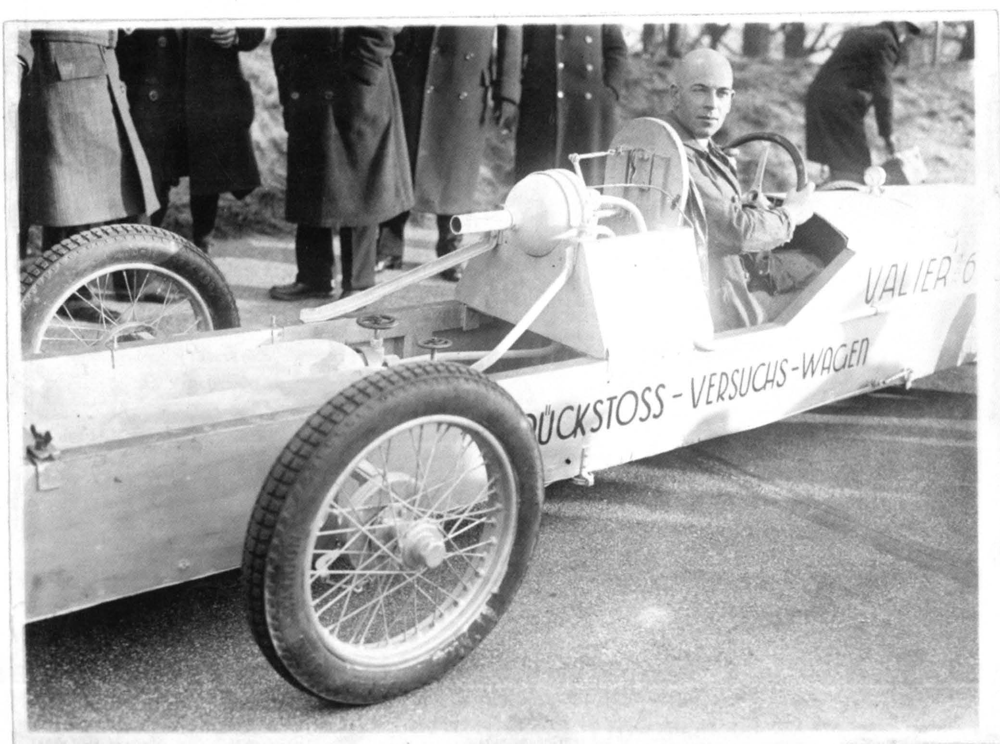
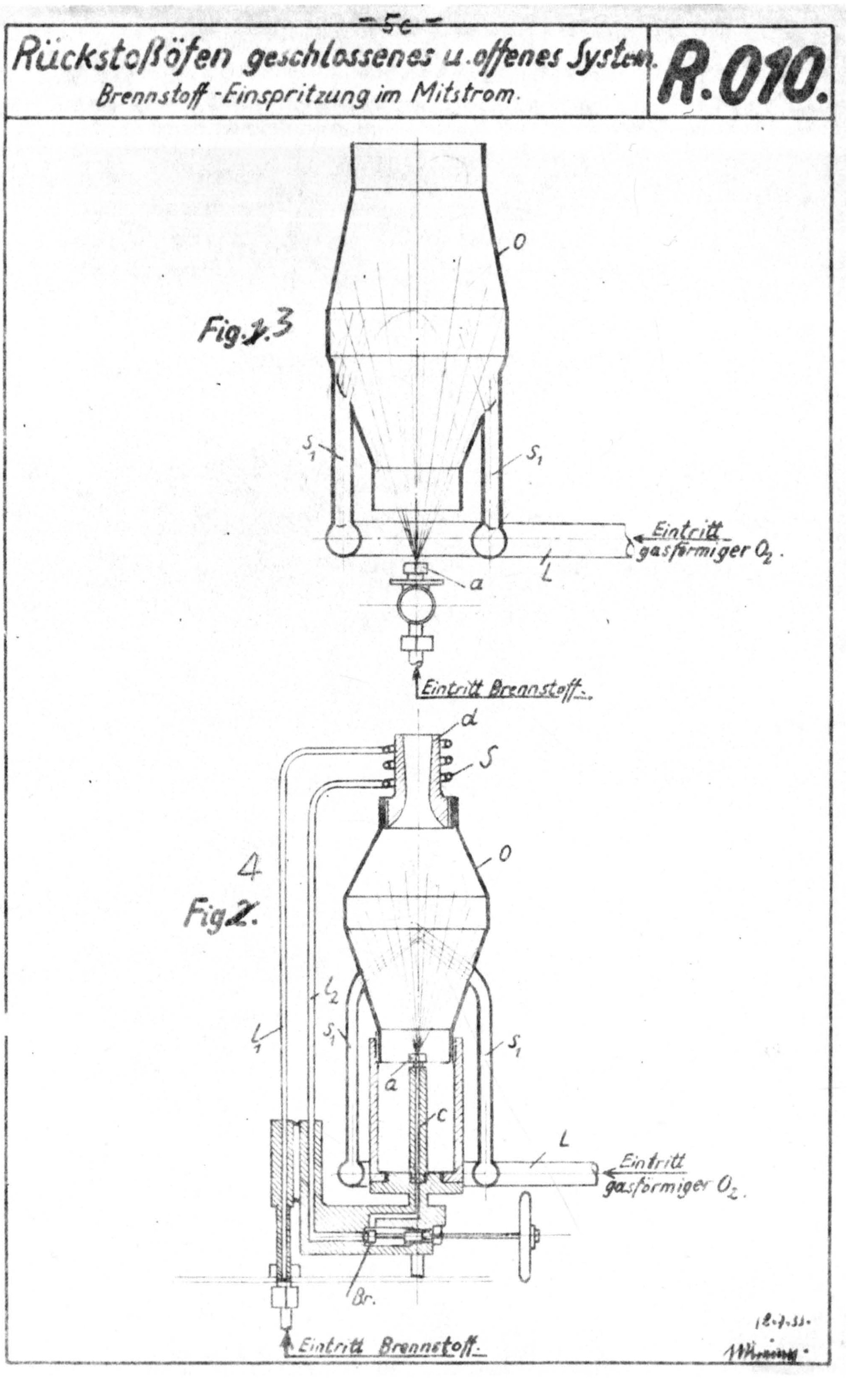


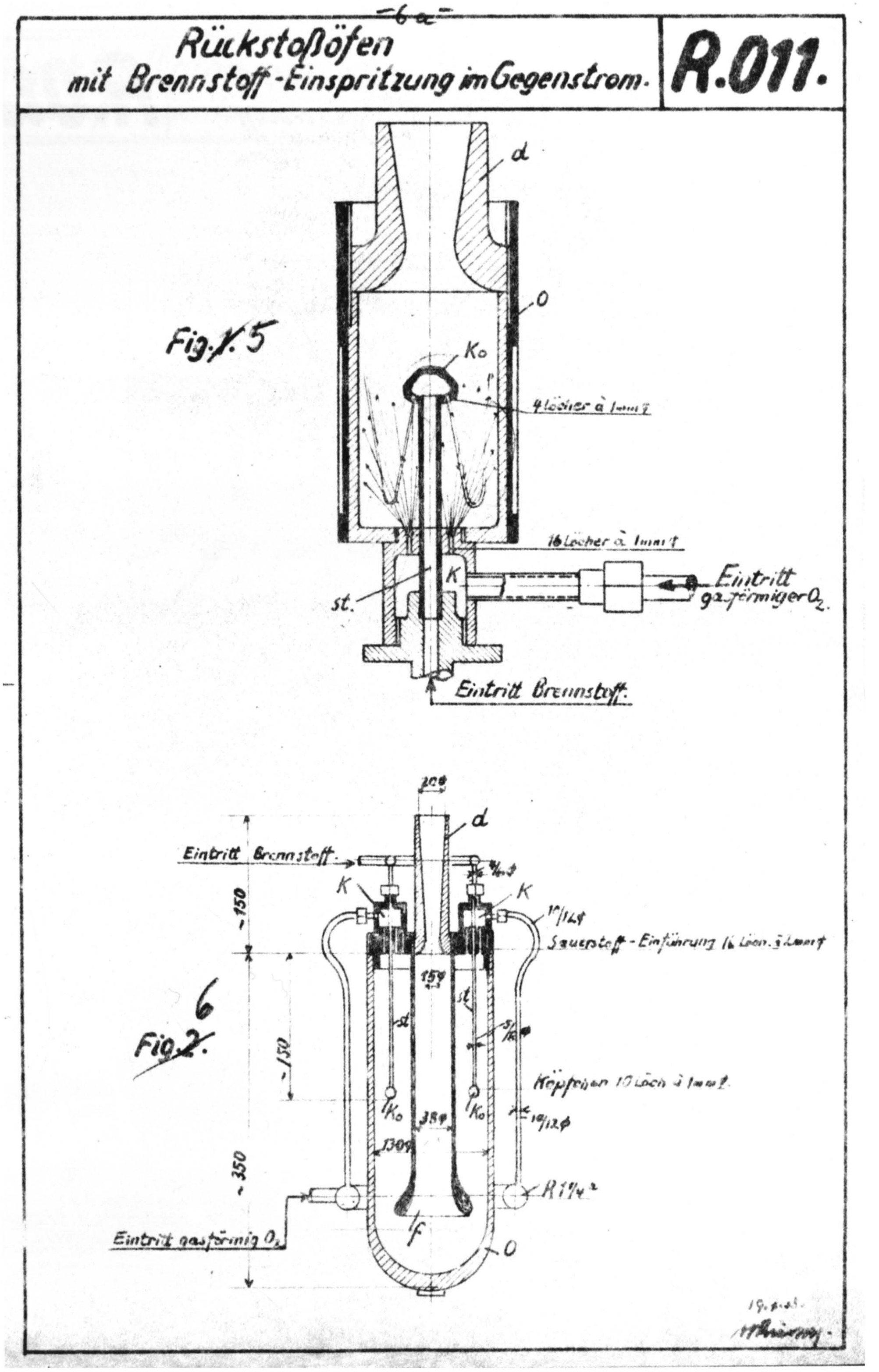
Bild 2.

Figs 1 and 2: Test drive with CO_2 on 22.12.29 on the Avus in Berlin



Figs 3 and 4: External and sectioned views of the combustion chamber – fuel injection in the direction of flow

Eintriff Brennstoff	admission of fuel
Eintritt gasförmiger O_2	admission of gaseous O_2

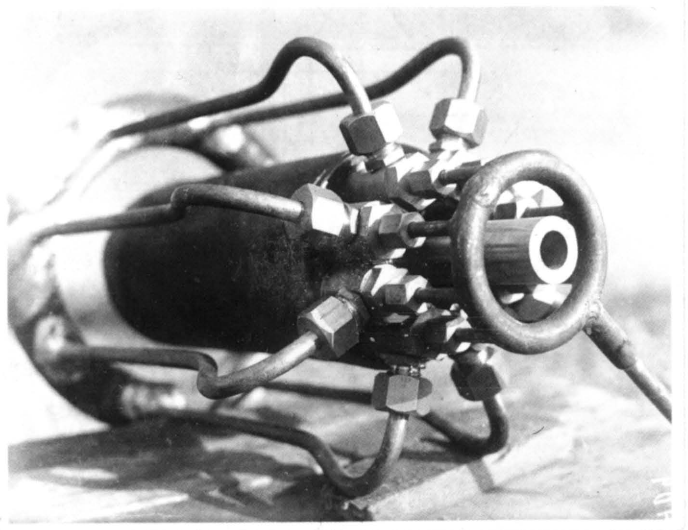


Figs 5 and 6: Combustion chamber with fuel injection in the contraflow direction

4 Löcher à 1 mm φ	4 holes @ 1 mm diameter
16 Löcher à 1 mm φ	16 holes @ 1 mm diameter
Eintriff Brennstoff	admission of fuel
Eintritt gasförmiger O_2	admission of gaseous O_2
Köpfchen 10 Löcher	small head with 10 holes
à 1 mm φ	@ 1 mm diameter
Sauerstoff-Einführung 16 Löcher	oxygen introduction through 16 holes
à 1 mm φ	@ 1 mm diameter

Rückstoßofen mit 8 Zerstäubern.
Treibstoff: Spiritus und gasförmiger Sauerstoff.

R.012.



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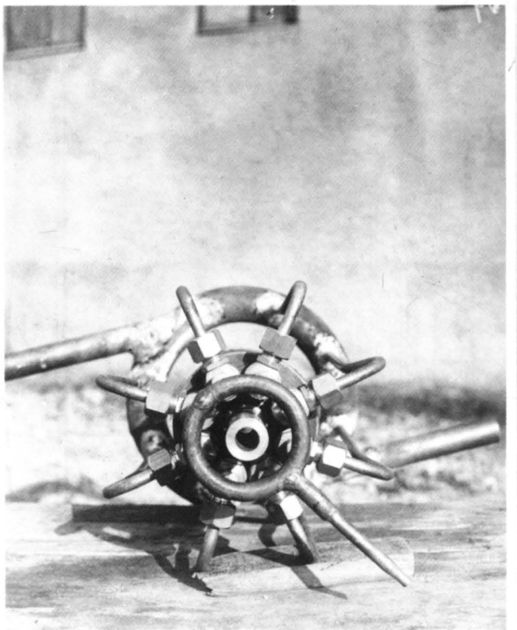

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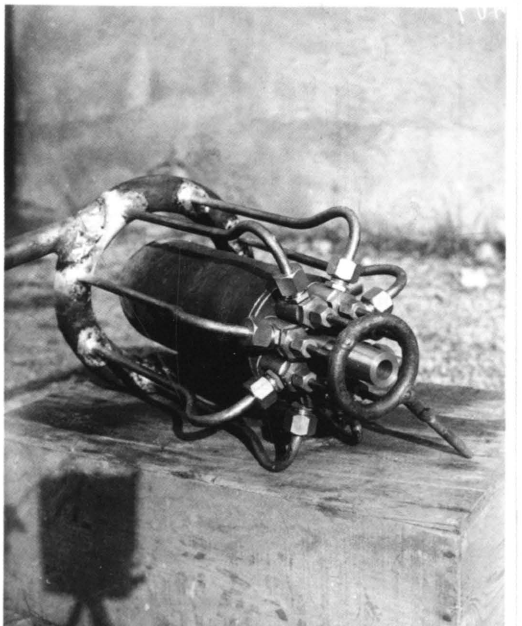


Bild 3.

1.7.33.

Figs 7, 8 and 9: Combustion chamber with 8 atomisers, Propellants: Ethyl alcohol and gaseous oxygen

Rückstoßofen mit 8 Zerstäubern. Treibstoff: Spiritus und gasförmiger Sauerstoff.	R.013.

Bild.1. 10

Ri.
1.7.33.

Figs 10: Combustion chamber with 8 atomisers, Propellants: Ethyl alcohol and gaseous oxygen

Rückstoßofen mit 8 Zerstäubern.
Treibstoff: Spiritus und gasförmiger Sauerstoff.

R.013.

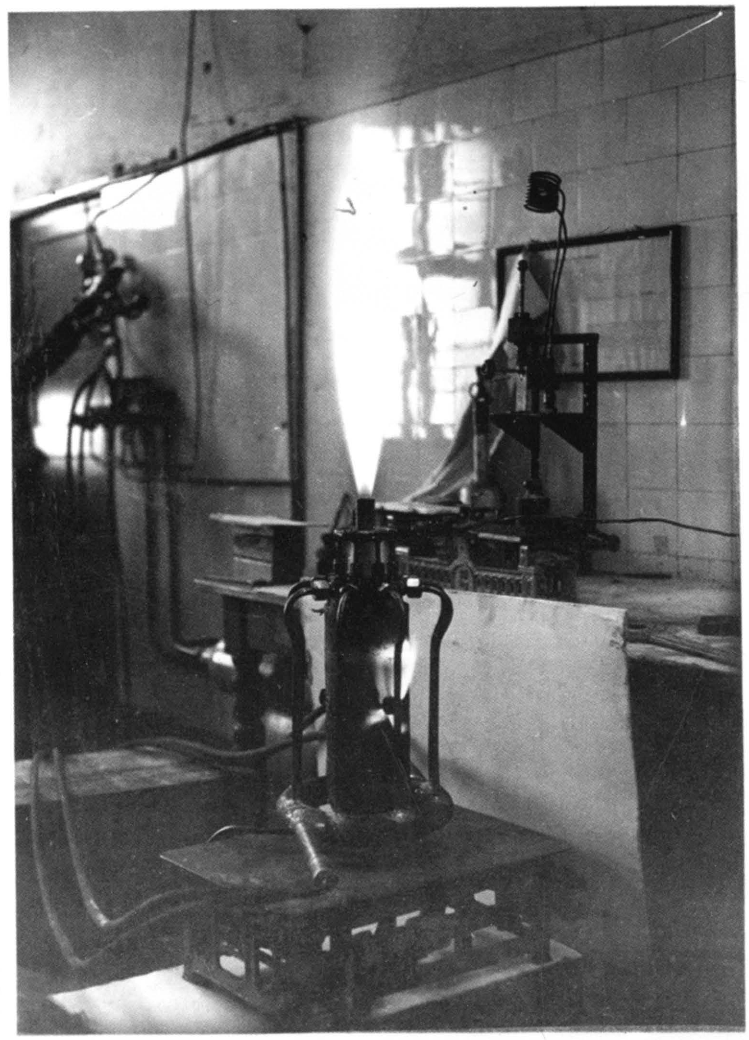
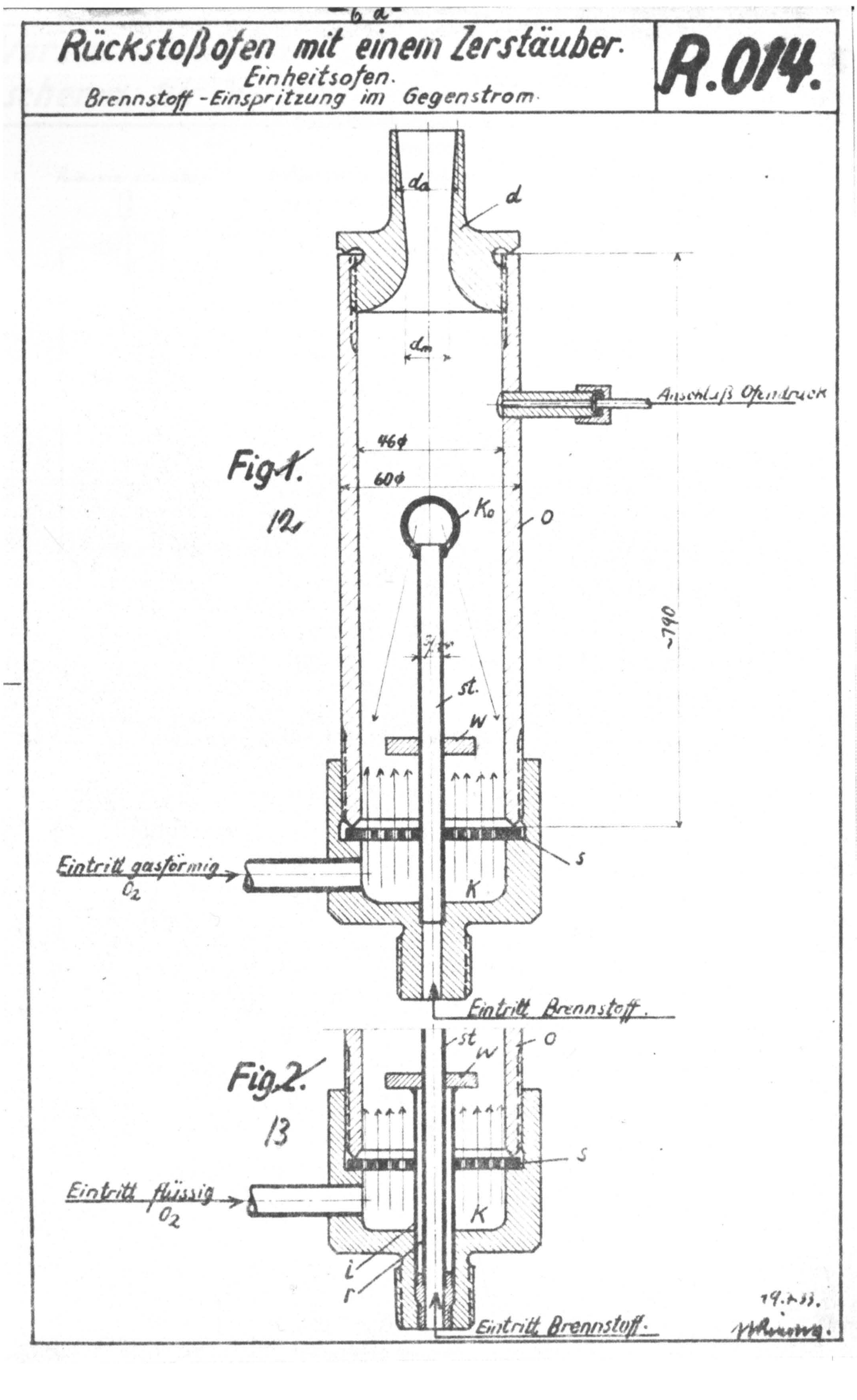


Bild 2. II

Figs 11: Combustion chamber with 8 atomisers, Propellants: Ethyl alcohol and gaseous oxygen

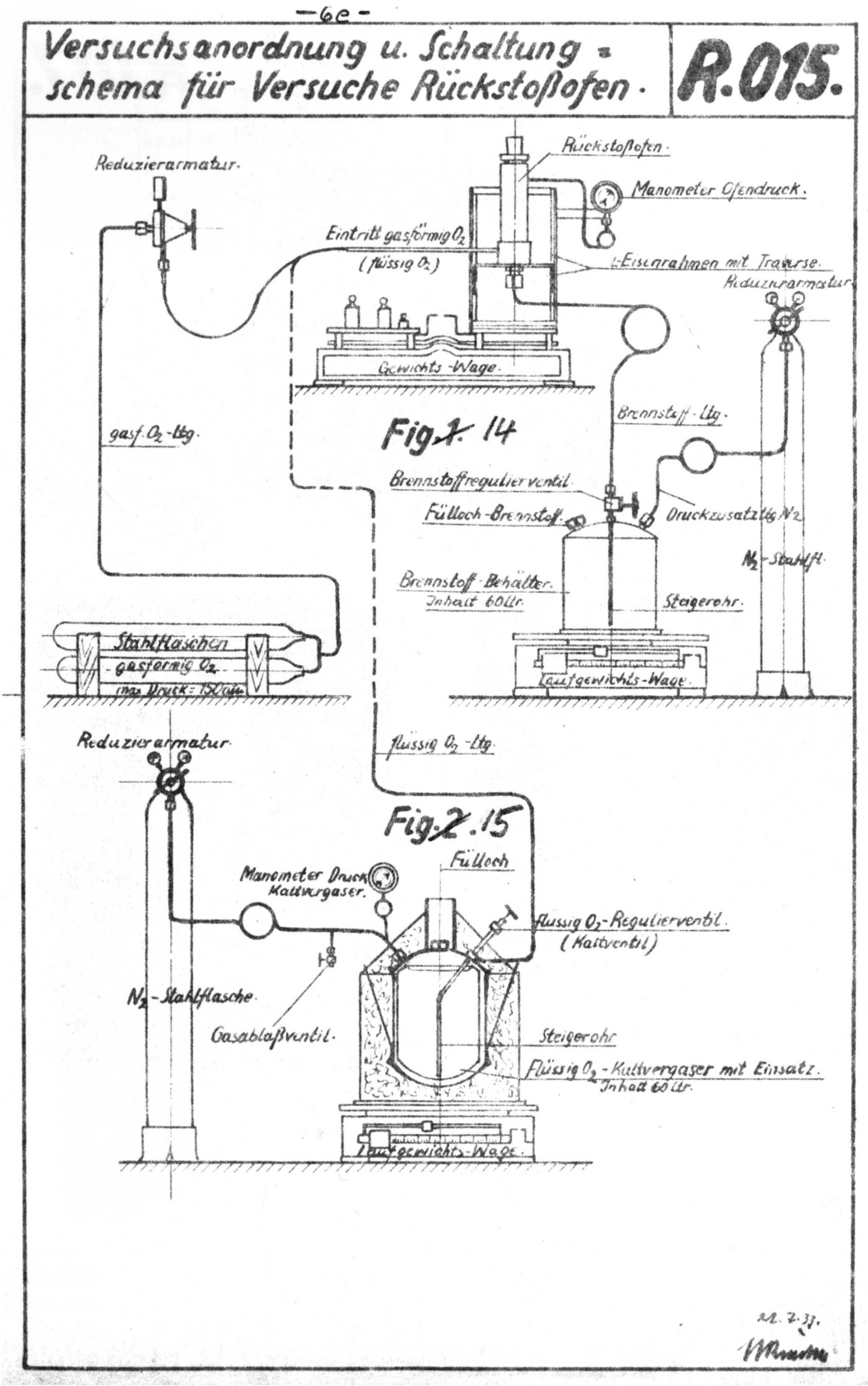


Figs 12 and 13: Combustion chamber with one atomiser, Unit chamber, Fuel injection in the contraflow direction

Anschluß Ofendruck	chamber pressure tapping
Eintriff Brennstoff	admission of fuel
Eintritt flüssiger O_2	admission of liquid O_2
Eintritt gasförmiger O_2	admission of gaseous O_2

Figs 14 and 15:

Brennstoff-Behälter	fuel tank
Inhalt 60 Ltr	capacity 60 litres
Brennstoff-Ltg	fuel line
Brennstoffregulierventil	fuel regulating valve
Druckzusatzltg N_2	N_2 pressurising line
Eintritt gasförmiger O_2	admission of gaseous O_2
(flüssig O_2)	(liquid O_2)
Eisenrahmen mit Traverse	angle iron frame with traverse
flüssig O_2- Kaltvergaser mit Einsatz	liquid O_2 cold gasifier with insert
Inhalt 60 Ltr	capacity 60 litres
flüssig O_2-Regulierventil	liquid O_2 regulating valve
(Kaltventil)	(cold valve)
Fülloch	filler hole
Fülloch-Brennstoff	fuel filler hole
Gasablaßventil	gas blow-off valve
gasf O_2-Ltg	gaseous O_2 line
Laufgewichts-Wage	moving weight balance
Manometer Druck	combustion chamber pressure gauge
Kaltvergaser	cold gasifier
Manometer Ofendruck	combustion chamber pressure gauge
N_2 Stahlflasche	N_2 steel bottle
Reduzierarmatur	pressure-reducing valve
Rückstoßofen	combustion chamber
Stahlflaschen gasförmig O_2	gaseous O_2 steel bottles
(max Druck 150 atm)	(max pressure 150 atmospheres)
Steigerohr	riser pipe



Figs 14 and 15: Experimental configuration and system schematic for combustion chamber tests

Rückstoßofen mit 1. Zerstäuber.

Einheitsofen.

R.017.

16

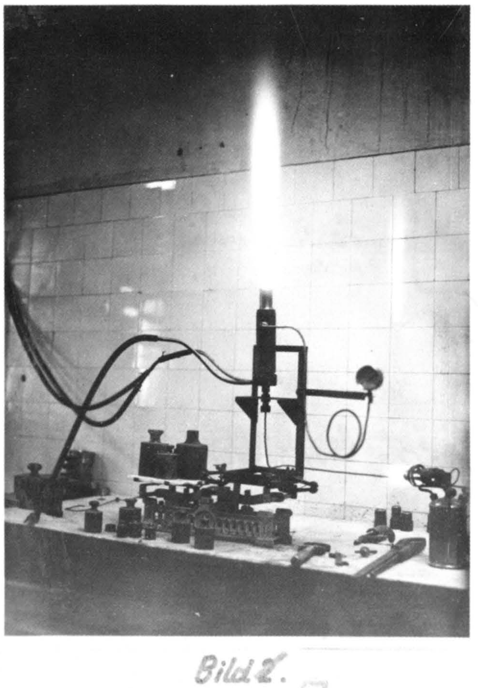


Bild 2. 17

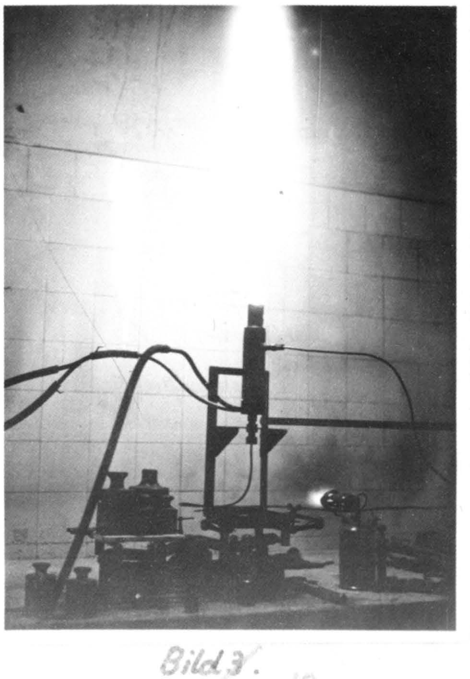
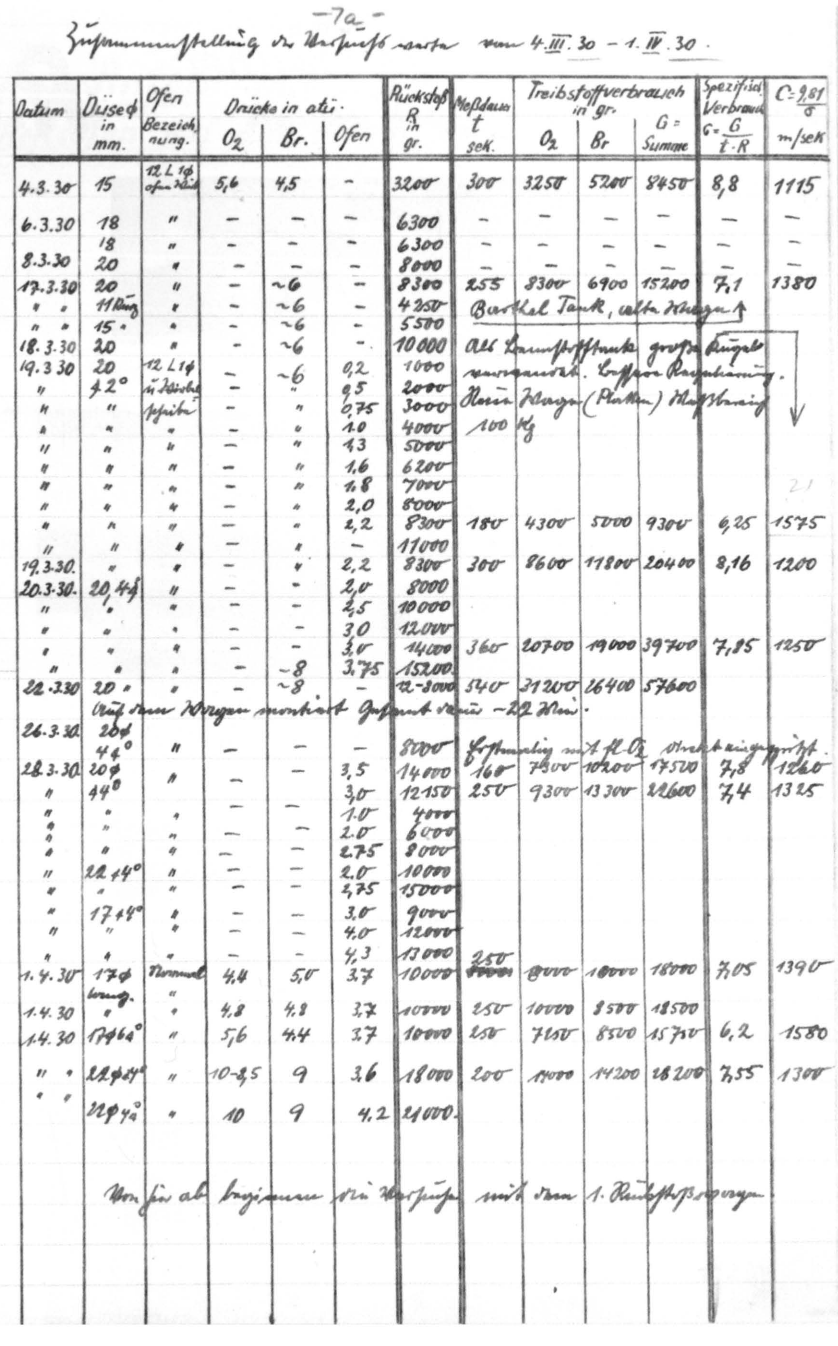


Bild 3. 18

Ri. 4.7.33.

Figs 16, 17 and 18: Combustion chamber with 1 atomiser, Chamber unit



-7a-

Zusammenstellung der [illegible] von 4.III.30 – 1.IV.30.

Datum	Düse φ in mm.	Ofen Bezeichnung.	Drücke in atü · O_2	Br.	Ofen	Rückstoß R in gr.	Meßdauer t sek.	Treibstoffverbrauch in gr. O_2	Br	G = Summe	Spezifisch. Verbrauch $G = \frac{G}{t \cdot R}$	$C = \frac{9{,}81}{\sigma}$ m/sek
4.3.30	15	12 L 1φ [illegible]	5,6	4,5	–	3200	300	3250	5200	8450	8,8	1115
6.3.30	18	"	–	–	–	6300	–	–	–	–	–	–
	18	"	–	–	–	6300	–	–	–	–	–	–
8.3.30	20	"	–	–	–	8000	–	–	–	–	–	–
17.3.30	20	"	–	~6	–	8300	255	8300	6900	15200	7,1	1380
" "	11 Ring	"	–	~6	–	4250	Barthel Tank, [illegible]					
" "	15 "	"	–	~6	–	5500						
18.3.30	20	"	–	~6	–	10000	[illegible]					
19.3.30	20	12 L 1φ [illegible]	–	~6	0,2	1000	[illegible]					
"	42°	[illegible]	–	"	0,5	2000	[illegible] (Platten) [illegible]					
"	"	[illegible]	–	"	0,75	3000	100 Kg					
"	"	"	–	"	1,0	4000						
"	"	"	–	"	1,3	5000						
"	"	"	–	"	1,6	6200						
"	"	"	–	"	1,8	7000						
"	"	"	–	"	2,0	8000						
"	"	"	–	"	2,2	8300	180	4300	5000	9300	6,25	1575
"	"	"	–	"	–	11000						
19.3.30.	"	"	–	"	2,2	8300	300	8600	11800	20400	8,16	1200
20.3.30.	20, 44	"	–	–	2,0	8000						
"	"	"	–	–	2,5	10000						
"	"	"	–	–	3,0	12000						
"	"	"	–	–	3,0	14000	360	20700	19000	39700	7,85	1250
"	"	"	–	~8	3,75	15200						
22.3.30	20 "	"	–	~8	–	12–8000	540	31200	26400	57600		
	[illegible] ~22 [illegible]											
26.3.30	20φ 44°	"	–	–	–	8000	[illegible] fl. O_2 [illegible]					
28.3.30	20φ	"	–	–	3,5	14000	160	7300	10200	17500	7,8	1260
"	44°				3,0	12150	250	9300	13300	22600	7,4	1325
"	"	"	–	–	1,0	4000						
"	"	"	–	–	2,0	6000						
"	"	"	–	–	2,75	8000						
"	22 44°	"	–	–	2,0	10000						
"	"	"	–	–	2,75	15000						
"	17 44°	"	–	–	3,0	9000						
"	"	"	–	–	4,0	12000						
"	"	"	–	–	4,3	13000						
1.4.30	17φ lang.	Normal	4,4	5,0	3,7	10000	250	8000	10000	18000	7,05	1390
1.4.30	"	"	4,8	4,8	3,7	10000	250	10000	8500	18500		
1.4.30	17φ 64°	"	5,6	4,4	3,7	10000	250	7250	8500	15750	6,2	1580
" "	22φ 24°	"	10–8,5	9	3,6	18000	200	14000	14200	28200	7,55	1300
" "	22φ 44°	"	10	9	4,2	21000						

Von hier ab beginnen die Versuche mit dem 1. Rückstoßwagen.

Fig 18A:

Zusammenstellung der [illegible] von 4.III.30 - 1.IV.30	Compilation of exhaust values from 4.III.30 to 1.IV.30
Datum	date
Drücke in atü	pressures in atm
Düse φ in mm	nozzle diameter in mm
Meßdauer t sek.	measurement duration t in secs.
Ofen Bezeichnung	combustion chamber designation
Rückstoß R in gr.	thrust R in gm
spezifisch. Verbrauch	specific consumption
Summe	total
Treibstoffverbrauch in gr.	propellant consumption in gm.

(other writing illegible)

-16-

Rückstoßofen mit 1. Zerstäuber.

Einheitsofen auf dem Wagen montiert.

R.018.

Bild 1. 19

10.7.8

Bild 2. 20

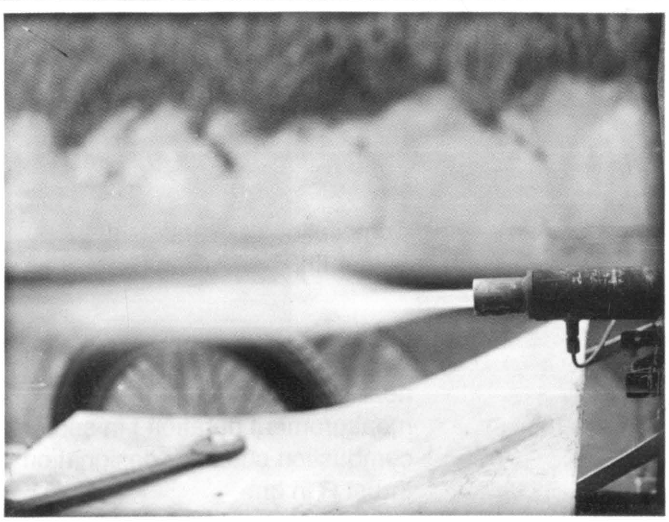


Bild 3. 21

1.7.33.

Figs 19, 20 and 21: Combustion chamber with 1 atomiser, Chamber unit mounted on the car

-70-

Rückstoßofen mit einem Zerstäuber. R.019.

Einheitsofen auf dem Wagen montiert.

22.3.30

22

Bild 1.

Bild 2.

Ri.
1.7.33.

Fig 22: Combustion chamber with 1 atomiser, Chamber unit mounted on the car

-7d-

Rückstoßofen mit 1.Zerstäuber. Einheitsofen.

R.016.

20.3.30

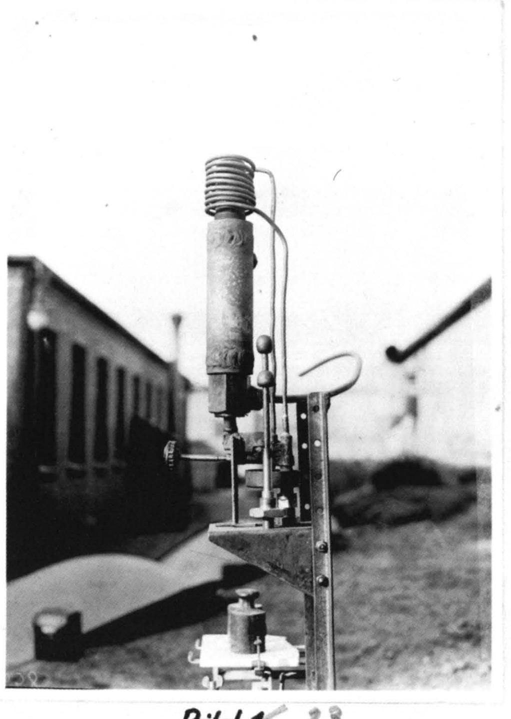


Bild ~~1.~~ 23

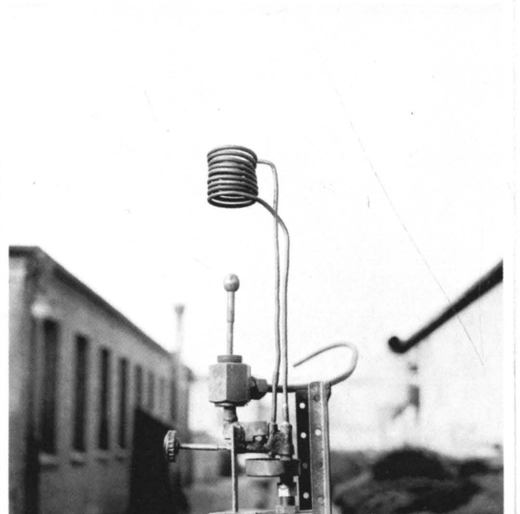


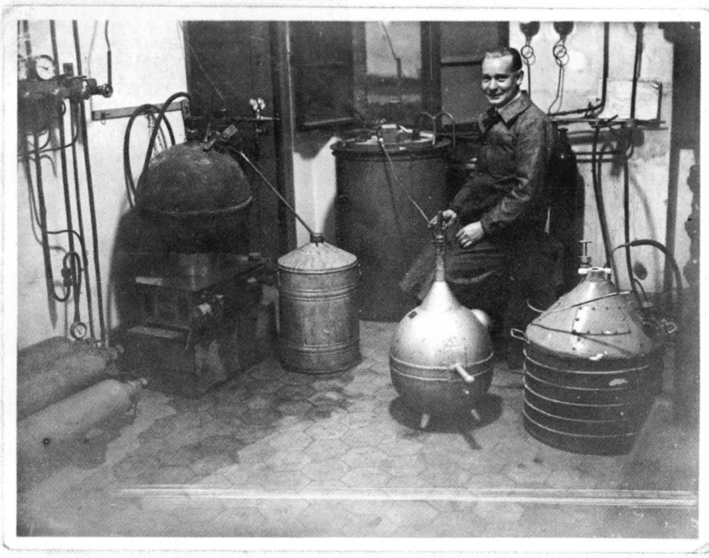
Bild ~~3.~~ 24

Ri. 1.7.33.

Figs 23 and 24: Combustion chamber with 1 atomiser, Unit chamber

- 78 -

Versuchseinrichtungen für flüssig O_2-Betrieb. R.020.



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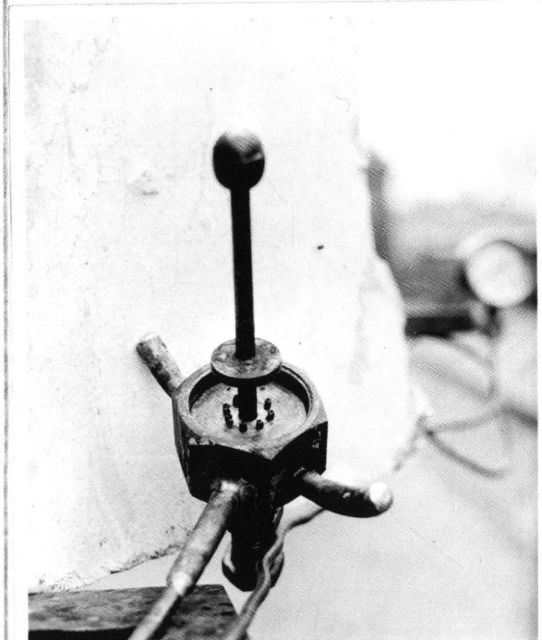


Bild 2 25

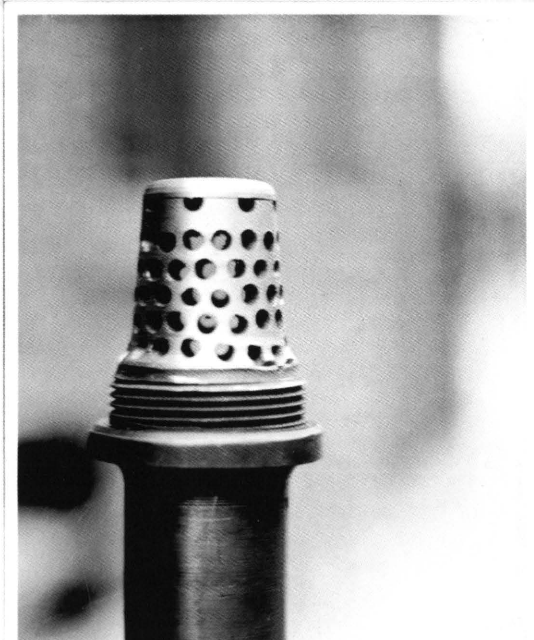


Bild 3.

Ri.
1.7.33.

Fig 25: Test equipment for liquid O_2 operation

-8a-

Bilder von der Vorführung des 1. Rückstoß-
wagens betrieben mit flüssig O_2 u. flüss. Spiritus. **R.031.**

Am 17. u. 19.4. 1930.

Fig 26A: Pictures of the demonstration of the 1st thrust car propelled by liquid O_2 and liquid ethyl alcohol

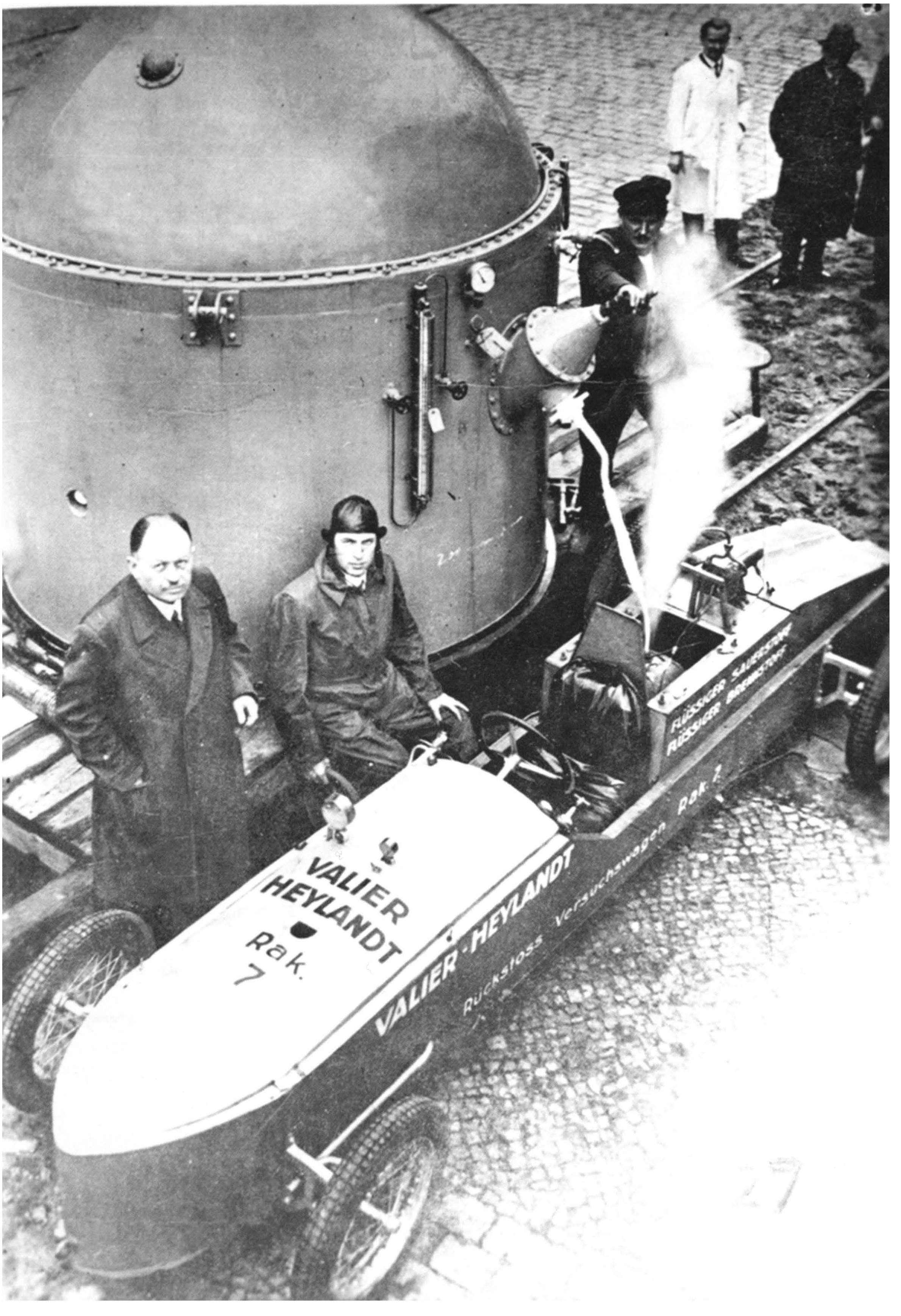
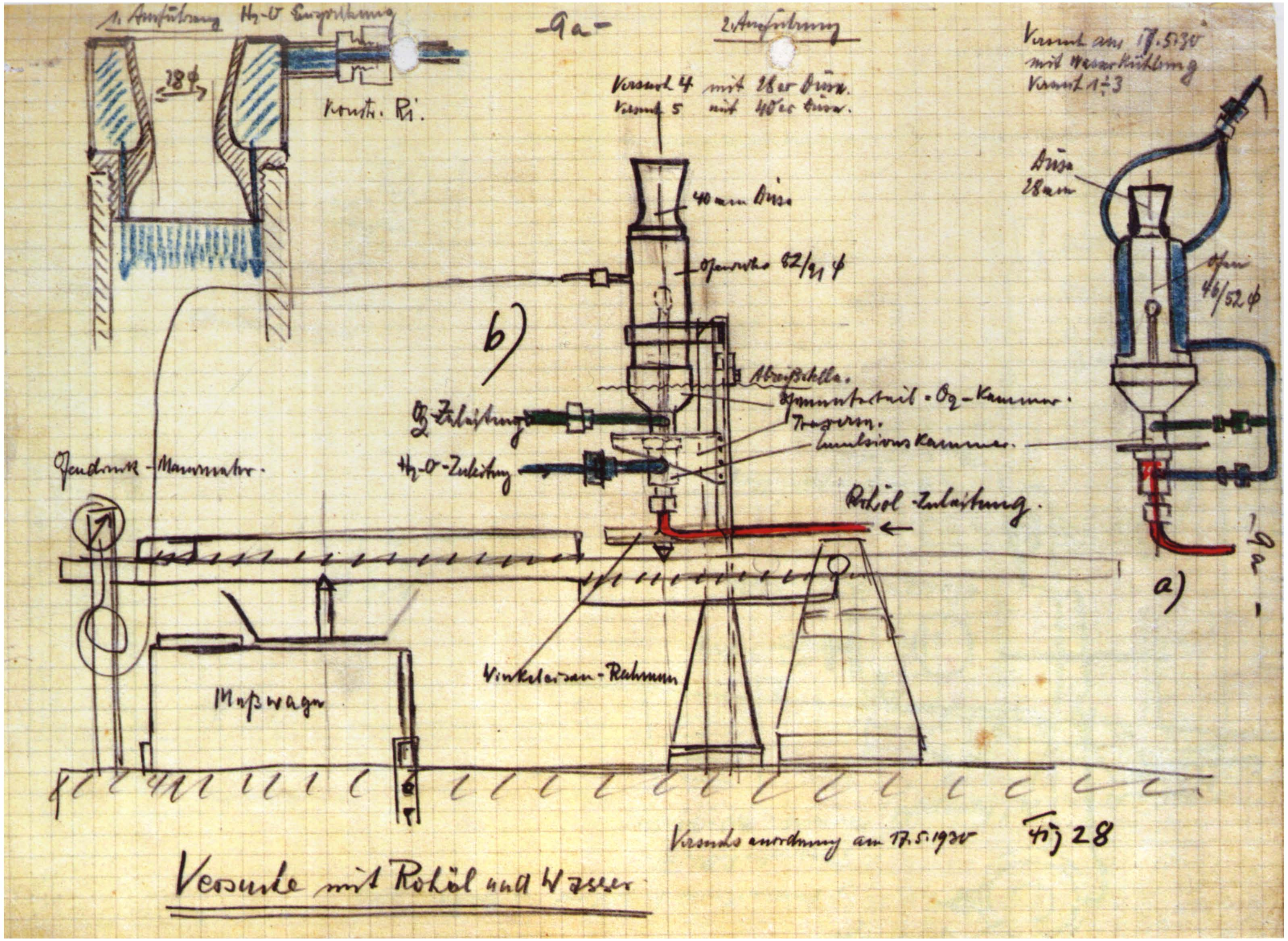


Fig 27: Shows Max Valier and Dr Heylandt near Rak 7 as the liquid oxygen is being tanked aboard.

Fig 28:

40 mm Düse	40 mm diameter nozzle
Abreiß [???]	fracture plane?
Druckzusatzventil für Rohöl- und H_2O-Behälter	pressurising valve for paraffin and H_2O tanks
Düse 28 mm	28 mm dia nozzle
Emulsions-Kammer	emulsion chamber
H_2O-Behalter	H_2O tank
H_2O-Ltg	H_2O line in
H_2O-[???]ventil	H_2O [???] valve
H_2O-Zuleitung	H_2O line in
Kupferschmiede	coppersmiths
Kupferschmiede-Waschraum	coppersmiths' washroom
Manometer H_2O-Behalter	H_2O tank pressure gauge
Manometer Ofendruck	combustion chamber pressure gauge
Manometer Rohöl-Behalter	paraffin tank pressure gauge
Meßwage	measuring scales
O_2-Leitung	O_2 line in
O_2-Zuleitung	O_2 line in
Ofen 46/52 φ	combustion chamber 46/52
Ofendruck-Manometer	combustion chamber pressure gauge
Ofenrohr	combustion chamber pipe
Preßluftbehalter	compressed air tank
Rohöl-Behalter	paraffin tank
Rohöl-Ltg	paraffin line in
Rohöl-Zuleitung	paraffin line in
Treppe z. Keller	steps to cellar
Versuch 1, 2, 3	tests 1, 2, 3
Versuch 4 mit 28er Düse	test 4 with 28 mm dia nozzle
Versuch 5 mit 40er Düse	test 5 with 40 mm dia nozzle
Versuch am 17.5.30 mit Wasserkühlung	test on 17.5.30 with watercooling
Winkeleisen-Rahmen	angle iron frame

[other writing illegible]



Figs 28 a and b: Tests with paraffin and water, Test configuration as at 17.5.1930

Fig 29:

Böschung	bank
Düse	nozzle
Emulsionskammer	emulsion chamber
Fl. O_2 Tank	liquid O_2 tank
Kupferschmiede	coppersmiths
Meßwage	measuring scales
Methan-Schuppen	methane tank
Ofen	combustion chamber
Ofenunterteil	lower section of combustion chamber
Raketenstand	rocket test stand
Rohöl-Zuleitung	paraffin line in
Sauerstoff-Zuleitung	oxygen line in
Standort Riedel	Riedel's position
Standort Rudolph	Rudolph's position
Standort Valier	Valier's position
Traverse	traverse
Wagebalken	balance beam
Waschraum Kupferschmiede	coppersmiths' washroom
Wasser-Zuleitung	water line in
Winkeleisenrahmen	angle iron frame

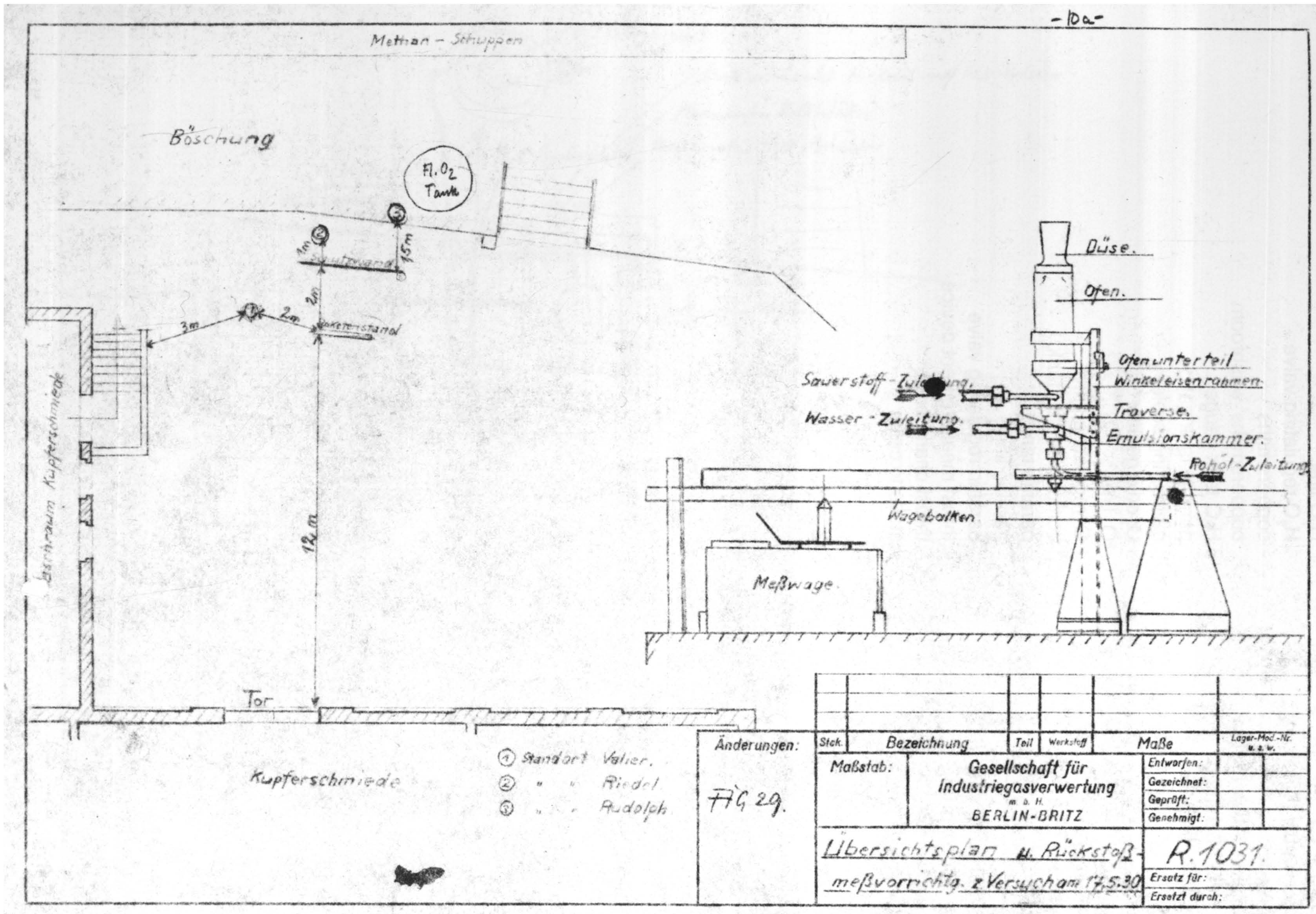


Fig 29: Overview plan and thrust measurement equipment for test on 17 May 1930

Fig 29A:

Druckzusatzventil für Rohöl- und H_2O-Behälter	pressurising valve for paraffin and H_2O tanks
H_2O ltg	H_2O line
H_2O-Regulierventil	H_2O regulating valve
Kupferschmiede	coppersmiths
Kupferschmiede - Waschraum	coppersmiths' washroom
Manometer H_2O-Behälter	H_2O tank gauge
Manometer Rohölbehalter	paraffin tank gauge
Meßwage	measuring scales
O_2 - Kaltvergaser	O_2 cold gasifier
O_2-Leitung	O_2 line
O_2 -Regulierventil	O_2 regulating valve
Preßluftbehalter	compressed air tank
Rohölbehalter	paraffin tank
Rohöl ltg	paraffin line
Rohöl-Regulierventil	paraffin regulating valve
Rückstoßmeßvorrichtung	thrust measurement device
Rückstoßofen	thrust chamber
Treppe z. Keller	stairs to cellar

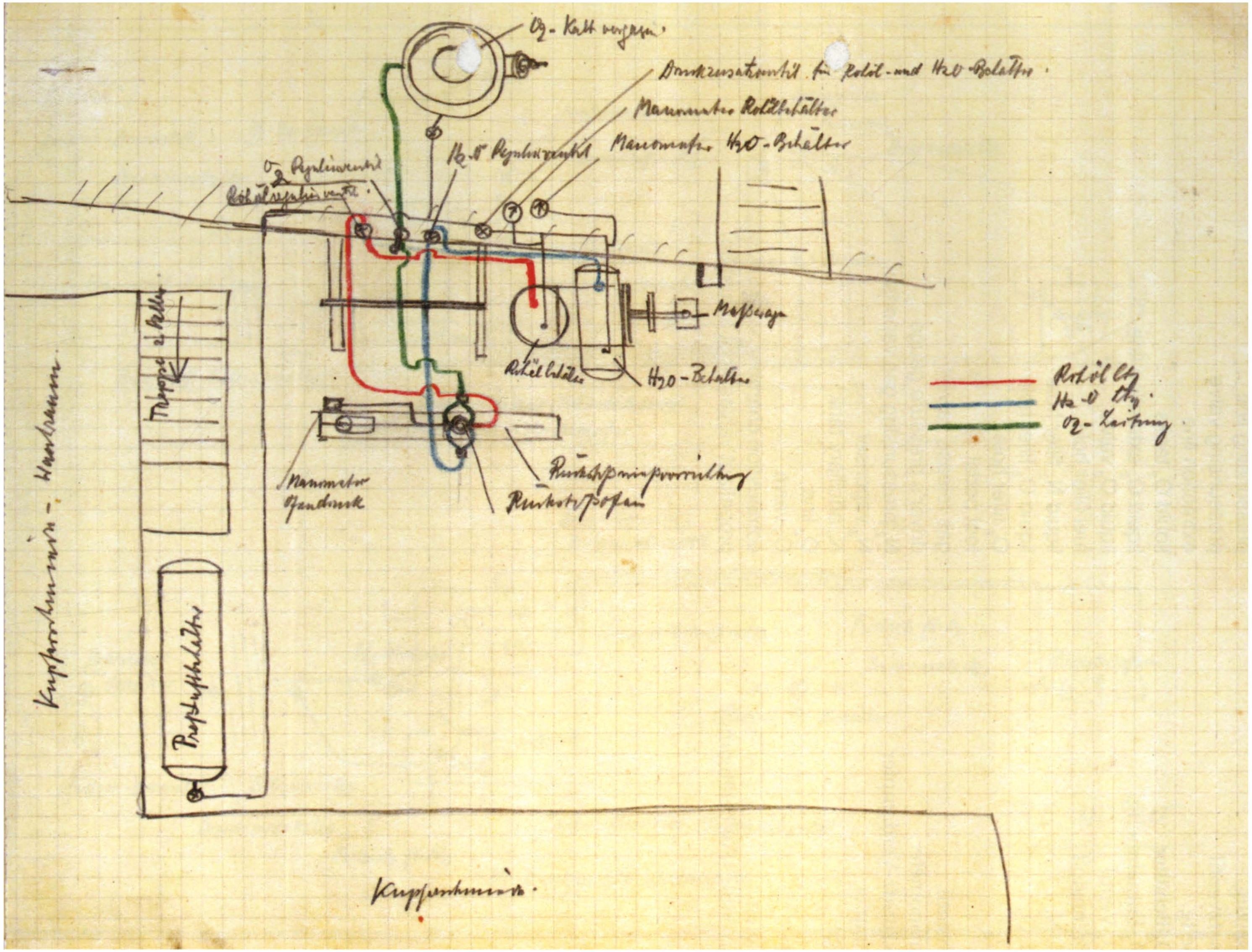


Fig 29A: Test cell layout

Fig 30:

Brennstoff-Behälter	fuel tanks
Brennstoff-Entnahmeltg.	fuel extraction line
Brennstoffventil	fuel valve
Br-Ltg.	fuel line
Druckzusatzltg.	pressurising line
Druckzusatzventil	pressurising valve
Entnahmeltg.	extraction line
Flüssig-O_2-Behälter	liquid O_2 tanks
Flüssig-O_2-Entnahmeltg.	liquid O_2 extraction line
Flüssig-O_2-Ventil	liquid O_2 valve
Fülloch-Brennstoff	fuel filler hole
Fülloch fl. N_2	liquid N_2 filler hole
Fülloch fl. O_2	liquid O_2 filler hole
Fülloch O_2	O_2 filler hole
Fußtritt	foot pedal
Gasablaßventil	gas release valve
Kontrollmanometer	driver's pressure gauge
N_2-Druckzusatz-Verdampfer	N_2 pressurising gas vaporiser
N_2-Verdampfer	N_2 vaporiser
N_2-Vorlage	N_2 ancillary tank
O_2-Ltg.	O_2 line
O_2-Ventil	O_2 valve
Rückstoßofen	combustion chamber
Treibstoffventile (Fußbetätigung)	propellant valves (foot actuation)

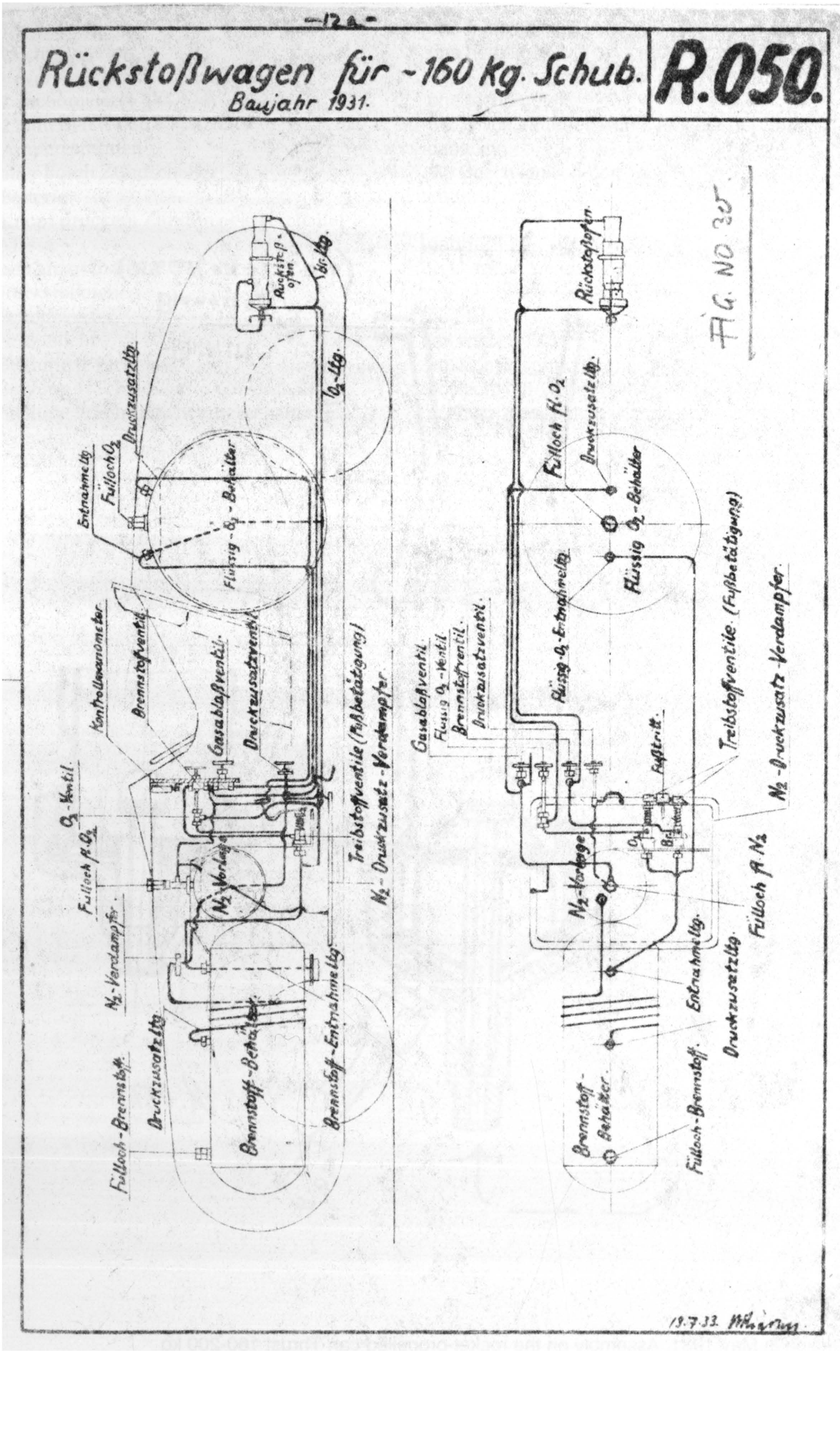


Fig 30: Rocket-propelled car with 160 kg thrust, Build year 1931

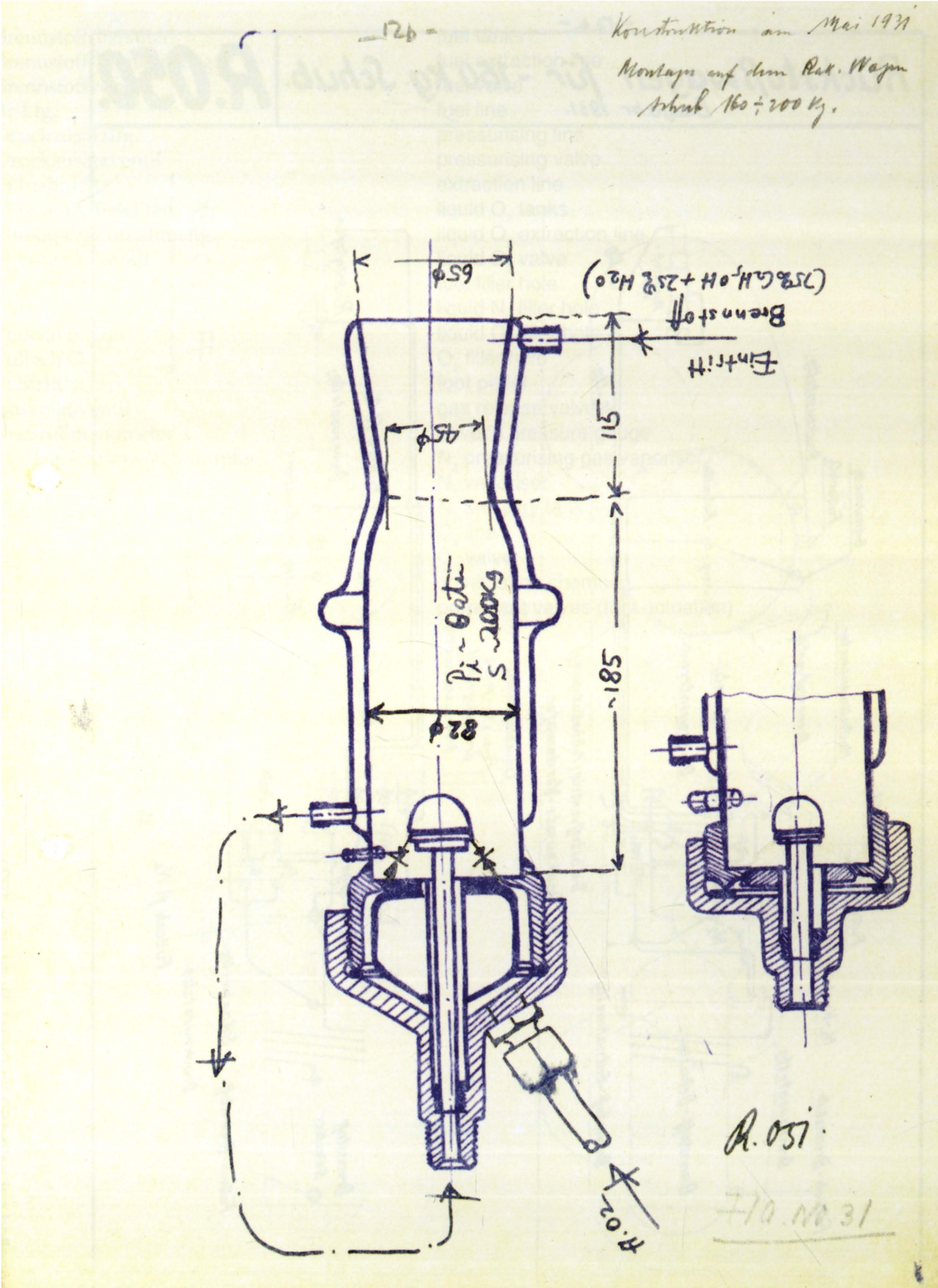


Fig 31: Design in May 1931, Assembly on the rocket-propelled car, Thrust 160-200 kg

Eintriff Brennstoff	fuel admission

Fig 32:

1 Magnetapparat	one magneto unit
1 Scheinwerfer (Verbrauch nicht mehr als 0.7)	one headlight (consumption not more than 0.7)
1 Tachometer	one tachometer
2 Batterien 6 Volt Kapazität 7 Amperestunden	two 6-volt batteries with 7 ampere hours capacity
alter Bosch Zündschalter	old Bosch ignition unit
Batterie	battery
Knopf drucken: Zündung eingeschaltet	press knob: ignition switched on
Masse	earth
neu anzuschaffen	to be newly procured
Rückstoßofen	combustion chamber
Scheinwerfer	headlight
Schlußlicht	tail light
Stellung 0: Licht aus	position 0: light off
Stellung 1: Scheinwerfer eingeschaltet	position 1: headlight switched on
Stellung 2: Schlußlicht eingeschaltet	position 2: tail light switched on
Vibrator	trembler
Zündkerze	spark plug

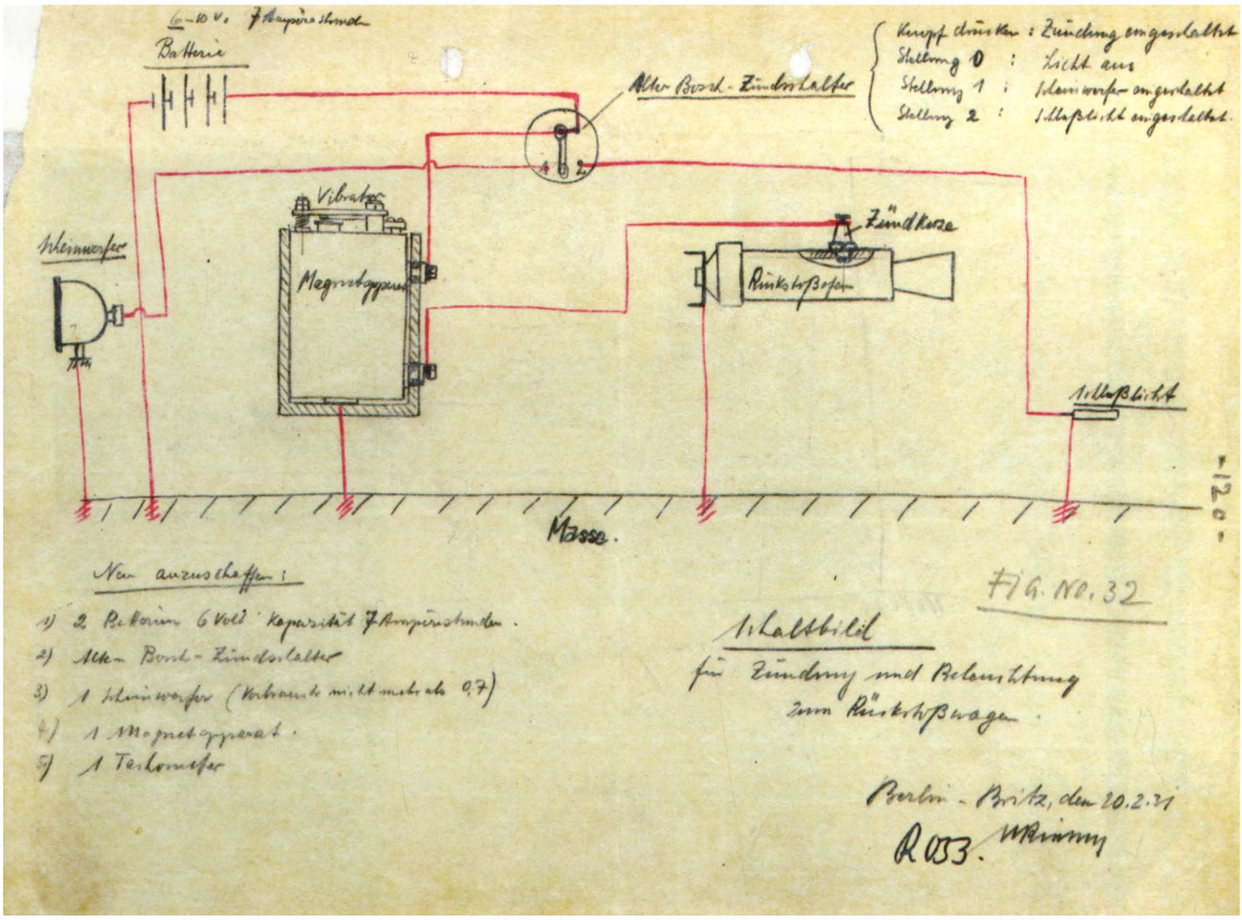
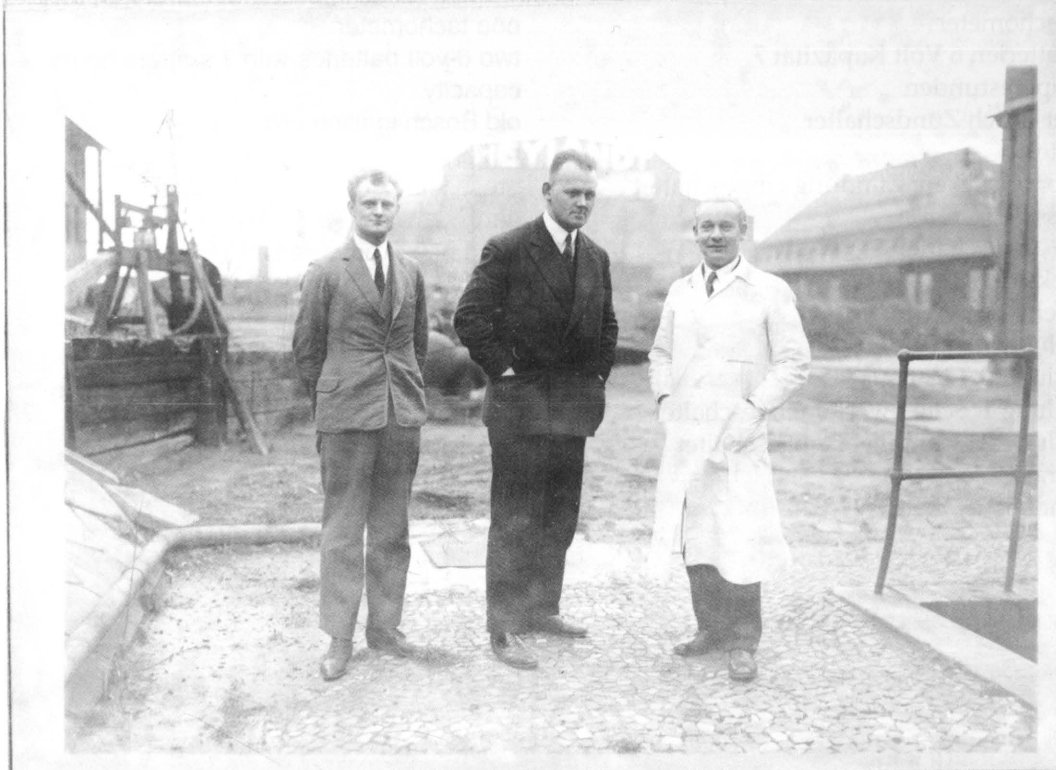


Fig 32: System diagram for ignition and lighting on the rocket-propelled car

—13—

Rückstoßwagen für ~ 160 kg Schub. **R.054.**

Baujahr Mai 1931.



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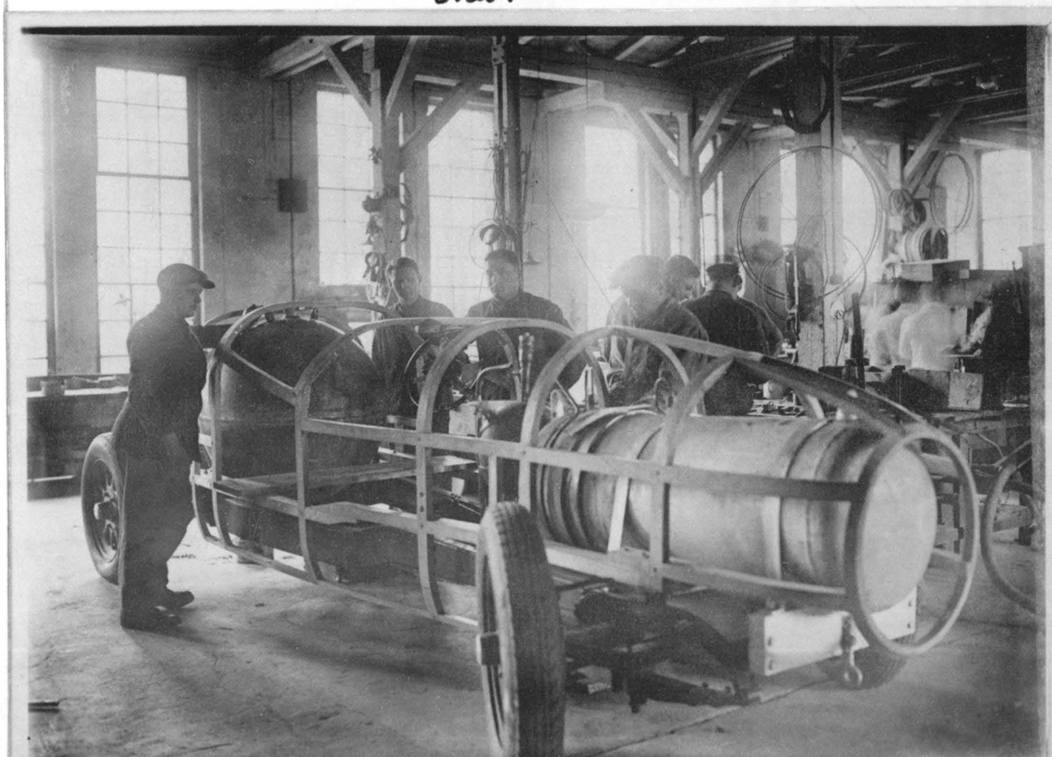


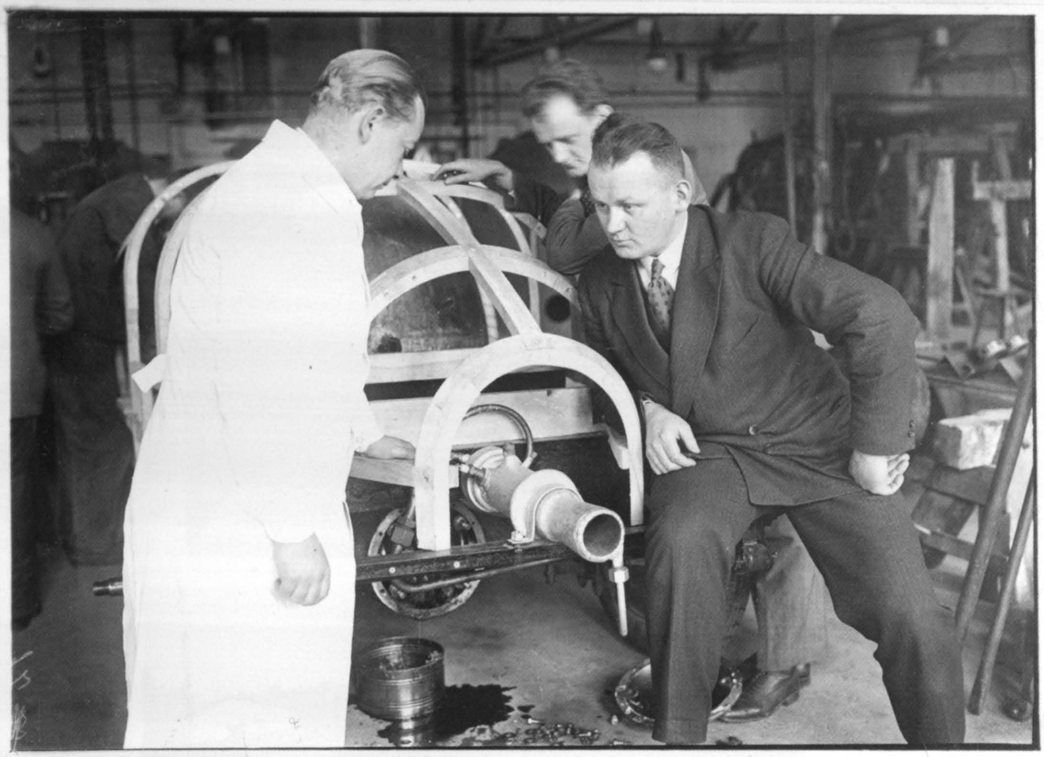
Bild.2. 1.7.33

Fig 33: Rocket-propelled car with 160 kg thrust, Build year May 1931

-136-

Rückstoßwagen für-160 kg. Schub. **R.055.**

Baujahr 1931.



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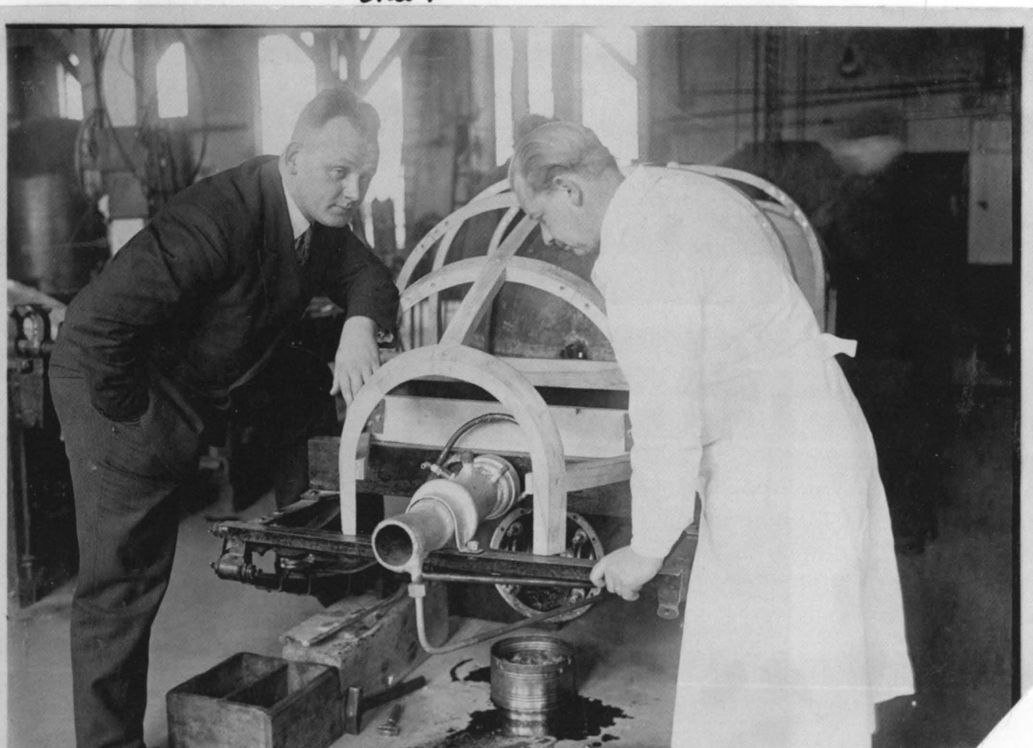


Bild 2. 1.7.33.

Fig 34: Rocket-propelled car with 160 kg thrust, Build year 1931

-13c-

Rückstoßwagen für ~160kg Schub.

Baujahr 1931.

R.056.

Fzg No 35a

Bild 1.

Fzg No 35b

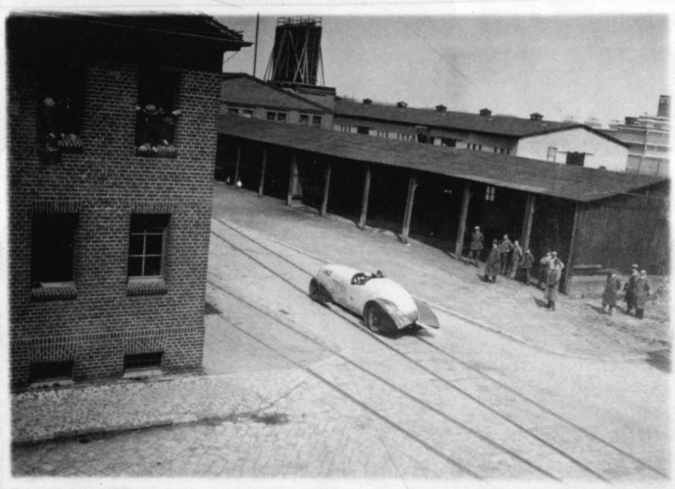


Bild 2.

Fzg No 35c

Bild 3.

Ri. 1.7.33.

Figs 35 a-c: Rocket-propelled car with 160 kg thrust, Build year 1931

-13a-

Rückstoßwagen für ~ 160 kg Schub. **R.057.**

Baujahr 1931.

Fz Nr 36a

Bild 1.

Fz Nr 36b

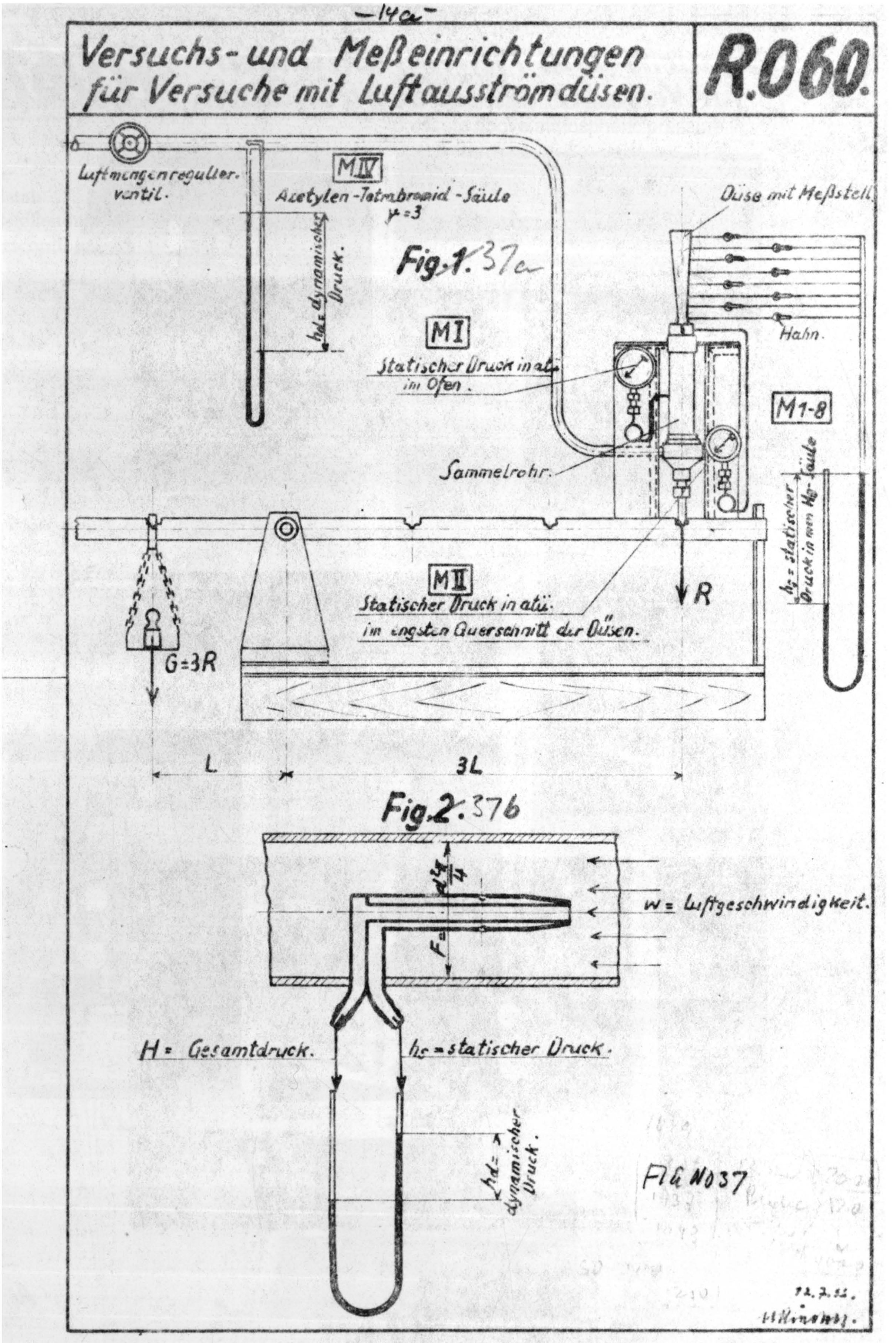
Bild. 2.

1.7.33.

Figs 36 a-b: Rocket-propelled car with 160 kg thrust, Build year 1931

Fig 37:

Azetylen-Tetrabromid-Säule	acetylene-tetrabromide column
Düse mit Meßstell.	nozzle with tappings
dynamischer Druck	dynamic pressure
Gesamtdruck	total pressure
Hahn	tap
Luftgeschwindigkeit	air velocity
Luftmengenregulierventil	air quantity regulating valve
Sammelrohr	manifold pipe
statischer Druck	static pressure
statischer Druck in atü im engsten Querschnitt der Düsen	static pressure in atmospheres in nozzle throat
statischer Druck in atü im Ofen	static pressure in atmospheres in combustion chamber
statischer Druck in mm Hg-Säule	static pressure in mm mercury column



Figs 37: Test and measurement equipment for tests with air exhaust nozzles

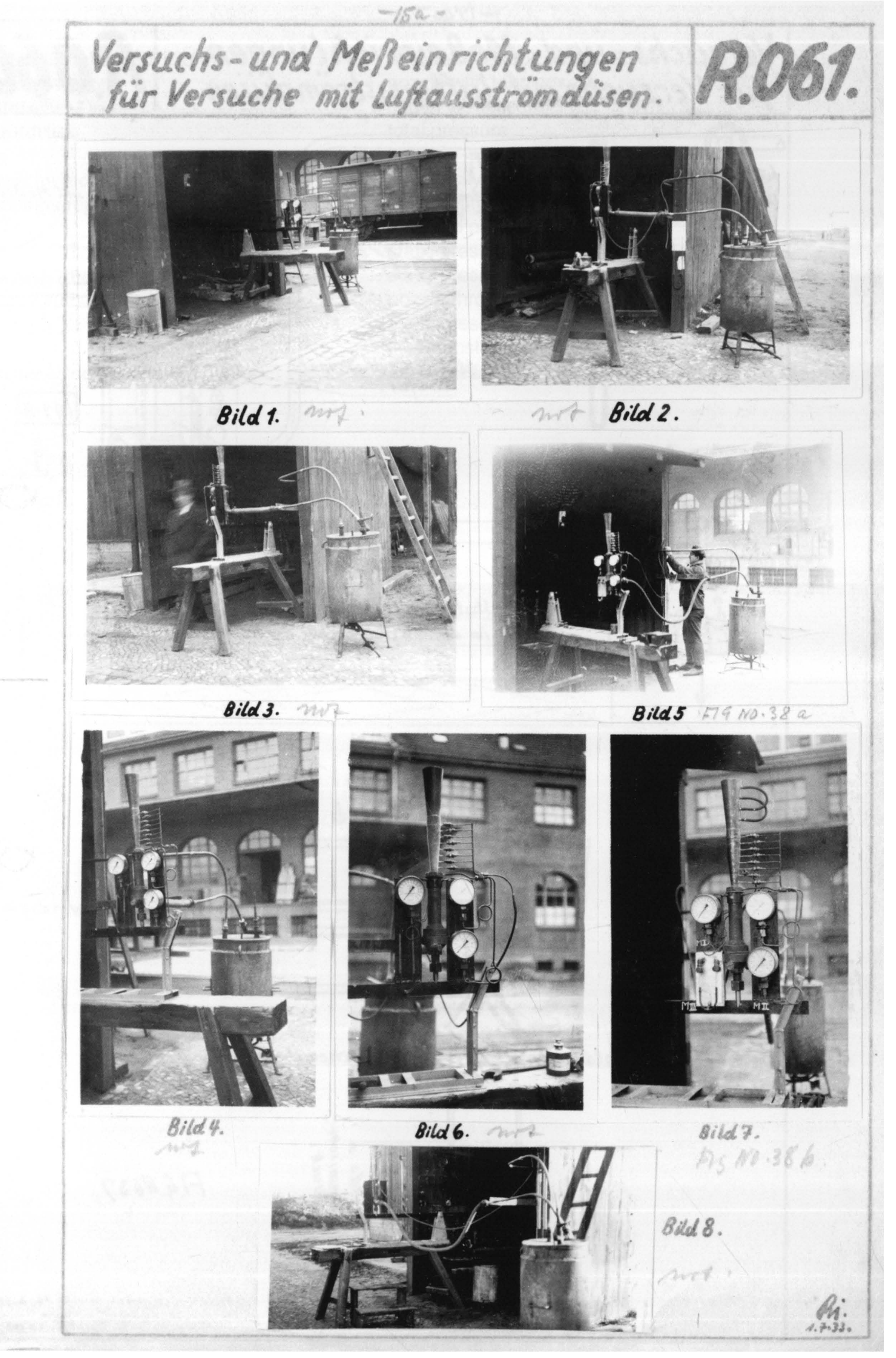


Fig 38: Test and measurement equipment for tests with air exhaust nozzles

Fig 39

Anlage 4	attachment 4
Atmosphärische Linie	line of atmospheric pressure
atü	pressure above atmospheric pressure in atmospheres
Düse	nozzle
Maßstab	scale
Meßstellen im Abstand vom	distances of measurement ports from throat engsten
Querschnitt in mm	section in mm
mm Hg-Säule	mm of Hg column
Null-Linie	zero pressure line
Rückstoß in Kg	thrust in kg
Statischer Druck	static pressure

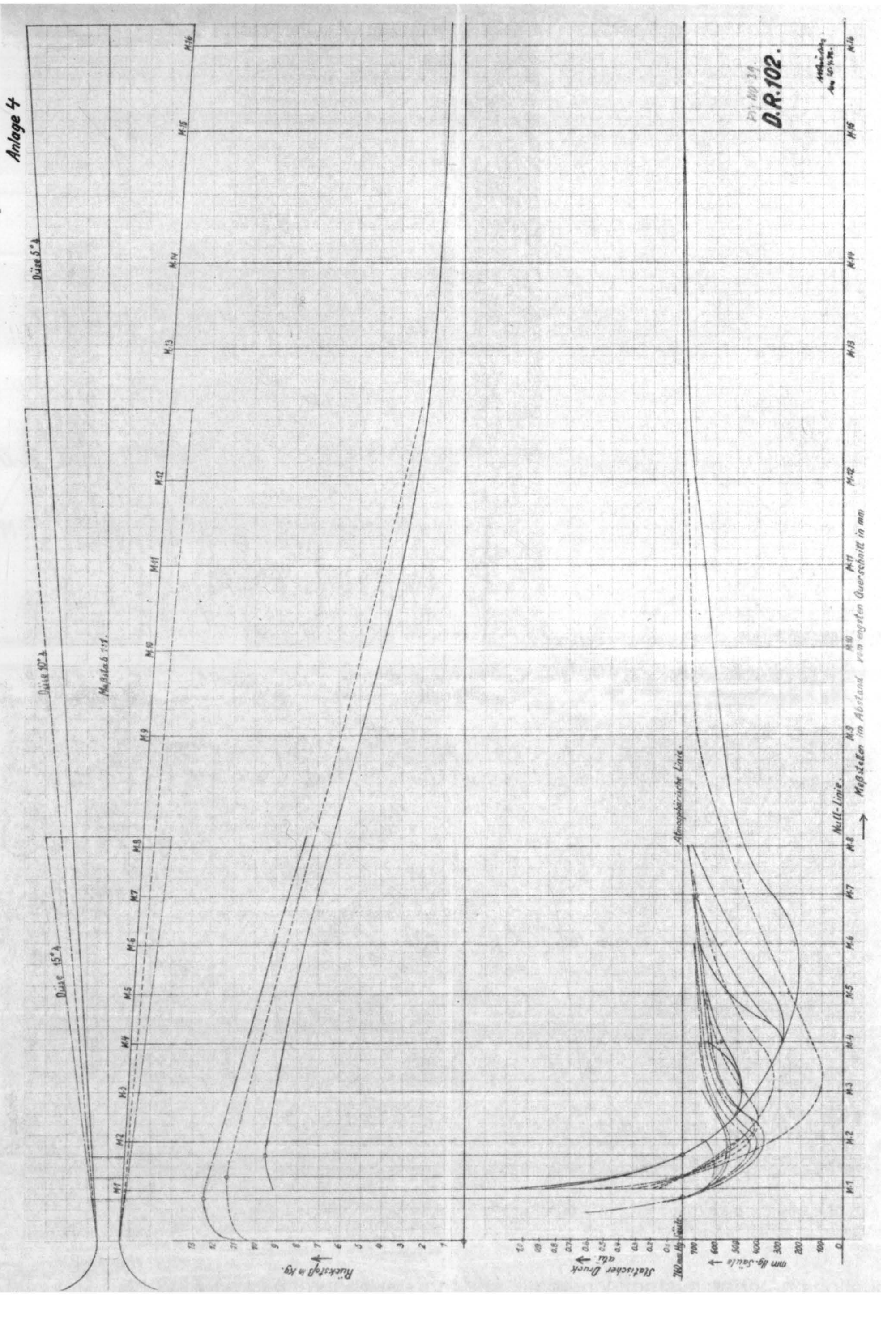


Fig 39: Test results, shown as a function of nozzle length

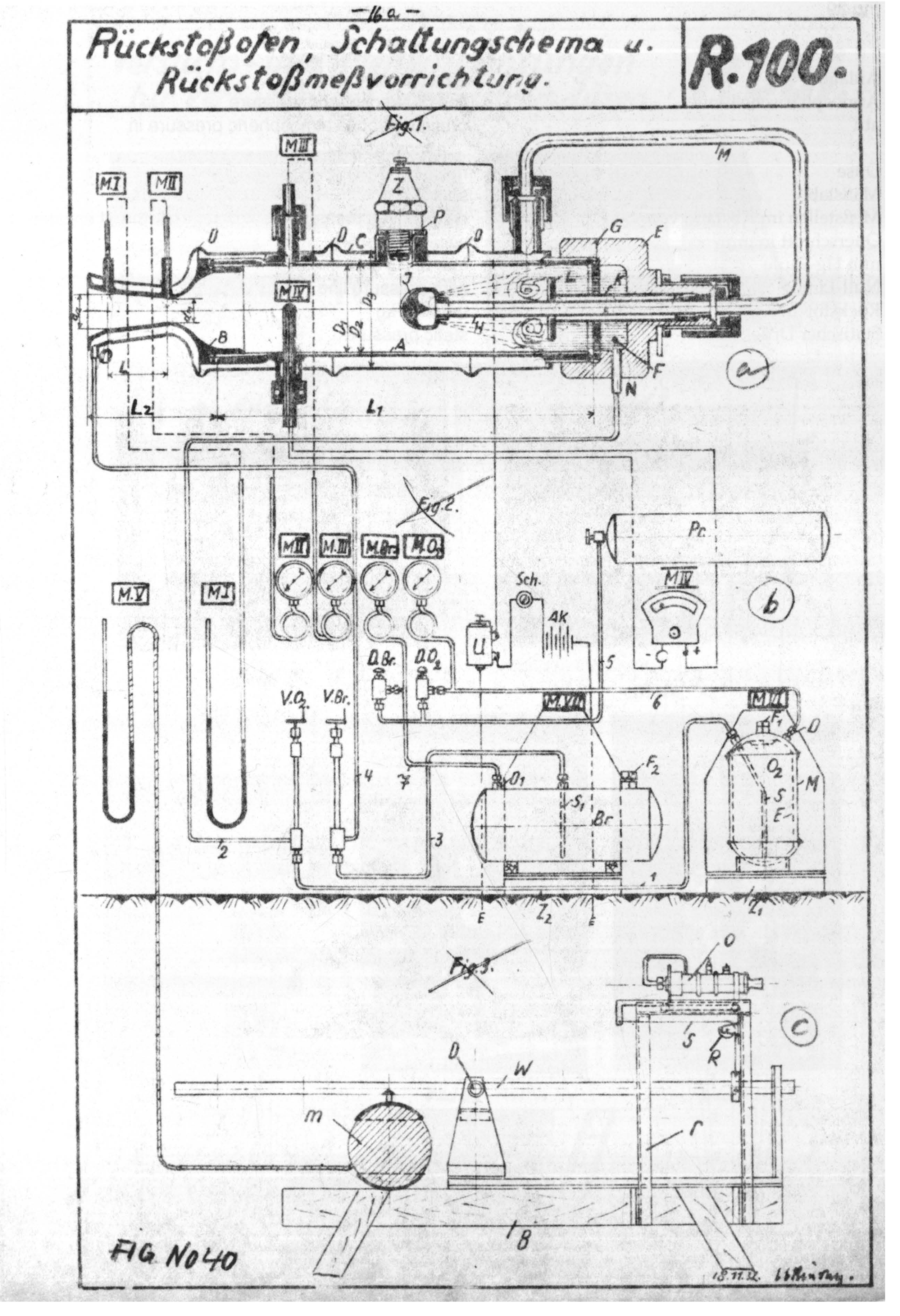


Fig 40: Combustion chamber, system schematic and thrust measurement equipment

–17a–

Meßvorrichtungen für Versuche Rückstoßofen. | R.101.

FIG NO 41

Bild 1. (a)

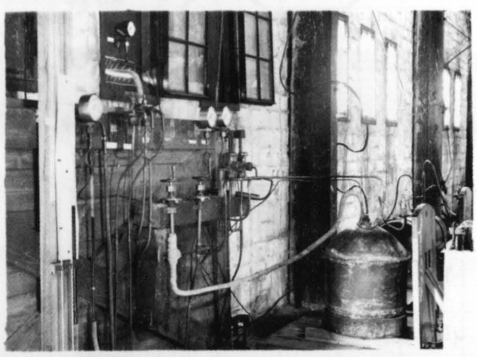


Bild 2. (b)

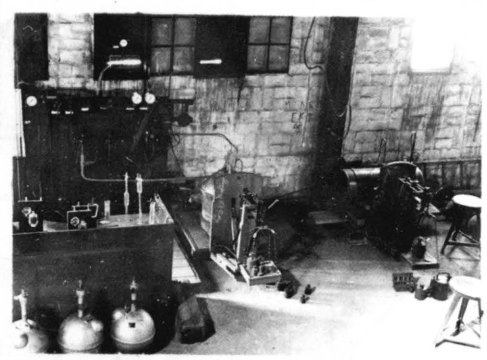


Bild 3. (c)

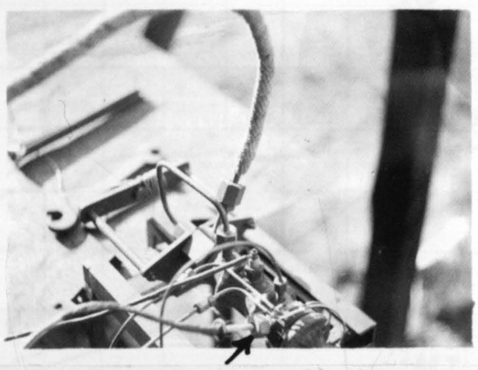


Bild 4. (d)

Ri.
1.7.33.

Fig 41: Measurement equipment for combustion chamber tests

Fig 42:

Ausströmgeschwindigkeit	exit velocity
Brenndauer	burn duration
Brennstoff-Verbrauch	fuel consumption
Datum: 30.9.1932	date: 30.9.1932
Rückstoß	thrust
Sauerstoff-Verbrauch	oxygen consumption
Sek.	Seconds
Spezifischer Verbrauch	specific consumption
Stat. Druck Düsenmündung	static pressure in the nozzle exit plane
Stat. Drücke in Kg/cm2	static pressures in kg/cm2
Stat. Druck engste Stelle Düse	static pressure in the nozzle throat
u. Rückstoß in Kg	and thrust in kg
Treibstoff-Verbrauch in Kg	propellant consumption in kg
Verbrauch für 18 Kg Rückstoß	consumption for 18 kg thrust
Versuch Nr:3	test no.3
Zeit in min.	time in minutes

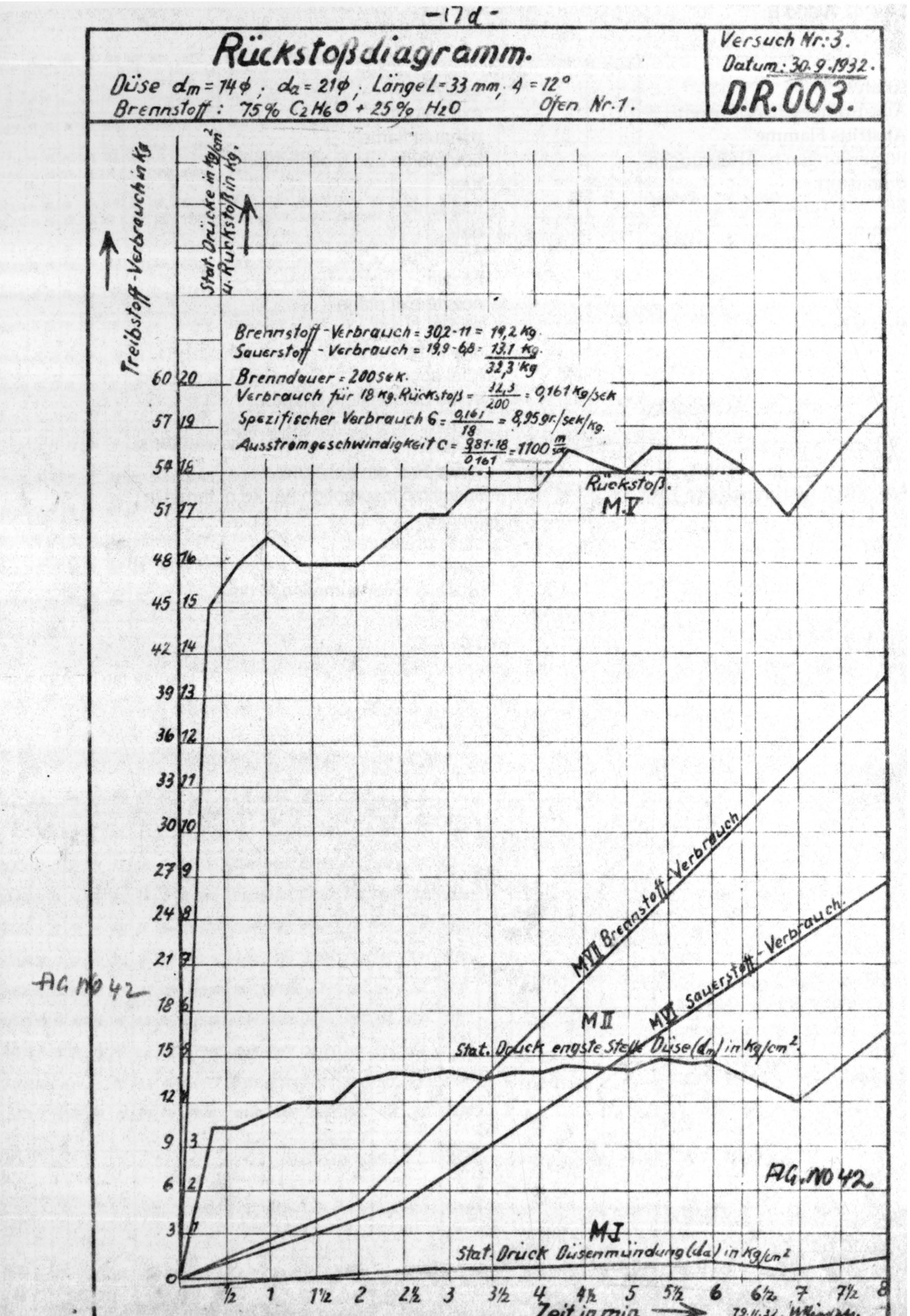


Fig 42: Thrust diagram
Nozzle $d_m = 14\varphi$; $d_a = 21\varphi$; length L = 33 mm; angle = 12°
Fuel: 75% C_2H_6O + 25% H_2O Combustion chamber No.1

Figs 42 A and B:

Analyse	analysis
Ausstromgeschwindigkeit	exit velocity
Austritts Flamme	exhaust flame
Bemerkungen u. Änderungen	comments and modifications
Brennstoff	fuel
Brennst. Tank	fuel tank
Datum	date
Drücke	pressures
Düse	nozzle
Düsenmündung	nozzle exit plane
engste Stelle	throat
Gas-Temperatur	gas temperature
Gesamtverbrauch G pro R kg in gr./sek.	total consumption G per kg R in gm/sec
im Ofen	in the combustion chamber
Meßdauer sek.	measurement duration in secs
O_2 Tank	O_2 tank
Rückstoß R in gr. absolut	thrust R in gm absolute
Spezifisch. Verbrauch pro 1 Kg	specific consumption per kg of thrust in
Rückstoß in gr./sek.	gm/sec
statische Drücke	static pressures
Summe	total
Treibstoffverbrauch in gr.	propellant consumption in gm

[other writing illegible]

dm | MO_2 | MBr | MIII | MII | MI | MV | MVI | MVII | MVI u. VII | G_1 | 6

Datum	Düse Ø mm	Düse ∢ °	Drücke kg/cm² O_2 Tank	Drücke kg/cm² Brennst. Tank	Drücke kg/cm² Ofen	Statische Drücke kg/cm² Düse engste Stelle	Statische Drücke kg/cm² Düsenmündung	Rückstoß R in gr. absolut	Treibstoffverbrauch in gr. O_2	Treibstoffverbrauch in gr. Brennstoff	Treibstoffverbrauch in gr. Summe	Meßdauer sek	Gesamt-Verbrauch G pro R kg in gr/sek	Spezifisch. Verbrauch pro kg Rückstoß in gr/sek	Ausströmgeschwindigkeit $c = \frac{9{,}81 R}{G}$ m/sek	Analyse CO_2 %	Analyse CO %	Analyse H_2O %	Analyse O %	Analyse H %	Analyse Brennstoff %	Gas-Temperatur °C im Ofen	Gas-Temperatur °C Austritts-Flamme	Bemerkungen u. Änderungen
16.9.32	10	12	14	14	10-12		max. -21,5	~10000	3800	2000	5800	55 Leist. 30	105	10,5	930									[illegible]
27.9.32	14	12	14	14	6-7 u. 9	max 4,2	cm 8-9	im Mittel 14000	19600	29600	49200	420	117,5	8,4	1165									Werte über die Gesamtzeit 75% C_2H_5OH + 25% H_2O
27.9.32	14	12	14	14	9	4,2	9	17000	8800	9800	18600	140	132,5	7,8	1260									Werte über die [illegible]
29.9.32	14	12	14	14	6-9	4,9	20	15000	25600	55000	80600	540	149	9,9	990									Durchschnittswerte über die Gesamtzeit 75% C_2H_5OH + 25% H_2O
29.9.32	14	12	14	14	9	4,9	20	18000	12000	24000	36000	225	161	9	1090									" " über die [illegible]
30.9.32	14	12	14	14	10	4,9	20	17000	26400	40000	66400	400	166	9,75	1070									Durchschnittswerte über die Gesamtzeit
30.9.32	14	12	14	14	10	4,9	20	18000	13100	19200	32300	200	161	8,95	1100									" " über die [illegible]
6.10.32	15	13	14	14	~10	4,9	9 cm	22000	56400 50000	65000 58800	121400 108800	980 690	158	7,16	1370									
13.10.32	15	13	14	14	10	4,9	6	23000	37600 17600	28600 15600	33200	420 200	166	7,2	1360							~940		75% C_2H_5OH + 25% H_2O
14.10.32	15	13	14	14	10	4,9	8	23500	25400	11600	37000	480 200	185	7,85	1245							~880		" "
20.10.32	15	13	14	14	10	4,8	8	21300	51400	28200	79600	420	189	8,9	1100									85% C_2H_5OH + 15% H_2O
21.10.32	15	13	14	14	~10	5,0	14 cm	22500	40600	22700	63300	340	185	8,25	1190									75% C_2H_5OH + 25% H_2O
4.11.32	15	13	14	14	9	5,1	10 cm	23000	50800	60200	111000	660	168	7,3	1345							1200		" "
8.11.32	15	13	14	14	8,9	4	2 cm	23000	24000	26100	50100	280	178	7,75	1270							1200		"
22.11.32	15	13	14	14	10	3,7	2 cm	22200	25400	20400	45800	270	169	7,63	1285									[illegible] eingebaut [illegible] eingebaut
22.11.32	15	13	14	14	10,5	3,7	2 cm	24000	9800	8800	18600	105	177	7,4	1335									75% C_2H_5OH + 25% H_2O
22.11.32	15	13	14	14	10,5	3,7	3 cm	24500	9000	8400	17400	100	174	7,1	1380									[illegible]
22.11.32	15	13	14	14	10,5	3,5	2 cm	23700	16000	13200	29200	150	195	8,2	1190									" "

Blatt I

Figs 42A: Test values

dm | MO_2 | MBr | MIII | MII | MI | MV | MVI | MVIII | MVI + VII | G_1 | G

Datum	Düse Ø mm	Düse ∢ °	Drücke kg/cm² O_2 Tank	Drücke kg/cm² Brennst. Tank	Drücke kg/cm² Ofen	Statische Drücke kg/cm² Düse engste Stelle	Statische Drücke kg/cm² Düsenmündung	Rückstoß R in gr. absolut	Treibstoffverbrauch in gr. O_2	Treibstoffverbrauch in gr. Brennstoff	Treibstoffverbrauch in gr. Summe	Meßdauer sek	Gesamt-Verbrauch G pro R kg in gr/sek	Spezifisch. Verbrauch pro kg Rückstoß in gr/sek	Ausströmgeschwindigkeit $c = \frac{9{,}81 R}{G}$ m/sek	Analyse CO_2 %	Analyse CO %	Analyse H_2O %	Analyse O %	Analyse H %	Analyse Brennstoff %	Gas-Temperatur °C im Ofen	Gas-Temperatur °C Austritts-Flamme	Bemerkungen u. Änderungen
22.11.32	15	13	14	14	11	3,8	4	24500	22000	24400	46400	255	182	7,43	1320									55% C_2H_5OH + 41% H_2O
23.11.32	15	13	14	14	10,5	3,8	3	24500	30800	34800	65600	345	190	7,75	1260									" "
23.11.32	15	13	14	14	10,5	3,8	3 cm	24500	12000	12400	24400	135	183	7,05	1390									" "
23.11.32	15	13	14	14	10,5	3,6	0,6	24300	16200	34400	50600	240	210	8,75	1135									55% C_2H_5OH + 45% H_2O [illegible]
6.12.32	14	12	14	14	~10	4,8	+15 cm	16900	9100	19200	26300	180	146	8,6	1135									55% C_2H_5OH + 41% H_2O } [illegible] 0,5 [illegible]
6.12.32	14	12	14	14	10	4,8	75	16500	27100	52000	79100	540	146	8,85	1110									" "
7.12.32	14	12	14	14	10	4,6	19	17400	39500	31100	55900	390	143	8,2	1190									55% C_2H_5OH + 45% H_2O [illegible] 1 Ø Ofen Nr. 1
7.12.32	14	12	14	14	11	4,6	+16	20000	15900	17500	33400	240	139	6,95	1410									55% C_2H_5OH + 45% H_2O [illegible] 1 Ø [illegible] Ofen Nr. 3
7.12.32	14	12	14	14	10	4,7	24	17100	15500	14800	30300	240	126	7,35	1330									55% C_2H_5OH + 45% H_2O [illegible] 1 Ø [illegible] Ofen Nr. 1

Blatt II.

Figs 42B: Test values

Fig 43:

Ausströmgeschwindigkeit	exit velocity
Brenndauer	burn duration
Brennstoff-Verbrauch	fuel consumption
Datum: 6.10.1932	date: 6.10.1932
Rückstoß	thrust
Sauerstoff-Verbrauch	oxygen consumption
Sek.	Seconds
Spezifischer Verbrauch	specific consumption
Stat. Druck Düsenmündung	static pressure in the nozzle exit plane
Stat. Drücke in Kg/cm2	static pressures in kg/cm2
Stat. Druck engste Stelle Düse	static pressure in the nozzle throat
u. Rückstoß in Kg	and thrust in kg
Treibstoff-Verbrauch in Kg	propellant consumption in kg
Verbrauch für 18 Kg Rückstoß	consumption for 18 kg thrust
Versuch Nr:4	test no.4
Zeit in min.	time in minutes

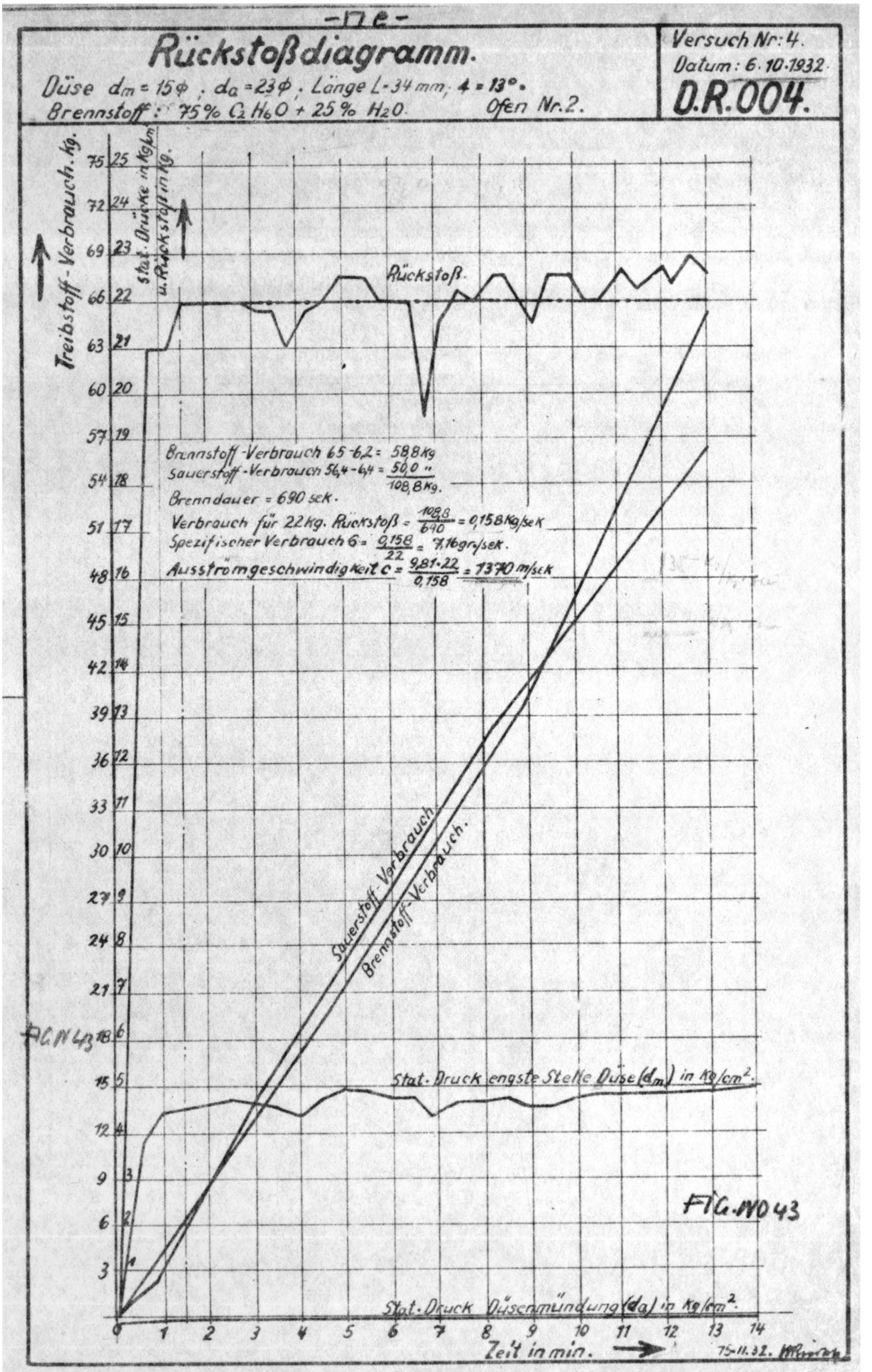


Fig 43: Thrust diagram
Nozzle d_m = 15φ; d_a = 23φ; length L = 34 mm; angle = 13°
Fuel: 75% C_2H_6O + 25% H_2O Combustion chamber No.2

Fig 44

Ausströmgeschwindigkeit	exit velocity
Brenndauer	burn duration
Brennstoff-Verbrauch	fuel consumption
Rückstoß	thrust
Sauerstoff-Verbrauch	oxygen consumption
Sek.	Seconds
Spezifischer Verbrauch	specific consumption
Stat. Druck Düsenmündung	static pressure in the nozzle exit plane
Stat. Drücke in Kg/cm2	static pressures in kg/cm2
Stat. Druck engste Stelle Düse	static pressure in the nozzle throat
u. Rückstoß in Kg	and thrust in kg
Treibstoff-Verbrauch in Kg	propellant consumption in kg
Verbrauch für R Kg Rückstoß	consumption for R kg thrust
Versuch Nr:	test no.
Zeit in min.	time in minutes

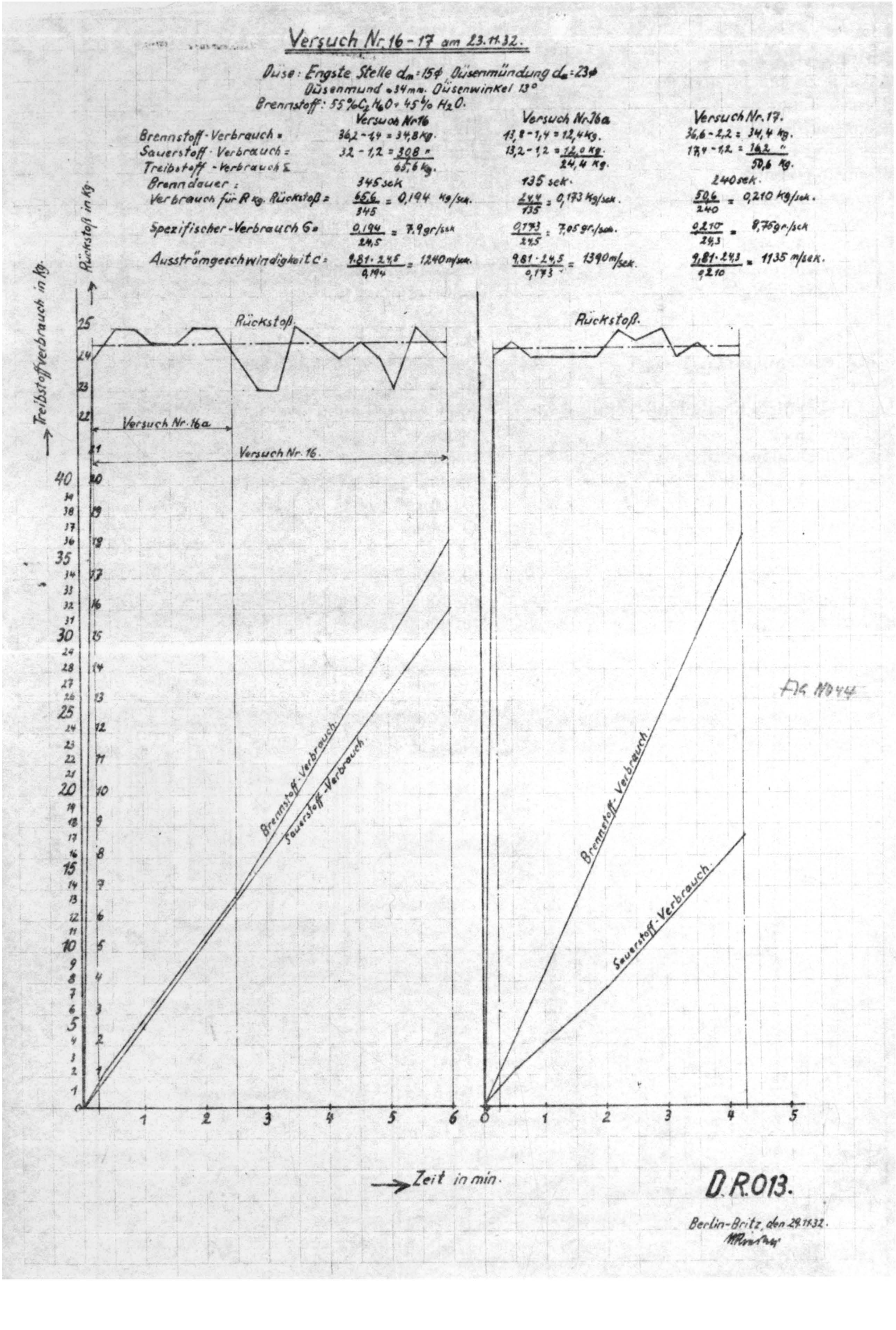


Fig 44: Test Nos. 16-17 on 23rd November 1932
Nozzle: throat $d_m = 15\varphi$; exit plane $d_a = 23\varphi$; nozzle length L = 34 mm; nozzle angle = 13°
Fuel: 55% C_2H_6O + 45% H_2O

Fig 45

Abzugschacht	removal shaft
Askania Zweifachschreiber	Askania twin pen recorder
Brennst.-Eintritt	fuel inlet
Brennstoff-Behälter	fuel tanks
Brennstoff-Ltg.	fuel line
Brennstoff-Ventil	fuel valve
Druckzusatz Brennstoff	fuel pressurising line
Druckzusatz O_2	O_2 pressurising line
Druckzusatzventil	pressurising valve
Eichgewichte	calibration weights
Entwässerungstopf	water removal pot
Feder	spring
Gasablaß-Ventil für Brennstoff	gas release valve for fuel line
Gasablaß-Ventil für O_2	gas release valve for O_2 line
Gestell	framework
Handhebel für Schnellschluß- ventil	manually-operated lever for fast-acting valve
Kolben	piston
Kugelrückschlagventil	ball check valve
Manometer-Anschluß	pressure gauge connection
O_2-Behälter	O_2 tanks
O_2-Eintritt	O_2 inlet
O_2-Ltg.	O_2 line
O_2-Ventil	O_2 valve
Ofendruck	combustion chamber pressure
Reduzierv.	reducing valve
Rückstoß	thrust
Rückstoßofen	combustion chamber
Schnellschlußventil	fast-acting valve
Umlenkrollen	deflection pulleys
vom Preßluftbehälter	from compressed air tanks

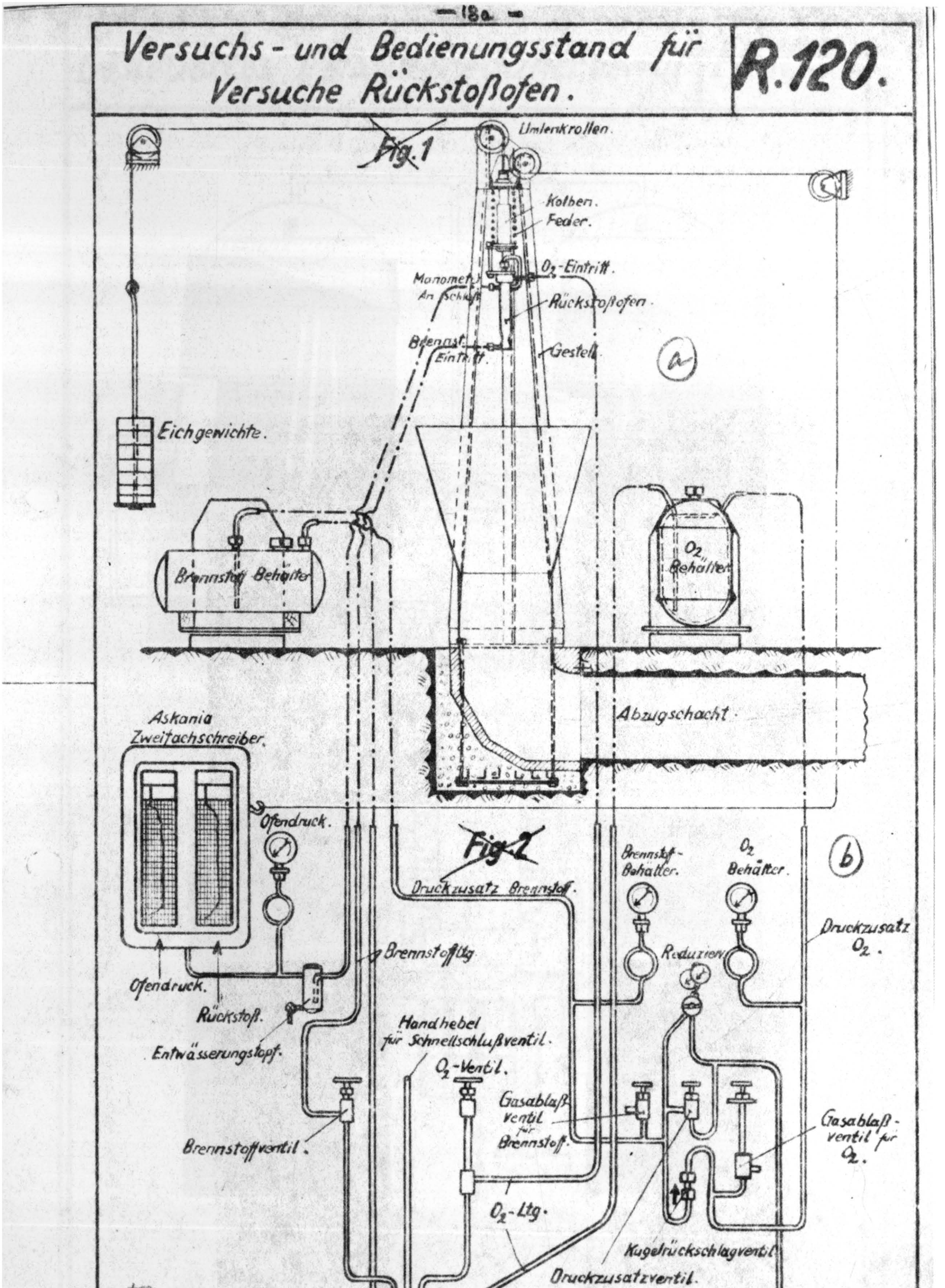
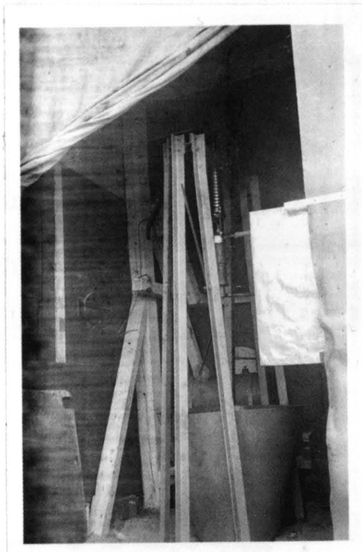


Fig 45: Test and operating stand for combustion chamber tests

-18 b-

R 121



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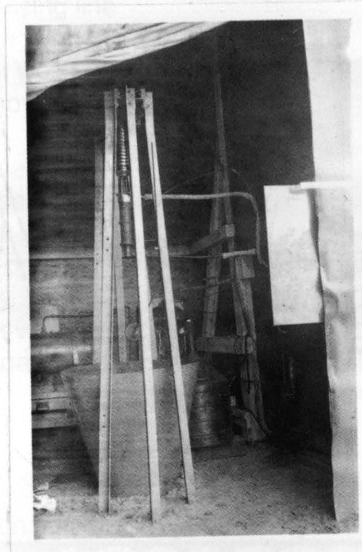

Bild 2 (b)

(From direction 1)

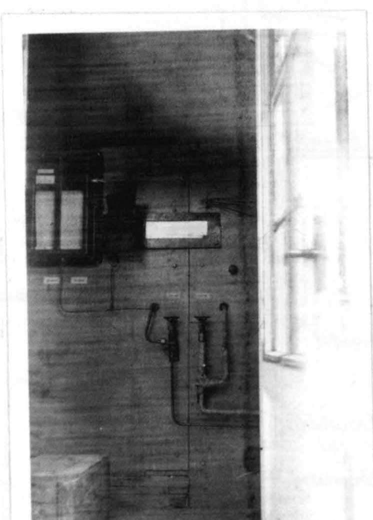

Bild 3 (c)

(From direction 2)

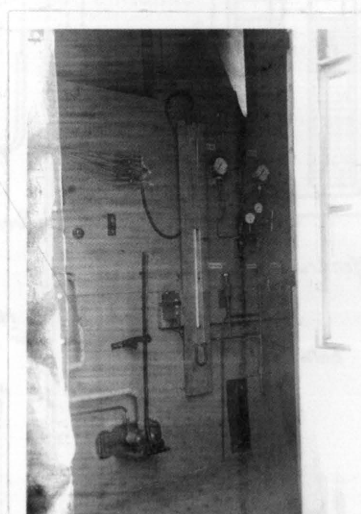

Bild 4 (d)

(From direction 3)

FIG NO 46

Ri: 20.12.33.

Fig 46: Views of testing (ref Fig 45c page 14)

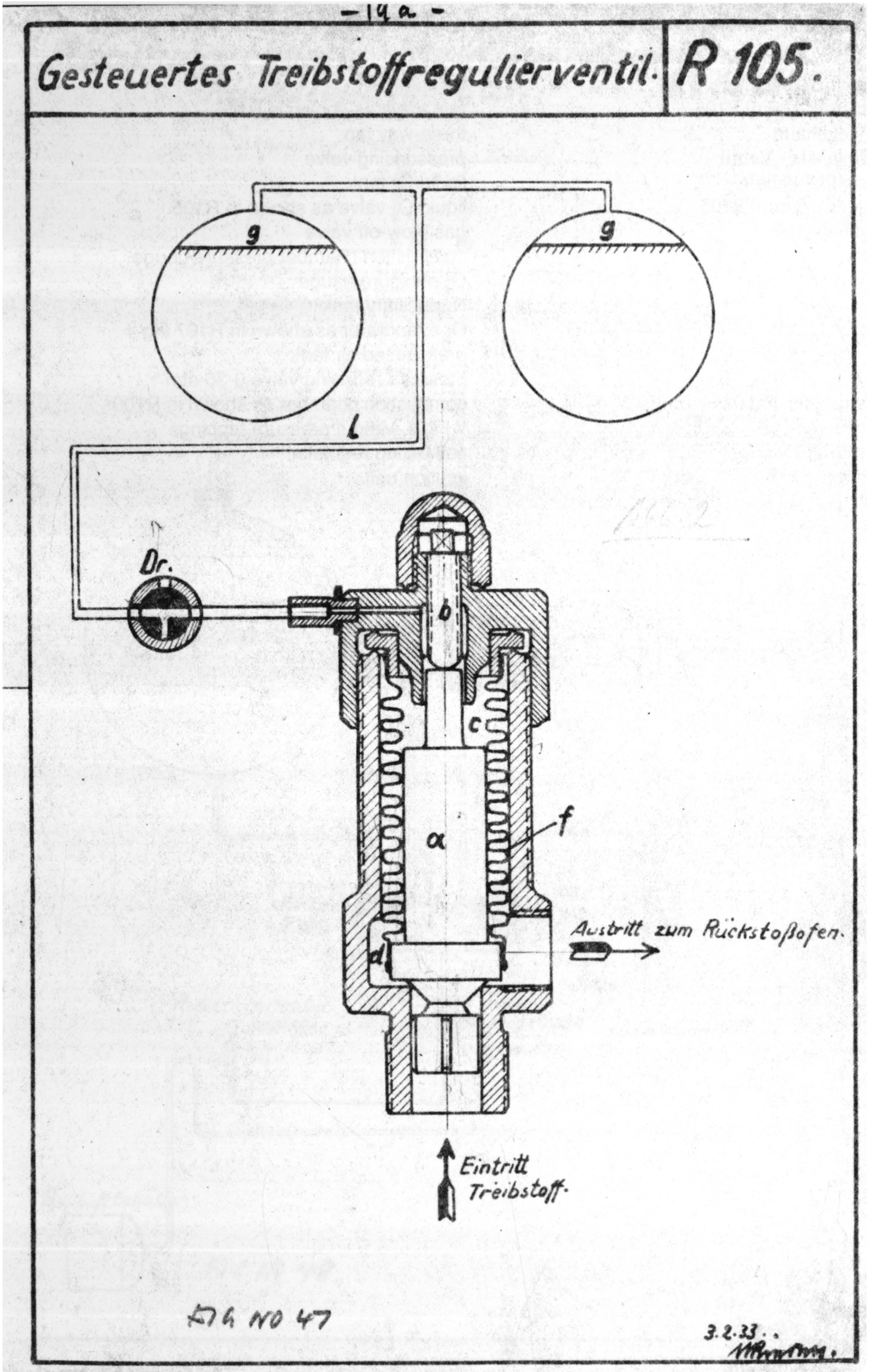

Fig 47: Controlled propellant regulating valve

Austritt zum Rückstoßofen	exit to combustion chamber
Eintritt Treibstoff	propellant entry

Fig 48

Brennstoff - Behälter	fuel tank
Brennstoff -Ventil R105	fuel valve as shown in R105
Dreiwegehahn	three-way tap
Druckzusatz - Ventil	pressurising valve
Flüssig O_2 - Behälter	liquid O_2 tank
Flüssig O_2-Ventil R105	liquid O_2 valve as shown in R105
Gasablaßventil	gas blow-off valve
Manometer Ofendruck	combustion chamber pressure gauge
Manometer O_2	O_2 pressure gauge
N_2 Vorlage	N_2 ancillary tank
O_2 - Verdampfer R107 Fig 4	O_2 evaporator as shown in R107 Fig 4
Preßluftbehälter	pressurised air tank
Reduzierarmatur 0-30 atü	pressure-reducing valve 0-30 atm
Rückstoßofen R100 Fig 1ohne Meßstellen	combustion chamber as shown in R100 Fig 1 without pressure tappings
Selbsttätiger Regler	self-acting regulator
Zündung	ignition unit

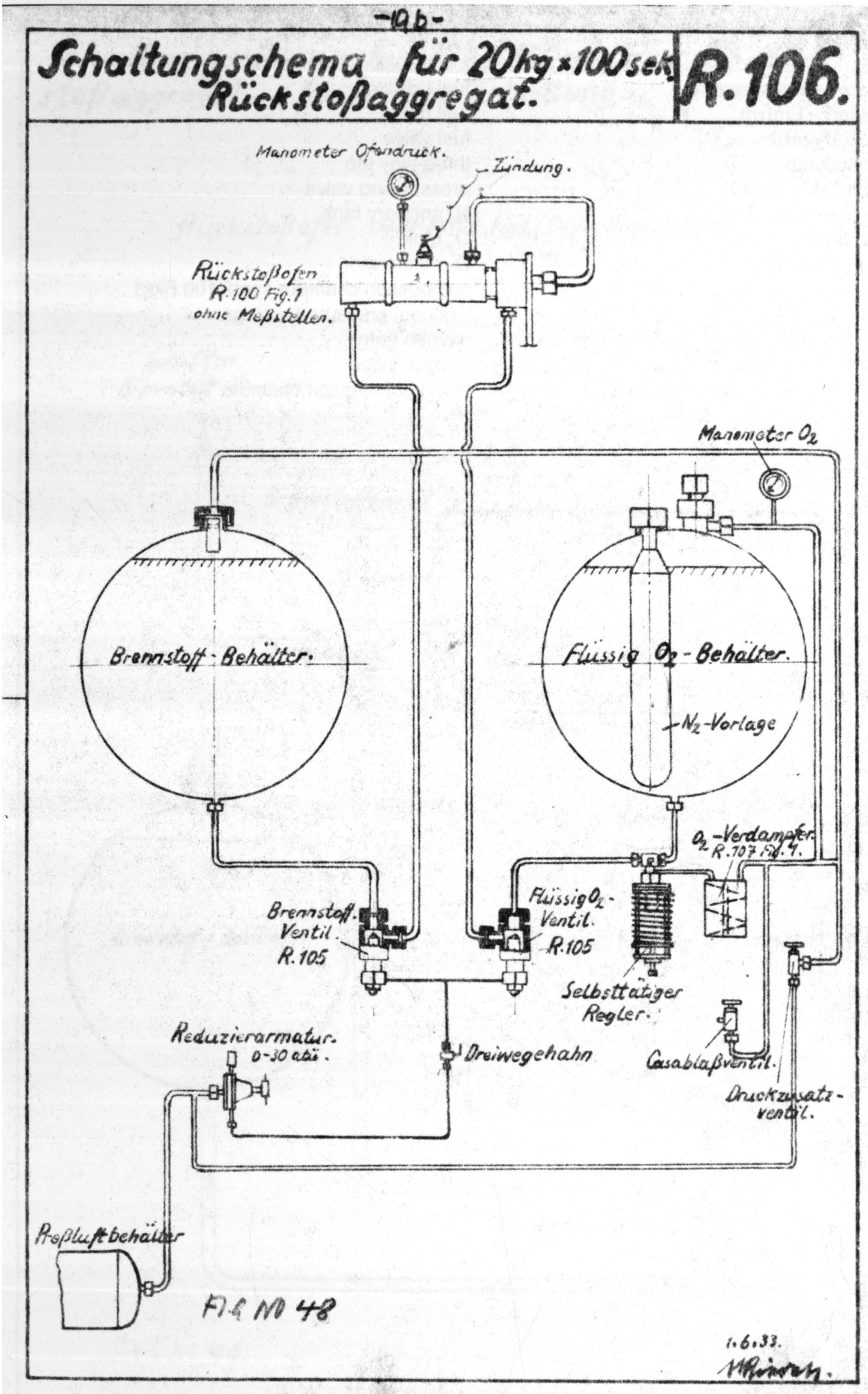

Fig 48: System schematic for 20 kg x 100 secs thrust unit

Fig 49

Brennstoff - Behälter	fuel tank
Brennstoff - Eintritt	fuel entry
Brennstoffventil	fuel valve
Dreiwegehahn	three-way tap
Druckzusatz - Ventil	pressurising valve
N_2 Vorlage	N_2 ancillary tank
O_2- Behälter	O_2 tank
O_2 - Verdampfer	O_2 evaporator
Rückstoßofen siehe R100 Fig 1 ohne Meßstellen	combustion chamber see R100 Fig 1 without pressure tappings
Sauerstoff - Eintritt	oxygen entry
Sauerstoffventil	oxygen valve
zum Ofen	to the combustion chamber

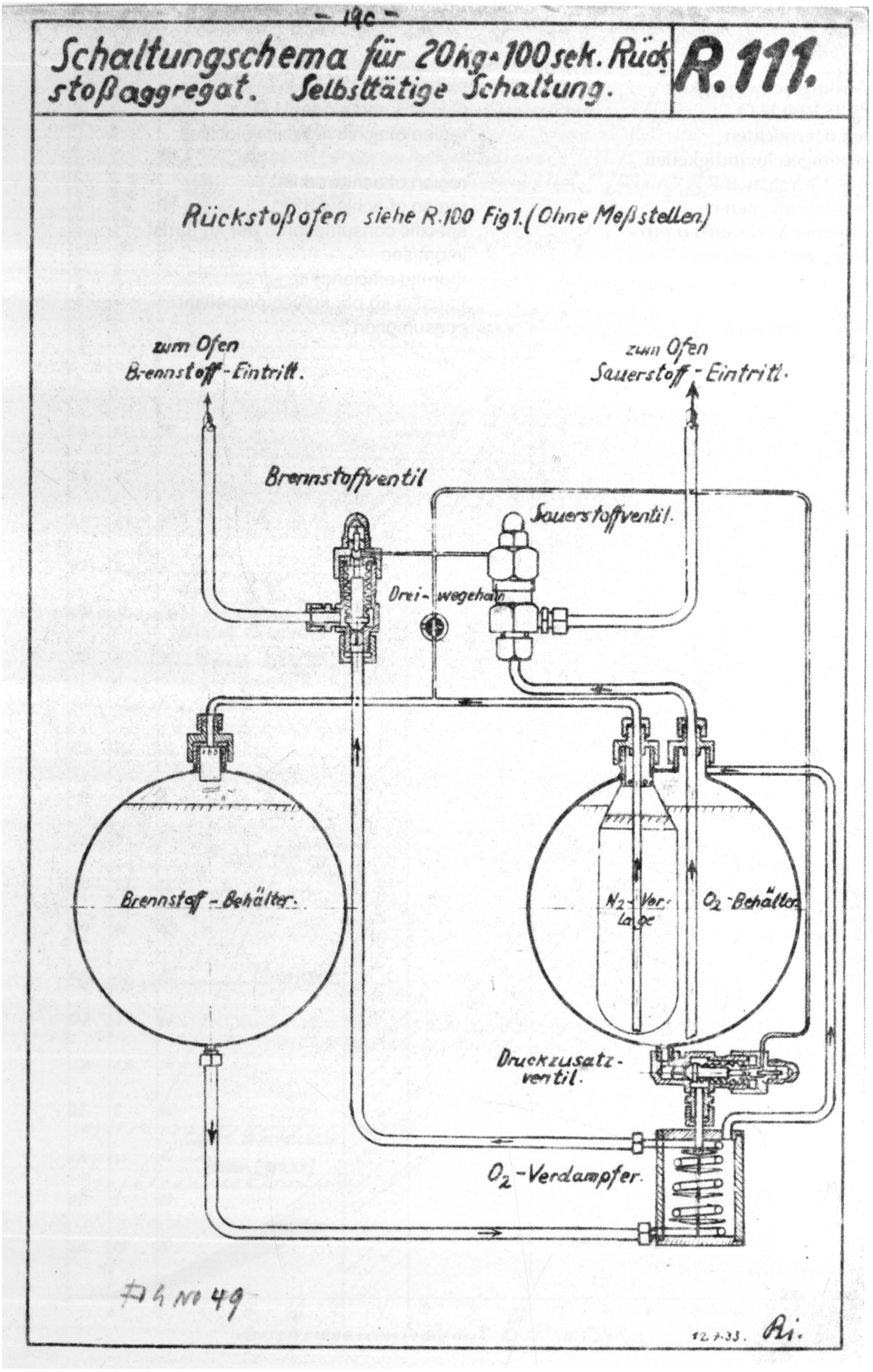

Fig 49: System schematic for 20 kg x 100 secs thrust unit, Self-acting system

Fig 50

Ausströmgeschwindigkeit	exit velocity
C_2H_5OH Rest H_2O	C_2H_5OH, remainder H_2O
Gebiet d. erreichten Ausströmgeschwindigkeiten	region of achieved exit velocities
Gebiet d. erreichten R_{prakt}	region of achieved R_{pract}
Gebiet d. erreichten $\eta_{therm\ (prakt)}$	region of achieved $\eta_{therm\ (prakt)}$
Spezifischer Verbrauch σ pro Kg Rückstoß in gm/sec	specific consumption σ per kg thrust in gm/sec
Thermischer Wirkungsgrad η_{therm}	thermal efficiency η_{therm}
Rückstoß in Kg pro Kg/Sek Treibstoffverbrauch	thrust in kg per kg/sec propellant consumption
σ_{prakt}	σ_{pract}
σ_{prakt}	σ_{theor}
$\eta_{therm/theor}$	$\eta_{therm/theor}$

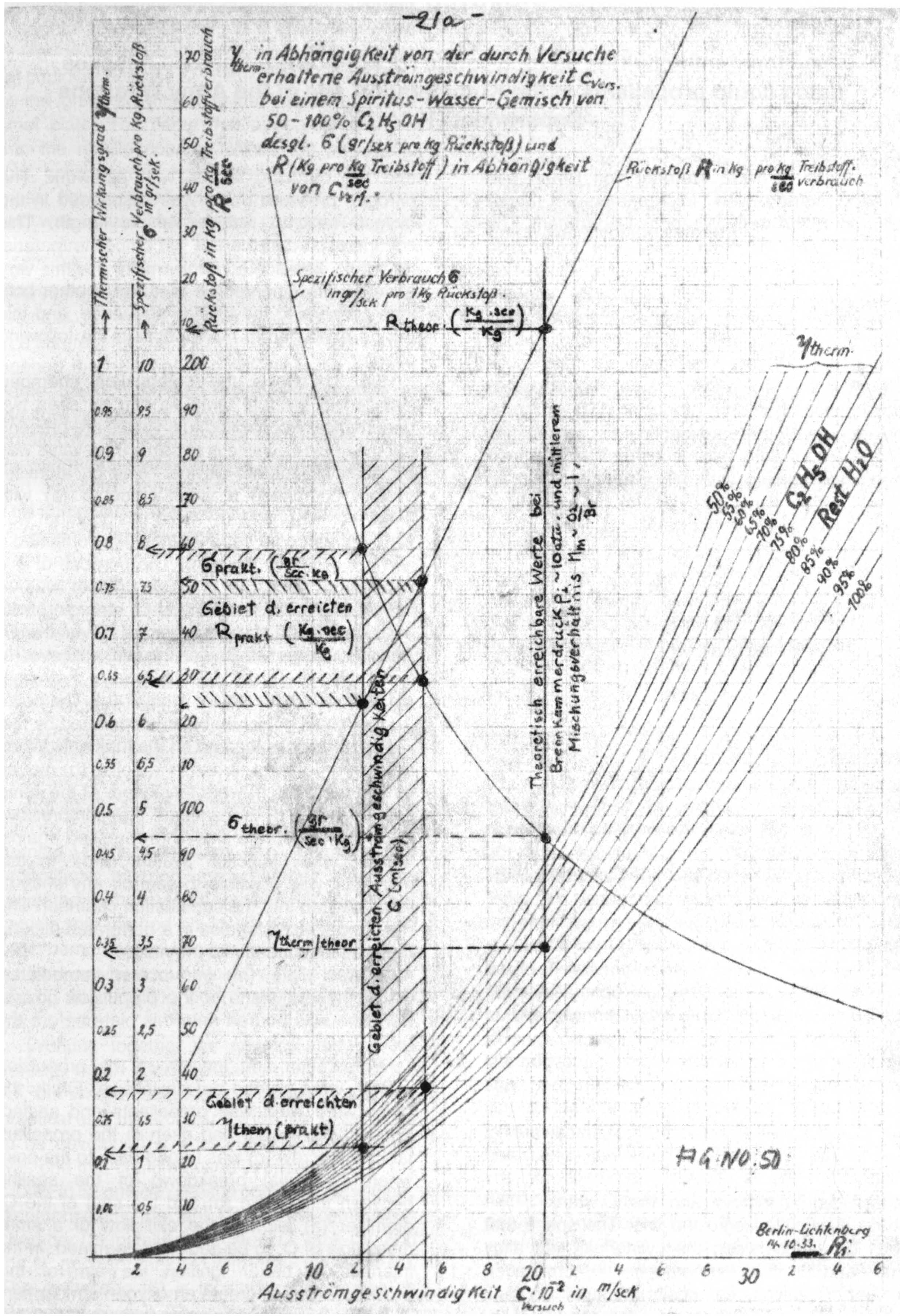

Fig 50:

η_{therm} as a function of the exit velocity c_{Vers} for an ethyl alcohol–water mixture of 50-100% C_2H_5OH; similarly σ (gm/sec per kg thrust) and R (kg per kg/sec of propellant) as functions of c_{Vers}.

CHAPTER TWO

Development activities on long-range rocket-powered guided missiles using liquid propellants at the Kummersdorf site of the Army Weapons Department (1934-1937)

At the end of 1932 Wernher von Braun had already started work in Kummersdorf under contract to the Army Weapons Department. The contract was an open agreement to provide evidence for the possible use of rocket propulsion systems in missiles. By January 1934, when the collaboration between Wernher von Braun and myself began, he had already carried out a series of tests on combustion chambers. Starting with steel water-cooled combustion chambers producing 150 kg thrust, development had advanced to combustion chambers of light alloy construction and self-contained cooling with fuel producing 300 kg thrust. At the same time a complete propulsion system had been developed for a flight vehicle (the A1) and four such systems had already been manufactured. This was a very remarkable achievement if one remembers that von Braun, despite his youth (he was just 20 years old at the time), had been able to complete this work in a little more than a year, working with just one, extremely capable craftsman, Heinz Grünow.

When I started work in Kummersdorf in January 1934, von Braun had thus manufactured the four propulsion systems (for the A1) and was about to test them on the test rig. Since at that time there were no drawings in existence, only free-hand sketches, it is not possible to show an accurate scheme of the propulsion system. I have reproduced a number of technical details, but only from memory. Nevertheless these explain the fundamentals.

The body of the missile consisted of an approx 1.2 m long cylindrical light alloy tube of 0.3 m diameter. Onto this tube was bolted the combustion chamber, whose exhaust nozzle was welded on with a hemispherical base. Above the combustion chamber was positioned the liquid oxygen tank, and this consisted of a cylindrical tube made out of a moulded material (Turbax) with base and head. The liquid oxygen line connected the combustion chamber and the O_2 tank. The latter was bolted onto the line. The space that was formed between the cylindrical light alloy tube and the installed components (combustion chamber, valves, composite material O_2 tank and lines) served to accommodate the fuel load. Above the composite material O_2 tank was a bulkhead that sealed off the lower space (the fuel volume) from the nose section. In the nose section were located the stabilising gyroscopes and the reducing valves with pipework. The nitrogen pressure bottle was suspended in the oxygen tank to reduce vehicle length. This configuration and the use of composite material for the liquid O_2 tank were both very adventurous. The vehicle featured another bold idea concerning the ignition sequence, and this will be explained in more detail in the following chapter.

Fig 51 shows the combustion chamber, installed in the fuel tank. As can be seen two pneumatically-controlled fuel valves are present, but the liquid O_2 valve is missing. This valve was replaced by another device. The O_2 atomiser system comprised a small chamber (a) with small atomiser holes (b). Onto this chamber was fitted a mushroom head (c) that also contained a number of small holes (d). The purpose of this mushroom head, as is easy to see, was to deflect and atomise the liquid O_2 emerging from the holes (b) in the chamber (a). Over the O_2 atomiser system (a-d) was placed a sleeve (e) that ended in a rod (f). At the end of the rod (f) sat a screw (g) located in a collar (h). The collar (h) had small hooks that were connected by thin wires (I) to hooks located on the fuel tank. When the screw (g) was turned, the collar (h) moved so that the wires (I) were tensioned. At the same time the rod (f) transmitted the compressive force with which the sleeve (e) pressed against the O_2 spray injection system (a-d). In this manner it was possible to seal off any entry of liquid oxygen into the combustion chamber. The rod (f) was also steadied in a perforated disk (k) that was introduced into the nozzle.

A steel plate[7] (m) was located immediately below the exit plane of the propulsion nozzle. Benzene was poured onto this plate before the test.

Preparation and ignition of the propulsion system were carried out as follows. Firstly the tanks were filled with propellants and sealed. When the pressure had risen in the propellant tanks the screw (g) was turned back to the point where a partial breakdown of the sealing between the sleeve (e) and the seat of the O_2 atomiser (a) allowed the exit flow of a small mass flow of O_2 to be audibly determined. In the interests of better ignition the aim of this procedure was to create an oxygen atmosphere in the combustion chamber such that the fuel

[7] *This plate was hinged to the test rig frame so that it could be moved away from the jet efflux.*

entering the combustion chamber encountered a certain amount of oxygen present. After this operation the vehicle was ready. Now the ignitor (n) could be exercised. The pilot flame generated by the ignitor set alight the fuel (benzene) on the steel plate. The flame that appeared flickered into the nozzle opening. When the pneumatic fuel valves were now opened, the full fuel mass flow entered the combustion chamber and was ignited. As a result components (e-k) were ejected and the main liquid oxygen mass flow similarly entered the combustion chamber. Everything was very well thought through in principle, but in practice the process progressed in a different manner! When the fuel valves were opened the fuel that was set alight by the pilot flame could only burn externally because of the low amount of O_2 released by the partial breakdown of the sealing on the O_2 atomiser. A very short time later the wires (i) burned through and all of the components (e-k) were ejected. This immediately released the full mass flow rate of liquid O_2 into the combustion chamber. The externally-burning flame flashed back into the combustion chamber and an explosion followed. Since in this state of the ignition sequence there was no back pressure in the combustion chamber, the mass flow rates of both propellants were far larger that those corresponding to the cross sectional areas and pressure differences for normal combustion. This was therefore the end result of the attempt to initiate combustion in the chamber without an O_2 valve.

For tests on the combustion chamber alone ignition could be achieved using this externally burning flame, because the quantities of propellants entering the chamber could be regulated using manual valves. For the rocket vehicle this method could not be used, as had been demonstrated in practice!

So I survived four rocket vehicle explosions shortly after starting work in Kummersdorf, but the A1 died.

Working together we now created the A2 vehicle, which used the basic principles of the A1, but was redesigned so that it was of some practical use. In particular the ignition system had to be developed so that the ignition sequence was one that could be used in practice.

In Fig 52 one can see the complete A2 vehicle. It comprises the fuel tank (1) with the combustion chamber (2) installed, the liquid O_2 tank (3), and the N_2 ancillary tank (4) with reducing valve (5). The gyroscope (6) is located approximately in the centre section. The missile shell is made up of a cylindrical Turbax section (7), section (8) and the nose (9). An alloy of Al, Si, Mn, and Mg was the primary material. The gyroscope was made of steel.

The missile body overall dimensions were:

max diameter	314 mm
max length	1610 mm

Propellants:

Fuel: 65% C_2H_5OH + 25% H_2O		20 kg
Oxygen carrier: liquid oxygen		20 kg
Total propellant weight		40 kg
Empty weight of the vehicle		110 kg
Total weight		150 kg
Thrust		~ 300 kg
Specific thrust[8]		~ 150 sec
Burn time		~ 16 sec
Combustion chamber		
Pressure	p_i	~ 10 atm
Tank pressure	p_t	~ 15-18 atm
Mixing ratio	$M = O_2/Fuel$	~ 1

The operation is easy to discern from Fig 52. The nitrogen driver gas in the sphere (4) was at approx 150 atm. When the stop valve was opened, the nitrogen flowed via the reducing valve (5) to emerge at reduced pressure. The flow now branched, one path being via a non-return valve directly onto the liquid surface of the liquid oxygen in tank (3). The other path was via a pipe, through the liquid oxygen tank, into a manifold pipe fitted with holes, and hence onto the liquid surface of the alcohol. A small pipe also fed into this manifold pipe via a piston valve that was connected to the spring bellows of the two fuel valves. The oxygen supply pipe that was connected to the O_2 atomiser of the combustion chamber similarly opened out into a larger manifold pipe, which was located at the bottom of the O_2 tank and was fitted with holes forming a connection with the O_2 tank. This pipe volume was created to provide a gas buffer ahead of the O_2 intake pipe. The configuration was adopted because it was found to be beneficial for the ignition sequence.

After the disasters with the A1, ignition was now accorded particular attention and the system that was developed can be seen in Fig 53[9]. The propellants were no longer ignited from an external flame, but instead an ignition source was used in which ignition occurred directly in the combustion chamber. As can be seen, the rod (f) carried a pyrotechnic ignition source. Three small pipes (q) opened out into the chamber (p) formed by the sleeve (e). The openings of these pipes were sealed off with Wood's metal and the pipes were embedded in

[8] *Also known as 'specific impulse'*

[9] *Fig 53 does not contain all the details of the ignition process, but they are retained in the text for completeness.*

the combustion unit. The rod (f) featured a hole along its length through which a small powder ignitor (s) was introduced. The ignitor was connected to a powder-firing unit (r) that in turn was connected to the actual ignition source. This arrangement should be compared with the system in Fig 51.

When the vehicle had been prepared for combustion and the propellant tanks were subjected to driver gas pressure, ignition was initiated. Electrical power flowed through the small powder ignitor (s) via a closed contact and a pilot flame was generated, and as a result the firing unit (r) was ignited. This flame burned through to the actual pyrotechnic ignitor unit that started to burn from the head end. When the ignitor unit had burned down to the openings of the three small pipes (q) the low melting Wood's metal liquefied because of the high temperature and the openings were freed. The oxygen could now exit the chamber (p) formed by the sleeve (e) and enter the combustion chamber. As observed externally this step of the process was very easy to discern, since with the entry of the oxygen the ignition flame burned significantly more brightly and intensely. The small piston valve (t) was held by a thin wire (n) in a position such that driver gas pressure on the spring bellows side of the fuel valves (10) held these valves closed. The main switch was then switched to the 'on' position so that a current flowed through the bridge (v) and melted the thin wire (n). A spring in the valve (t) moved the piston into a position in which the spring bellows sides of the valves (10) were ventilated to atmosphere, the driver gas pressure was blocked off and the valves (10) opened. The fuel then entered the combustion chamber (2) and encountered a hot oxygen-rich flame, so that combustion was immediate. This ignition sequence was totally reliable, and no further explosions occurred.

Two complete rocket vehicles were manufactured in the course of 1934 and in December of the same year these were launched from the island of Borkum. The launch was carried out vertically from a ~ 10 m high launch platform. The launch platform was an angle iron structure of rectangular cross-section. Four guide rails were installed along its length to guide the launch vehicle. At approximately one-third height, part of the launch platform was removable so that the launch vehicle could be introduced from outside. After the launch vehicle had been introduced this part was reset in position. By means of a suitably configured support the launch vehicle could be held at this height.

As can also be seen from Fig 52, a gyroscope (6) was installed in the rocket vehicle. This gyroscope was spun up to a rotational speed of ~ 12,000 rpm to stabilise the vehicle during the vertical climb. To bring the gyroscope up to its rotational speed before launch the stator of an AC motor was installed on the launch platform. In the launch bunker at the launch site was an AC unit comprising a motor coupled with a dynamo. The motor was set in rotation by an electrical power source. This generated a rotating field in the dynamo corresponding to the rotation of the motor. This rotating field was transferred via electrical cables to the stator on the launch platform and thus set the gyroscope in rotation. Shortly before launch the gyroscope was brought up to speed in this manner. The combustion chamber was then ignited, the rotating field was switched off and shortly thereafter the main switch to open the valves (10) was actuated.

Both launches proceeded successfully. The stabilisation provided by the gyroscope maintained the vehicle almost exactly in a vertical position. When the gyroscope (6) started to slow down the level of stabilisation reduced and shortly before the vehicle arrived at the apogee (a height of ~ 2 km) it began to oscillate somewhat, as could easily be observed from the launch site. After achieving its maximum height the vehicle started to fall back, and as a result of its inherent instability it cartwheeled a number of times.

As a result of these two successful launches the Army Weapons Department decided to promote further development and made further funding available.

For long-range rocket-powered missiles it was necessary to develop a control system that could maintain the vehicle in a prescribed flight path. To test a control system that was still under development a vehicle was therefore required with which flight trials of the control systems could be performed.

From 1935 onwards the A3 was developed, and this can be seen in Fig 54[10]. This vehicle used the propulsion system that had already been developed in 1933 on the contract awarded by the Army Weapons Department to the Heylandt company in Berlin-Britz. This can be seen in Figs. 40 and 49 and has been described in the previous chapter. In the A3 vehicle this system found its practical application.

The propulsion system consisted of the fuel tank (1) with the in-built combustion chamber (2). This layout had already been used in the A1 and A2 and saved propulsion system length, although the vehicle's dimensions meant that the combustion chamber became rather long if, as

[10] *The original Fig 54 was missing from the manuscript. The substitute figures do not show sufficient detail for all the items referred to. As many as possible have been annotated.*

chamber's injection system was to be retained. The exhaust nozzle of the combustion chamber (1) was connected to the fuel tank by means of expansion corrugations (3). The combustion chamber (1) featured a thin-walled cooling jacket (4) that was strengthened by five rings. The jacket was welded to these rings in a manner such that these locations could tolerate the relative expansion between combustion chamber and jacket.

The atomiser system developed in Berlin-Britz was again used and this was accommodated in the head of the combustion chamber. The two propellant valves, namely the fuel valve (5) and the oxygen valve (6), were located above the head. Both were two-stage valves, the operation of which will be explained later in more detail in the description of the vehicle's operation. The oxygen propellant tank (7) with its in-built liquid nitrogen ancillary tank (8) was located above the propellant valves. In the nitrogen ancillary tank (8) there was a heater (9) manufactured from electrical resistance wire and formed into three modules. These electrical resistance modules could be heated up to ~ 800 °C using ~ 50 A current from an external power source. These heated resistances vaporised the liquid nitrogen such that the resultant driver pressure was directed into the oxygen tank.

A light metal alloy (Hydronalium) made from Al, Si, Mn, and Mg was used as the material for the vehicle.

When the propellants had been loaded up and the tanks sealed, the pressure in the oxygen tank rose as a result of heat transfer from the surroundings. Since the nitrogen ancillary tank was connected to the oxygen via the holes (a), the pressure could find its equilibrium in the space (c) above the liquid nitrogen via line (b). From this gas space the pressure pushed liquid nitrogen through pipe (g), via line (e) and the non-return valve (10) into the gas space (f) in the fuel tank. Here it vaporised because of the thermal capacity and temperature of the tank and fuel.

It will be recognised that this system generates an equal rise in pressure in all the propellant tanks. When the pressure reached a certain level, current was passed through the wires of the heater (9). This brought the wires up to the required temperature. The temperature could be monitored by means of a thermocouple. When the required tank pressure (on average ~ 15 atm) was reached, ignition took place, ie combustion was initiated in the ignitor (12). By means of an external switch the magnet of the solenoid valve (13) could be switched on. This vented the first stages of valves (5) and (6). As can be seen in Fig 54 each propellant valve had two stages. The first stage consisted of a small valve cone that fitted inside the large cone of each valve. The small cone was sealed by small spring bellows against the volume formed by the large spring bellows. Switching of the solenoid valve into first stage mode vented the first stage spring bellows volume through the line (g) and the solenoid valve (13). The small cones of both valves opened. Liquid oxygen entered through the large valve cone into the volume (h) and through the holes (i) into the valve body (j). From here a number of O_2 lines (k) led into the O_2 atomiser (l), through which the liquid oxygen entered the combustion chamber. In the fuel circuit the fuel entered via (m) into the combustion chamber cooling jacket, and flowed through the jacket to be directed via (n) through a number of holes into the valve space (o). From here the fuel entered the valve chamber (h') and passed through holes (i') into the valve body (j'). The fuel was then led through a number of holes (p) in the plenum chamber (q) through the stalk and heads (r) into the combustion chamber. The first stage mass flow rates had been adjusted to be such that the propellants would ignite 'softly' on the ignitor flame (12), producing a small combustion flame in the combustion chamber. When this flame could be seen at the nozzle exit, a switch could be made to the second stage. The magnet of the solenoid valve (13) switched to vent the large spring bellows volumes via line (s). The large valves opened and the full mass flow rates of the propellants entered the combustion chamber via the paths previously described. The full mass flow of propellants could now ignite on the flame already present in the chamber and burn. This procedure guaranteed a successful ignition sequence in the combustion chamber. No further ignition-related explosions were encountered.

Utilising the driver pressure method that has been described earlier, the pressure in the propellant supply system could be held nearly constant by vaporising the liquid nitrogen from the nitrogen ancillary tank. A drop in pressure of ~ 1-2 atm. occurred only towards the end of the burn time.

The pressure characteristics in the propellant supply system can be explained briefly as follows. If a pressure drop occurred in the oxygen tank as a result of the supply of propellants, then as a result of the initial pressure prevailing in the volume (c) liquid nitrogen was supplied via pipe (b) into the chamber with the heater wires (9). Here the liquid nitrogen vaporised on the heater wires and via the holes (a) impinged on the liquid surface of the liquid oxygen. Likewise equilibrium was achieved via pipe (d) and line (e) to the fuel tank. It should also be noted that this N_2 system provided security against the oxygen and fuel coming into contact.

After ~ 45 secs the magnet of the solenoid valve (13) was switched to the venting position, closing the valves. In those combustion tests in which the fuel had been totally consumed an explosion had occurred, destroying the combustion chamber and the fuel tank. This was easily explained. When the fuel tank was totally evacuated an oxygen-rich nitrogen mixture was able to enter the jacket of the combustion chamber. Together with the fuel residuals still present this mixture could ignite as a result of flash back of flame into the jacket, thus triggering an explosion. To overcome this problem combustion was always terminated after a certain time so that some fuel always remained in the fuel tank. This prevented the O_2-rich nitrogen mixture from entering the jacket of the combustion chamber.

I have now described the most essential details of the propulsion system. As can be recognised the propulsion system was simple and the conventional nitrogen driver gas method using gaseous nitrogen from heavy steel bottles was eliminated. Not only weight, but also space, was saved in the vehicle for the accommodation of other pieces of equipment.

The pressure in the combustion chamber was on average p_i ~ 10 atm and the pressure in the tank p_t on average was ~ 15 atm. The nozzle had an expansion ratio ξ ~ 12.7. As fuel a combination of 75% C_2H_5OH + 25% H_2O + liquid O_2 was used. The mixture ratio was again on average M = O_2/fuel ~ 1. The thrust S ~ 1500 kg. Propellant consumption was ~ 9 kg/sec and the total tank capacity G_T was ~ 450 kg. Thus the specific thrust T_S was ~ 167 kg/(kg/sec).

While the propulsion system was being developed an agreement was reached with the Kreisel-Geräte company in Berlin-Teltow to develop a more suitable control system. The Kreisel-Geräte company had much experience in this field and was well-known through its development of stabilised platforms for warship engine control rooms. This work was closely associated with the well-known specialist in this field, Captain Boykow.

In the case of the A3 a control system was required that was able to prevent deviations from the vertical trajectory. The movements that the vehicle can make during flight are: lateral movement of the centre of gravity, rotation about the centre of gravity, and rotation about the vertical axis of the vehicle (spin).

In accordance with the completely general control equation:

$$a(\varphi) + b(\dot{\varphi}) + c(\ddot{\varphi}) = 0$$

the position of the vehicle φ, the deviation velocity $\dot{\varphi}$ and the acceleration $\ddot{\varphi}$ must all be equal to zero if the trajectory is to be maintained. If these three deviations from the defined state are measured in some manner, their values can be used to control an appropriate device to return the vehicle to its prescribed trajectory.

The control system used for this purpose comprised basically the location unit (the command transmitter) and the actuation unit.

The location unit consisted of a stabilised platform that was suspended from the vehicle via two gimbal rings. Gyroscopes held this platform always in the same position. On this platform were located in each plane (thus at right-angles to each other) a system of small trolleys, one above the other. One of these trolleys tracked the transverse velocity ($\dot{\varphi}$), and the one located opposite tracked the transverse acceleration ($\ddot{\varphi}$), of a movement of the vehicle in the relevant plane. In other words, if a transverse velocity ($\dot{\varphi}$) occurred, the velocity trolley moved out from its null position, and the acceleration trolley behaved similarly if a transverse acceleration ($\ddot{\varphi}$) occurred. The movements of the trolleys were damped. The deviation from the null position was picked up as a voltage across a resistance corresponding to the movement. This voltage pick-up was amplified and used to execute a control movement. As developed the control system was two-dimensional. The third dimension, spin, was not provided for.

The actuation unit of the control system is to be understood as the part that amplifies the location sensor signals and translates them into movements that generate the control forces to restore the vehicle into its original trajectory.

The practical configuration of this control system can be seen in Fig 54 and consists of the power source (battery) (13), the transformer (14), the command transmitter unit (15), the actuation unit (16) with the related linkage (17) and the exhaust stream rudder vanes (18).

In the location unit (15) are the two gimbal rings (A) and (B) in axes at 90° to each other, located in bearings that are rigidly connected to the vehicle. On the upper platform can be seen the velocity and acceleration trolleys (C), also the sensor for the voltage pick-up (D) and the gyroscopes (E).

The actuation unit (16) consists of small motors and shafts. These were caused to rotate by the sensed and amplified voltages resulting from the trolley movements in each plane. The rotations actuated a lever linkage (17) that generated a to and fro movement. In each of the four spars of the vehicle was located a rod that was connected to a control box (19). In the control box the to and fro movement of the rod (17) was translated into a rotational movement, so that the exhaust stream rudder vanes (18) that sat in the vehicle exhaust stream also rotated. The rotation of the rudder vanes in the exhaust stream generated forces in each plane as a function of angle of rotation. These forces rotated the vehicle about its centre of gravity and thus restored the vehicle to its original orientation. The exhaust stream rudder vanes were manufactured in molybdenum (a high melting point material).

These details are sufficient to give a short overview of the control system. In real life the details, especially in the location unit are much more extensive and complicated and it is a science in itself to fulfil the control requirements correctly. While the vehicle or missile cannot be moved without the propulsion system, it is the control system that is the soul of the vehicle.

Propulsion system and control system could now be accommodated in a missile-shaped body, as can be seen in Fig 54. For the proposed application no precise design rules concerning shape and resistance values were available, so the size was increased geometrically, based solely on the ballistic shapes already defined for artillery rounds travelling at supersonic velocity. A vehicle with the following dimensions thus emerged:

Vehicle diameter	D ~ 674 mm
Length of the body (without fins)	L ~ 5413 mm
Corresponding approximately to a value for	L/D ~ 8
The supersonic shape for the nose was generated using	R ~ 12.5 D[11]

The vehicle was designed with a light alloy frame structure that was based on 4 'top hat' profile spars. Over their length these supported transverse stiffeners over installed components such as the control system and the two propellant tanks. A thin light alloy sheet provided the covering. This was strengthened by small profiles acting as rib stiffeners, so that the vehicle was enveloped by a completely enclosed and smooth hull.

The total weight of the vehicle including installed equipment and control system, etc amounted to ~ 300 kg.

For the vehicle to fly stably, the point of application of the summated aerodynamic forces had to lie behind the centre of gravity as measured from the nose. If it were to lie in front the vehicle would tumble over and over. Moreover it was known that the centre of gravity of the vehicle would be displaced rearwards as the propellants were consumed, an effect that could be calculated accurately. In contrast the actual point of application of the aerodynamic forces was not easily determined. Only an approximate analysis could be performed with the result that a tail unit of length ~ 1330 mm had to be fitted to maintain the point of application of the aerodynamic forces sufficiently rearwards under all circumstances. To stiffen the end of the tail unit a Turbax ring (20) was fitted in which the receiver and transmitter antennae were installed. A 'stop combustion' command could be received from the ground via the receiver antenna. Also using an installed transmitter signals could be received on the ground to check what influence the vehicle, and in particular the exhaust gas stream, had on transmission signals when in flight.

Other devices still to be mentioned included a thermo-barograph (21)[12] for temperature and pressure measurements at greater heights and a parachute in a container (22) that was to be released when the vehicle had achieved its maximum height so that the vehicle could be retrieved.

In addition to the vehicle developments the test rigs on which the tests were performed are also of interest. For testing of the combustion chambers and complete vehicles two types of rigs were developed and these will be described briefly in the following paragraphs.

The test facility shown in Fig 55 was used to test the combustion chambers and the propulsion unit. Basically it comprised the combustion rig (A), the observation station (B), and at either side of the latter the propellant tanks (C1) and (C2). The combustion rig (A) comprised a cell with concrete walls, one side of which could be closed by means of sliding doors. During tests the doors were open. A sliding roof (D) provided weather protection to the fitters while they were assembling the rig and was slid back during tests. Thus the combustion rig only had three walls so that in the event of an explosion the pressure build up would be much smaller than in a totally closed space.

The combustion chambers and powerplant units were suspended so that the exhaust gas stream was directed downwards. To remove the gases the combustion rig was fitted with an uninterrupted gas extraction channel (E). While combustion was taking place the exhaust gases impinged on a water-cooled deflection chute and passed through the gas extraction channel under the floor of the test rig to the two gas extraction shafts (F) and hence vertically upwards into the ambient air.

The combustion rig also featured the thrust frame (G) on which all pipe-work, measurement devices etc were installed. Into this frame was fitted the combustion chamber or propulsion unit.

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[11] *As in an ogive*

[12] *This number and that following in this paragraph cannot be identified in the figure.*

One wall of the combustion test cell was built of particularly strong concrete. Behind this wall was located the observation station. In addition to allowing direct observation of the rig this also housed everything that was required to operate the combustion chamber or propulsion unit. Direct observation was provided by a narrow viewing slit that was covered with two sheets of safety glass. The observation station housed all the equipment for rig operation and measurement. This equipment was conventional and I do not need to describe it further here. The propellant tanks were located next to the observation station in enclosed spaces (C_1) and (C_2) with all the weighing and measuring equipment.

The other type of test facility for the combustion testing of complete vehicles can be seen in Fig 56. It was designed taking into account that for tests on complete vehicles and propulsion systems the total mass of propellants would be located in tanks actually on the rig. In the event of an explosion all of the propellants, being concentrated in the rig space, would therefore be involved in the explosion or consequent combustion. The test facility was therefore designed on the principle that there should not be any even partially enclosed spaces. This was to avoid any build up of pressure in the event of an explosion.

As can be seen in Fig 56, such a test facility featured a combustion test site (A) that was fully open to ambient conditions with a free-standing combustion rig frame (B). A safety zone (C) surrounded the combustion rig. This safety zone was bordered by a 3 m high wall of sand (D). In this sand wall stood an iron framework structure covered with wire mesh (E) to act as a catcher for any larger pieces following an explosion. The safety zone had two openings (F). Outside the sand wall stood two stationary assembly towers (G) that were connected by a curved track. Along this track the mobile combustion rig frame (B) could be driven between the assembly towers and the combustion test site. All assembly and preparation activities for combustion tests were carried out in the fully enclosed assembly towers. The combustion test site (A) itself featured a concrete base (M) that was configured for extraction of the combustion gases. The deflection chute in the middle of the extraction channel was made of steel and water-cooled.

The combustion rig frame (B) possessed a mobile platform (P) that could be driven up to the frame while the vehicle was being prepared for test. During the actual combustion test this platform was moved to one side so that only the iron frame remained to support the vehicle on the test site.

The A3 launches took place at the end of 1937. Fig 57[13] shows the Greifswalder Oie from which the launches took place. Fig 58 is a general view of the launch site. The launch site included an observation bunker and an operations bunker as well as the launch platform from which the vehicle was fired.

Fig 59 shows just the launch platform. It seems appropriate to go into more detail concerning the configuration of the launch platform, since it shows much that is of interest.

The actual launch frame (A) consisted of a ~ 1 m high iron structure of approximately rectangular shape. It contained a plate on which the vehicle stood. The floor of the frame was fitted with an exhaust deflection chute (B) made of steel. During the assembly and preparation activities for the launch an assembly tower (C) was in position around the vehicle. The assembly tower (C) was a steel structure that had two platforms that could be reached by steps.

For the launch of the vehicle the whole tower could be lowered, as shown in Fig 59, so that the vehicle stood free on the launch platform, ready for firing.

To lower the assembly tower as prescribed, the launch platform featured a shaft that was rigidly connected to the tower. Via a system of gears this shaft could be rotated using an electric motor and the tower could thus be lowered into the horizontal position.

When complete vehicles were to be tested on the launch facility (Fig 59) each individual vehicle was loaded into a wooden packing case and brought directly to the launch site on a truck. The assembly tower of the launch platform was in the horizontal position (Fig 59). The roof (D) was removed so that the packing case together with the vehicle could be pushed inside on the guide rails provided in the assembly tower. The side walls of the packing case were removed to provide access to the vehicle. When the case had been pushed into the assembly tower the assembly tower was raised using the electrical drive until it stood in the vertical position. The vehicle was then lowered a little and set down on the plate of the launch platform. This arrangement provided weather protection to the operations crew and good working conditions for the launch preparations. Shortly before the launch, when all such preparations including the tanking up with propellants were completed the tower was tilted back into the horizontal position and the vehicle now stood free on the launch platform, ready for firing (Fig 58).

All the electrical circuits and pneumatic lines necessary for the firing passed through the fins on the supporting surfaces of the vehicle. To

[13] *Fig 57 is missing from the manuscript*

reduce the amount of rubbing and jamming of these circuits and lines during the launch to a minimum, connectors were designed for the electrical circuits, as shown in Fig 60[14].

At the locations where the electrical circuits passed through the fins, small insulators were located on the launch platform plate (1). These insulators contained small brass cups to which the electrical circuits were attached. The small cups were filled with mercury. Into the mercury liquid projected the pins of the vehicle's electrical circuits. The mercury provided the electrical connection for these electrical circuits, so that when the vehicle was taking off a frictionless de-connection was provided.

After describing the A3 vehicle, the test stands and the launch equipment I will now return to the actual launch procedure. The launches were only partially successful, since all vehicles tilted over at a low altitude soon after launch and fell back on to the island in the vicinity of the launch platform. After each such unsuccessful launch reasons were sought as to why the failures had occurred and remedies were found for the likely causes. We were successful in one respect at least. In each case the propulsion system, and in particular the ignition system, had functioned without any problems. The problems had to be in the control system. Only after all four unsuccessful launches was it established that the exhaust rudder vanes were too small and were incapable of compensating for fairly strong side winds. Thus the development of the A3 vehicle was effectively complete. The A3 vehicle in altered form, regarding the body, fins, propulsion system, control system, etc was from that point onwards designated as the A5 and is described in the next chapter.

This period (1934-1937) saw not only the developments in the long-range rocket missiles using liquid propellants already described, but also the first successes in the development of rocket propulsion systems for aircraft. Von Braun possessed a business aircraft, a Junkers Junior, in which he carried out his business trips. In 1935 he put forward the idea of installing a rocket propulsion unit in a Junkers Junior. His intention was to perform the tests with this system himself at an appropriate altitude. The system schematic is shown in Fig 61, which provides all the necessary information.

The propulsion unit featured a combustion chamber of familiar configuration for S ~ 300 kg thrust with pressurised tanks for the ethyl alcohol and liquid oxygen. The driver pressure requirement was met by nitrogen gas taken from high-pressure bottles via a reducing valve. The fuel and oxygen valves were located on the axis. To regulate the propellants valve actuation was configured such that the valve spindles were located together in a threaded sleeve, one valve shaft featuring a right-hand thread and the other a left-hand thread. The ends of the sleeve were correspondingly fitted with right-hand and left-hand threads. A key prevented both spindles from rotating so that rotational movement of the sleeve was converted into to and fro movements of the valve shafts. With rotation of the sleeve the valve seats thus moved and released more or less amounts of propellant, according to the direction in which the sleeve was rotated. The sleeve featured a tang by means of which rotation could be initiated. With this form of valve actuation the propellant cross-sectional areas could be altered so that the combustion chamber pressure could be regulated within the limits of 10 – 4 atm and the thrust could be varied in the same ratio. Ignition of the propellants took place by means of a powder ignitor. Electrical contact with the ignitor was provided via a battery.

This propulsion system was installed in the Junkers Junior and was tested in a large number of static tests. It operated without any defect, but no flight test ever took place because the Army Weapons Department would not permit von Braun to carry out the flight tests with the unit himself.

At about the same time (1936) we undertook the development of a propulsion system for a rocket fighter. This had the designation P1033 throughout its development, which was carried out in collaboration with the Heinkel Flugzeugwerke company. Heinkel were to produce the airframe and the Army Weapons Department site at Kummersdorf the engine.

This project can be seen in Fig 62. The propulsion system featured a turbo-pump to provide the drive for the supply of propellants. The driver gas for the turbine was to be provided from the decomposition of H_2O_2. The fuel tanks were designed to operate at zero-pressure differential, since they were to be installed in the wings. For the oxygen tanks not more than 10.5 atm was envisaged. Regulation of the mass of peroxide vapour, (for the purpose of regulating the turbo-pump and thus the propellant mass flow rates at constant atomiser cross-sectional areas in the combustion chamber) was achieved by means of a valve regulating the flow of H_2O_2 into the vaporiser.

The combustion chamber was designed for a thrust of ~ 750 – 1000 kg. Duration of burn was ~ 70 – 90 secs at maximum thrust and the corresponding weight of fuel G_t was ~ 400 kg. Ignition took place by means of an ignitor using on-board propellants. The propellants comprised 75% C_2H_5OH + 25% H_2O and liquid oxygen. The approximate estimated weights of

[14] *Figs 60-63 have been reconstructed from the text.*

the components can be extracted from the table[15] in Fig 62.

So there we have the project data. Comparing this system with the previous propulsion systems developed for rocket missiles I must emphasise how the use of a driver gas for the supply of propellants had now been replaced by a turbo pump. This supply system required new components and a production facility for the turbo pump drive. It was this system that provided the transition in the development sequence to the A4 (V2) that was to be developed later. This provides a striking example of how elements of a propulsion system designed for an aircraft could be transferred across to rocket missiles. At this point I feel I must point out once again that the opinions held by Max Valier turned out to be correct, despite the fact that he was so often contradicted by members of other groups. As will be seen later, propulsion systems of this kind found practical application in an aircraft three years earlier than in a rocket missile.

At this time a combustion chamber was manufactured from a light alloy that was suited to the aircraft application. In the development of the rocket missiles (A1 to A3) the combustion chambers had always been oriented vertically downwards, whereas this application required the combustion chambers to be oriented horizontally. Unexpectedly, this change of orientation introduced great difficulties and very many combustion chambers were destroyed as a result of burn through. More than a year of testing work was required to obtain a combustion chamber that would operate reliably. This meant that development of the propulsion system could not be completed until 1937.

In this connection suggestions were made by the Heinkel management that the lateral acceleration of the aircraft when performing curved manoeuvres would have a significant influence on the exhaust gases. They postulated that as a result of this acceleration the hot exhaust gases would increase in density and that the problems associated with cooling would be exacerbated as a result. It was therefore proposed that this phenomenon should be simulated in a test. The practical solution to this exercise was to place a propulsion system with combustion chamber on a turntable designed for the purpose. This turntable can be seen in Fig 63.

The turntable consisted of a strong iron structure (1) and was approx. 10 to 12 m in length. In the centre the structure featured a strong trunnion (2) and a drum (3). Around this drum was laid a brake band that was actuated to regulate the speed of rotation. The combustion chamber was attached to one side of the structure and on the other side were located the propellant tanks and driver gas bottles. The system was balanced. In the centre, above the trunnion (2), were located the observation and operation bunkers from which the propulsion system was operated. When the combustion chamber was fired the system began to rotate as a result of the thrust generated. Actuation of the brake lever controlled the system to the desired rotational speed, which in practice lay between 10 to 12 rpm, corresponding to a centrifugal acceleration of 3 – 13 m per sec^2.

Technically these tests provided the evidence that no influence of the acceleration on the exhaust gas stream could be detected, which was exactly what was to be expected. There was no exacerbation of any combustion chamber cooling problems.

With these comments I have described in rather sweeping terms the second phase of rocket development in the years 1934-1937 at the test site of the Army Weapons Department in Kummersdorf. This development was altogether successful until we encountered the unsuccessful launches of the A3, and the problems here lay with the control system. This achievement should be recognised, particularly when one considers that the work began with just three men and over the years only increased to approximately 120 in total, including administration personnel. The rapid and successful development coupled with the extent of the project demanded a larger site, and conditions in Kummersdorf were unsuited for any such expansion. The 'Peenemünde' project had been initiated quite a long time before we came to this conclusion. This provided for the construction of a development and test site on the island of Usedom near the fishing village of Peenemünde. In the middle of 1937 the transfer of the Kummersdorf test facilities to the Army test site in Peenemünde was finally carried out.

[15] *The table is not included in Fig 62, which was missing from the manuscript and has been redrawn.*

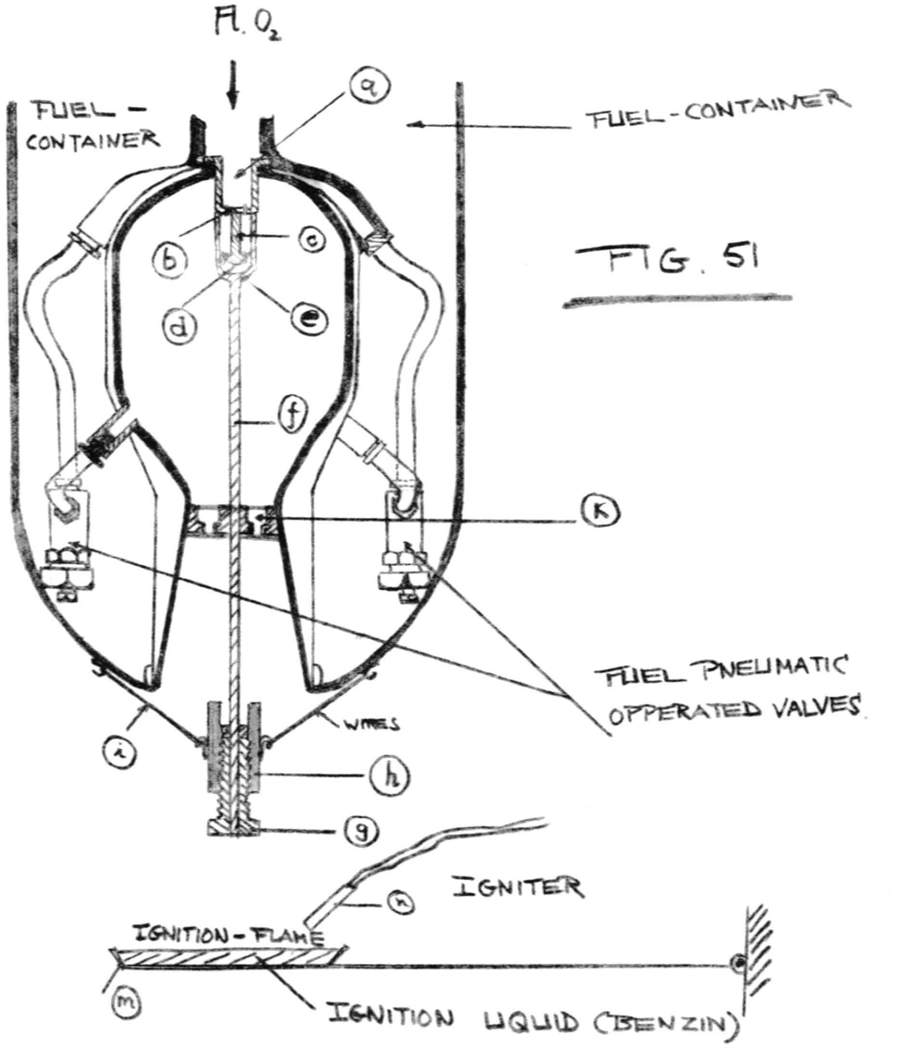
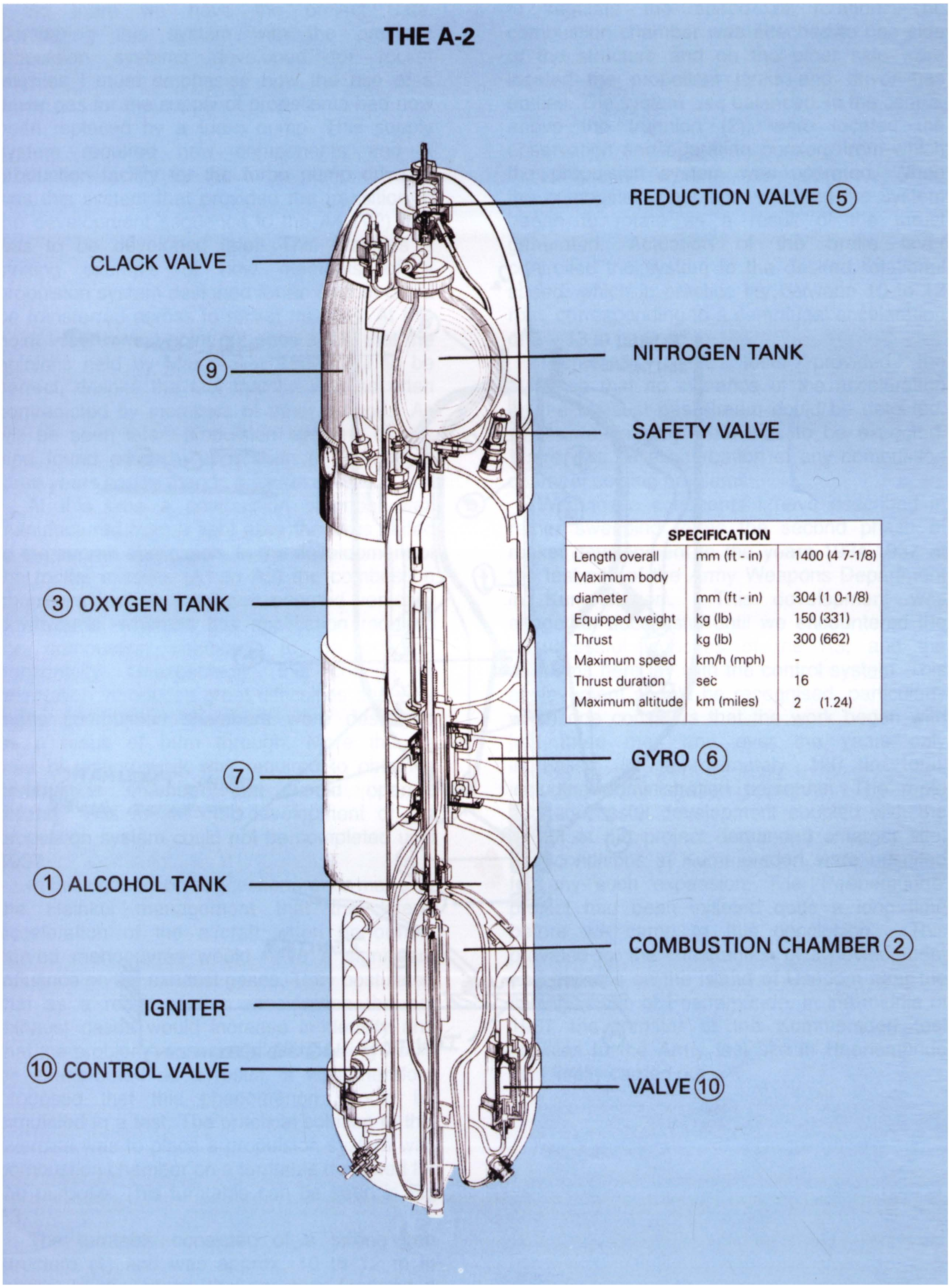


Fig 51: Combustion chamber



SPECIFICATION		
Length overall	mm (ft - in)	1400 (4 7-1/8)
Maximum body diameter	mm (ft - in)	304 (1 0-1/8)
Equipped weight	kg (lb)	150 (331)
Thrust	kg (lb)	300 (662)
Maximum speed	km/h (mph)	-
Thrust duration	sec	16
Maximum altitude	km (miles)	2 (1.24)

Fig 52: The A2

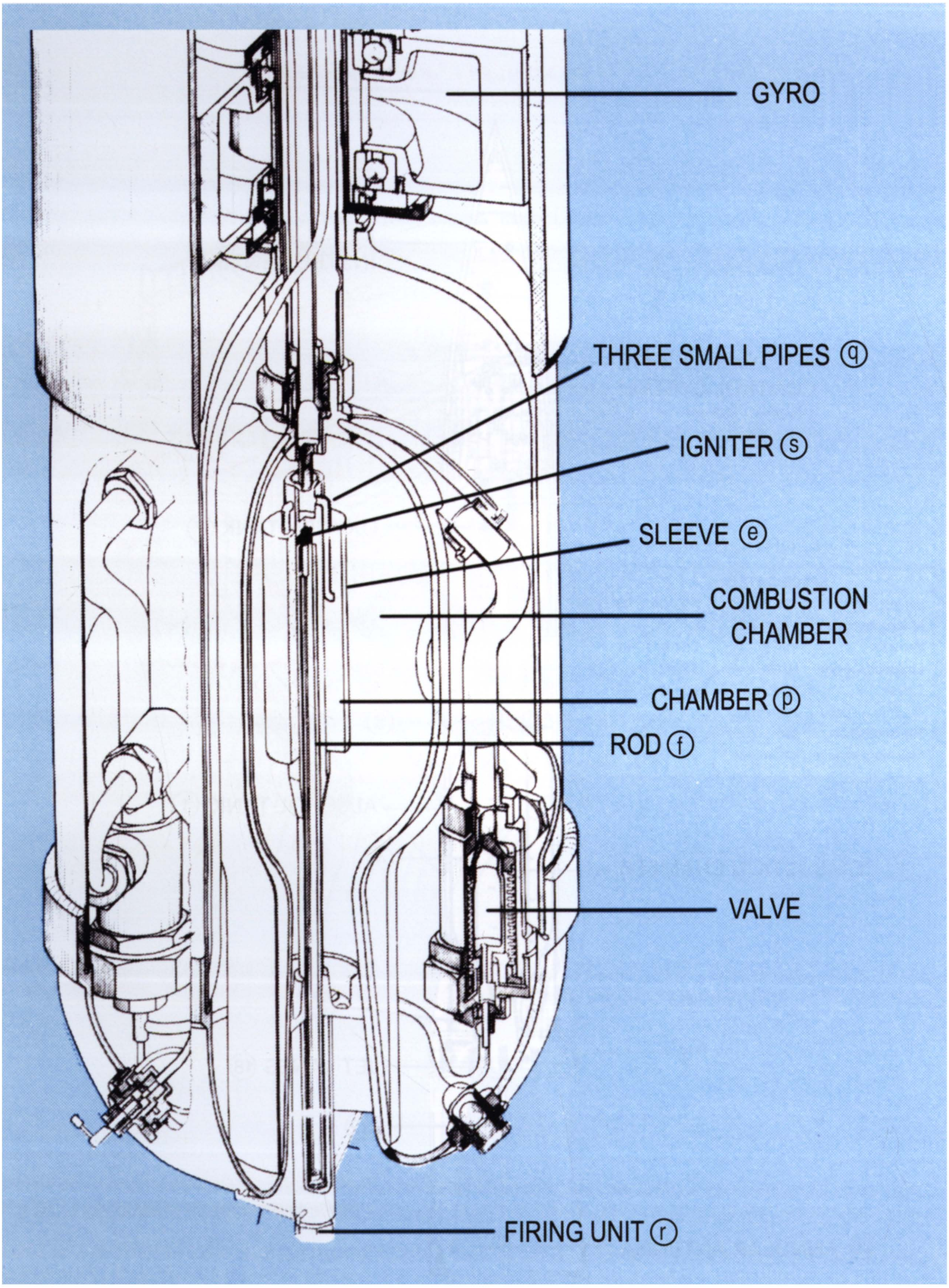
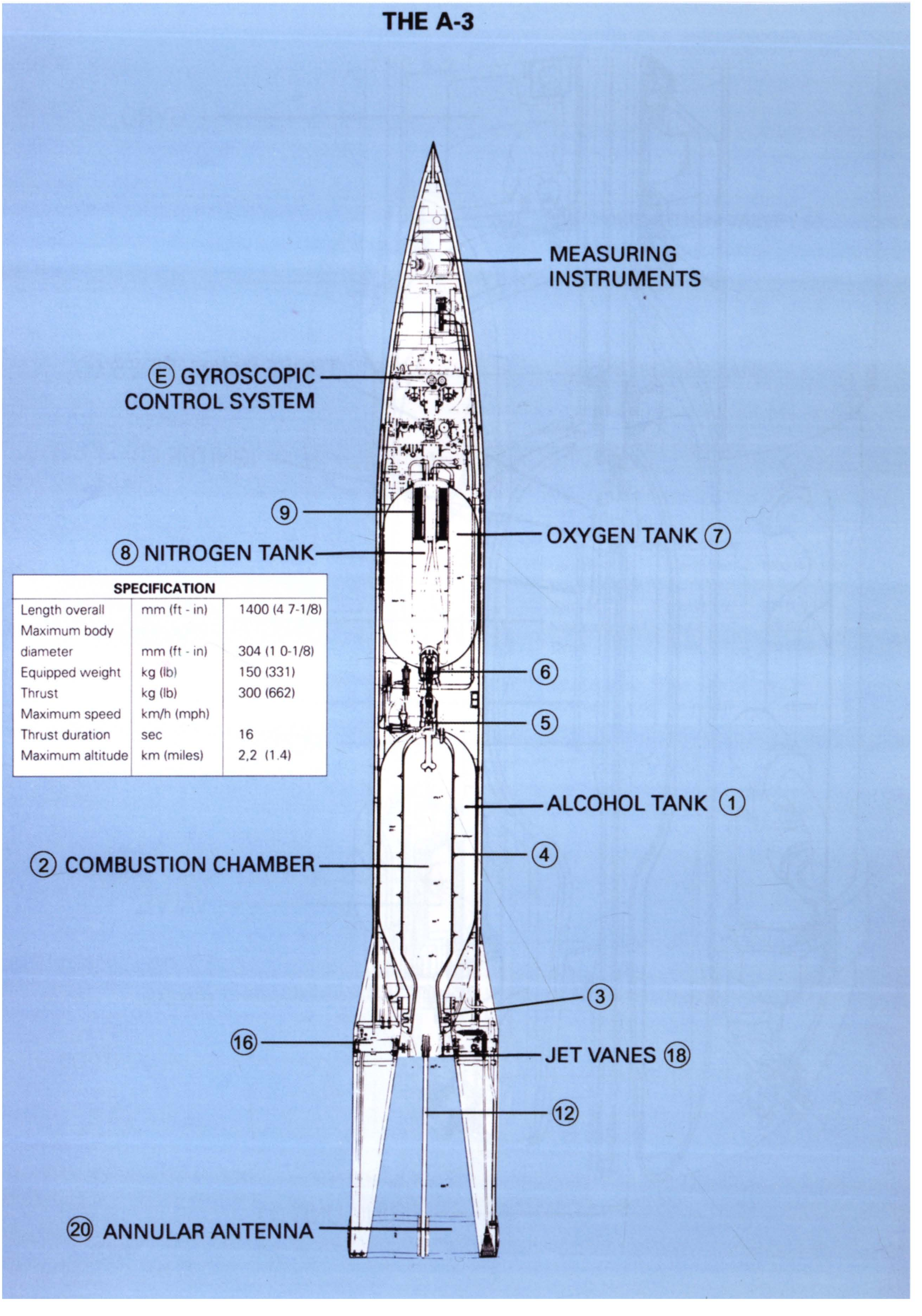


Fig 53: Ignition system of the A2 rocket



SPECIFICATION		
Length overall	mm (ft - in)	1400 (4 7-1/8)
Maximum body diameter	mm (ft - in)	304 (1 0-1/8)
Equipped weight	kg (lb)	150 (331)
Thrust	kg (lb)	300 (662)
Maximum speed	km/h (mph)	
Thrust duration	sec	16
Maximum altitude	km (miles)	2,2 (1.4)

Fig 54: The A-3

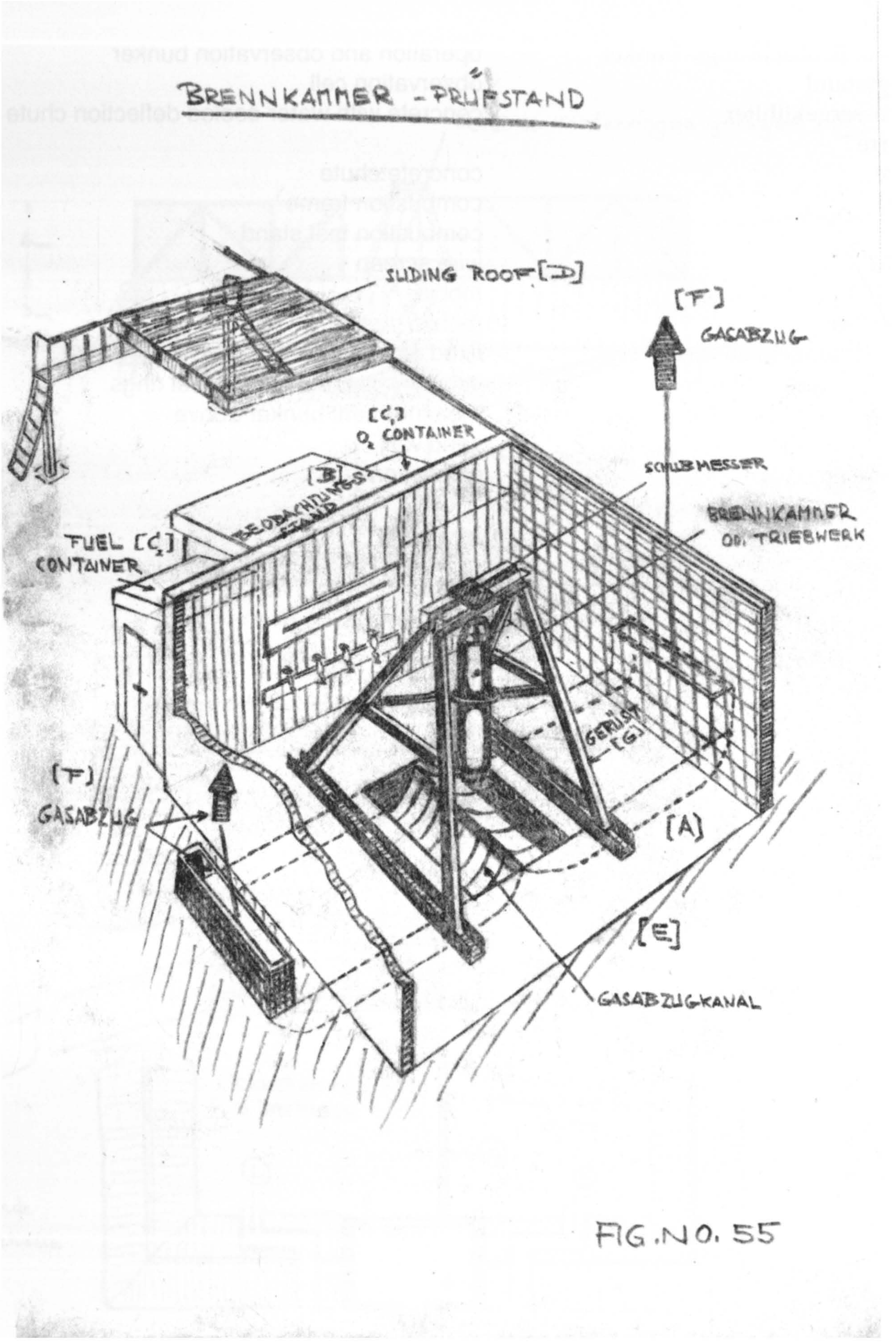


Fig 55: Combustion chamber test stand

Beobachtungsstand	observation cell
Brennkammer od. Triebwerk	combustion chamber or engine
Brennkammer-Prüfstand	combustion chamber test stand
Gasabzug	gas exhaust
Gasabzugkanal	gas exhaust channel
Gerüst	frame
Schubmesser	thrust measurement device

Fig 56

Bedienungs- u. Beobachtungs- bunker	operation and observation bunker
Beobachtungsstand	observation cell
Beton mit wassergekühlter Ablenkschurre	concrete with water-cooled deflection chute
Betonschurre	concrete chute
Brenngerüst	combustion frame
Brennstand	combustion test stand
Drahtgeflecht	wire screen
fahrbar	mobile
fahrbare Plattform	mobile platform
feststehende Montagehalle	fixed assembly hall
Gerät in Kardanringen gelagert	vehicle suspended in gimbal rings
Messbunker darüberliegend	measurement bunker above
Sandwall	sand wall
Sicherheitsbereich	safety zone

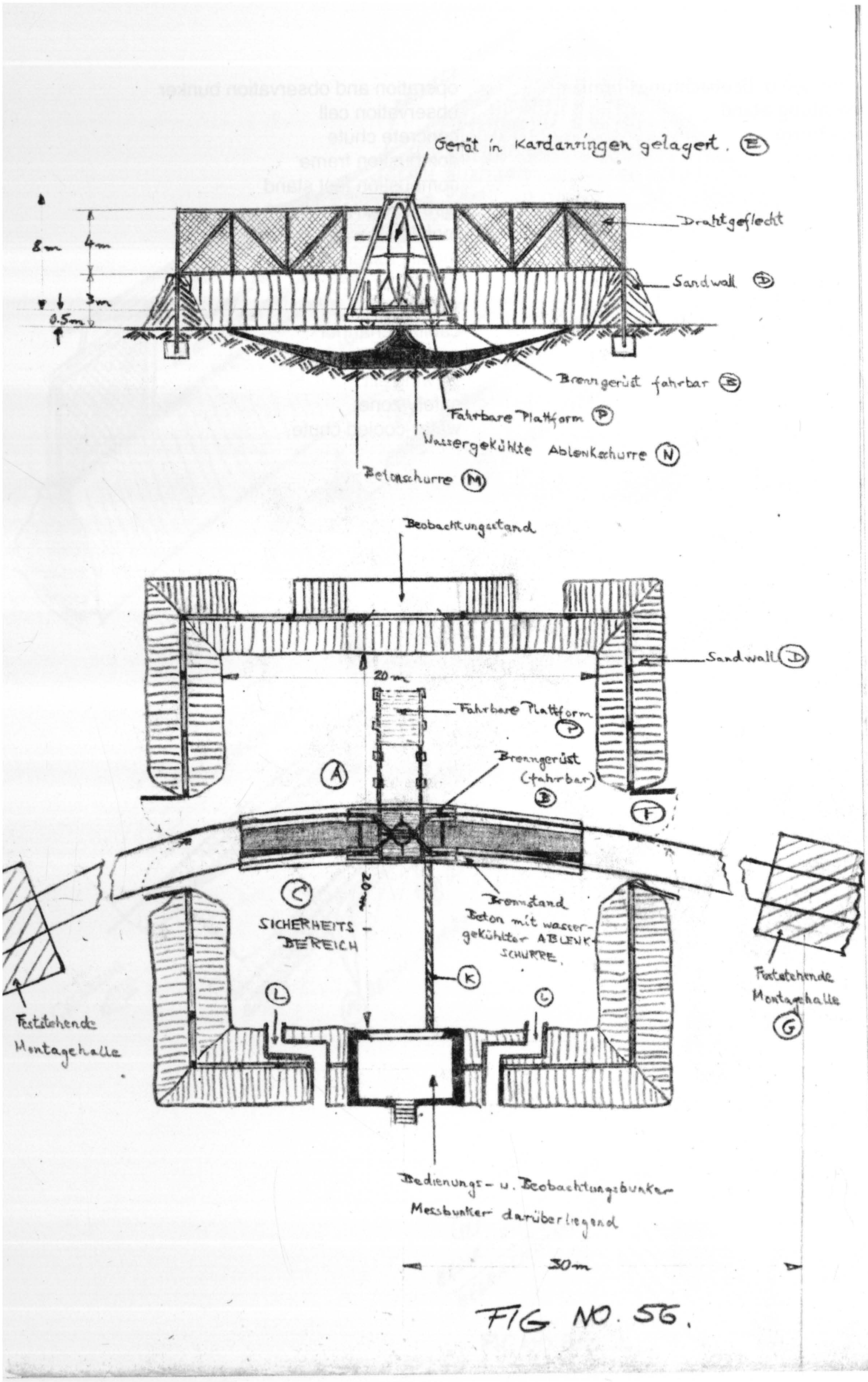


Fig 56: Test stand for complete vehicle

Fig 56A

Bedienungs- u. Beobachtungs-bunker	operation and observation bunker
Beobachtungsstand	observation cell
Betonschurre	concrete chute
Brenngerüst	combustion frame
Brennstand	combustion test stand
Drahtgeflecht	wire screen
fahrbar	mobile
fahrbare Montagebühne	mobile assembly platform
Gasabzug	gas exhaust
Gerät	vehicle
Kabelkanal	cabling channel
Sandwall	sand wall
Sehschlitz	viewing slit
Sicherheitsbereich	safety zone
wassergekühlte Schurre	water-cooled chute

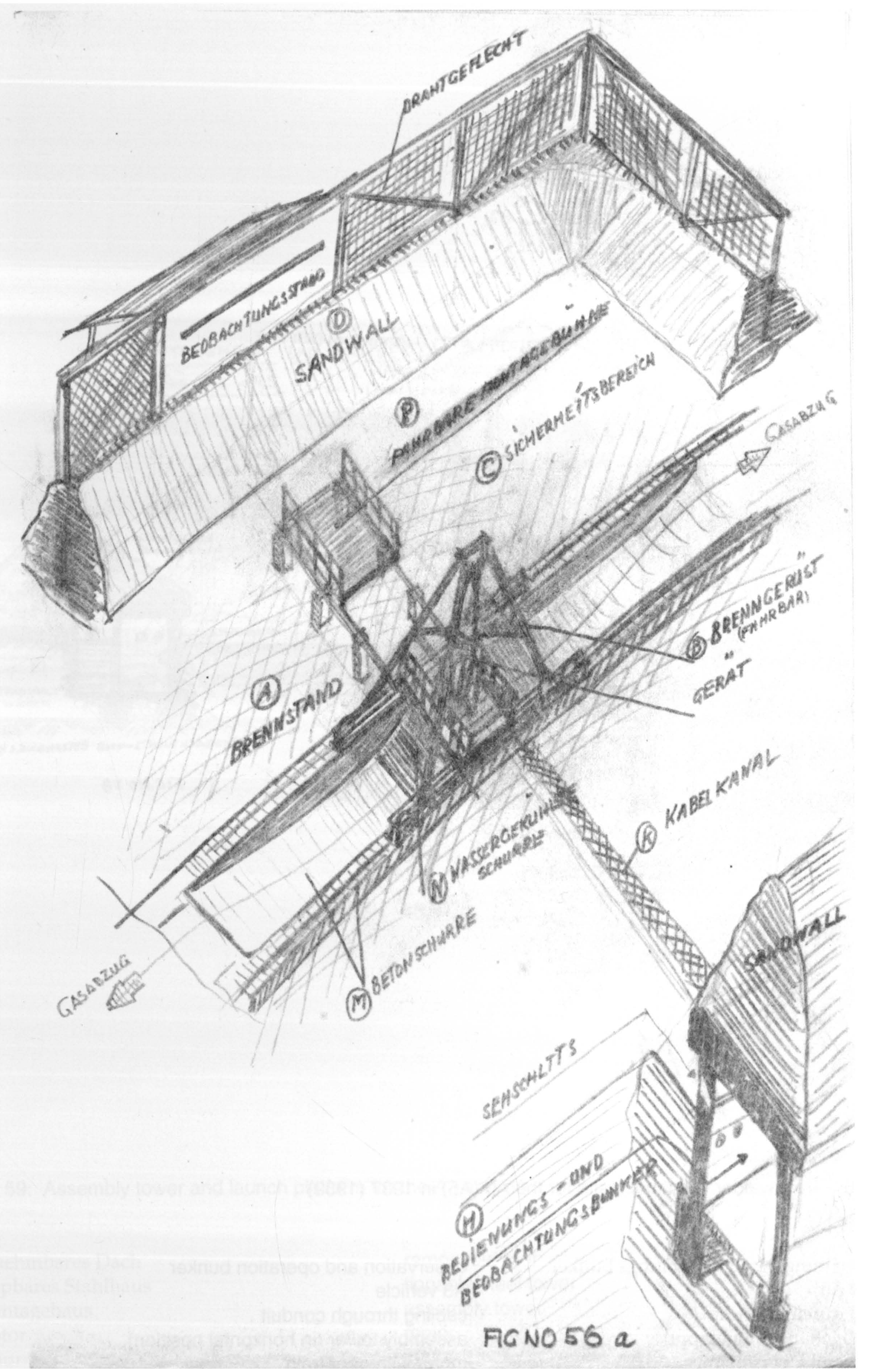


Fig 56A: Further details of test stand

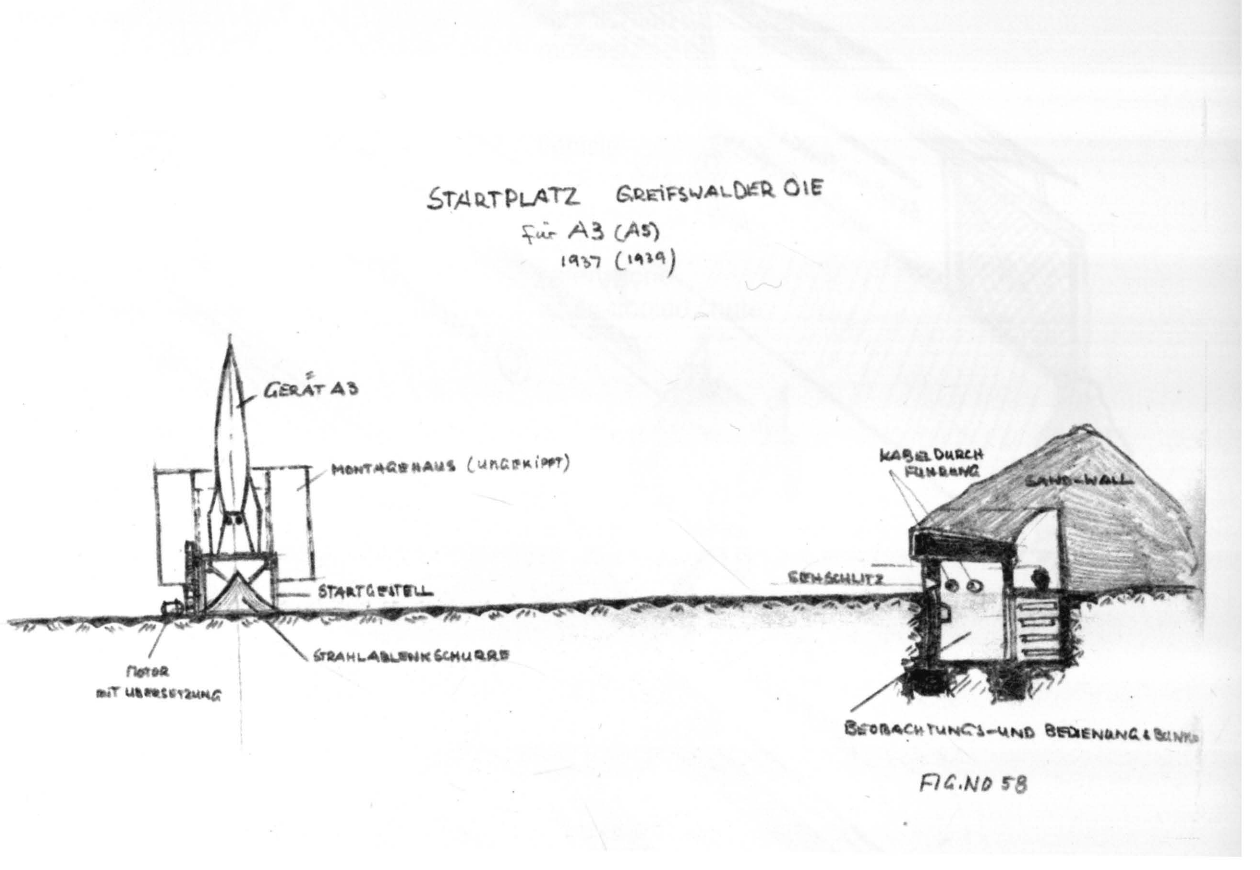


Fig 58: Greifswalder Oie launch site for the A3 (A5) in 1937 (1939)

Beobachtungs- und Bedienungs bunker	observation and operation bunker
Gerät A3	A3 vehicle
Kabel durch Führung	cabling through conduit
Montagehaus (umgekippt)	assembly tower (in horizontal position)
Motor mit Übersetzung	motor with gear train
Sandwall	sand wall
Sehschlitz	viewing slit
Startgestell	launch platform
Strahlablenkschurre	exhaust deflection chute

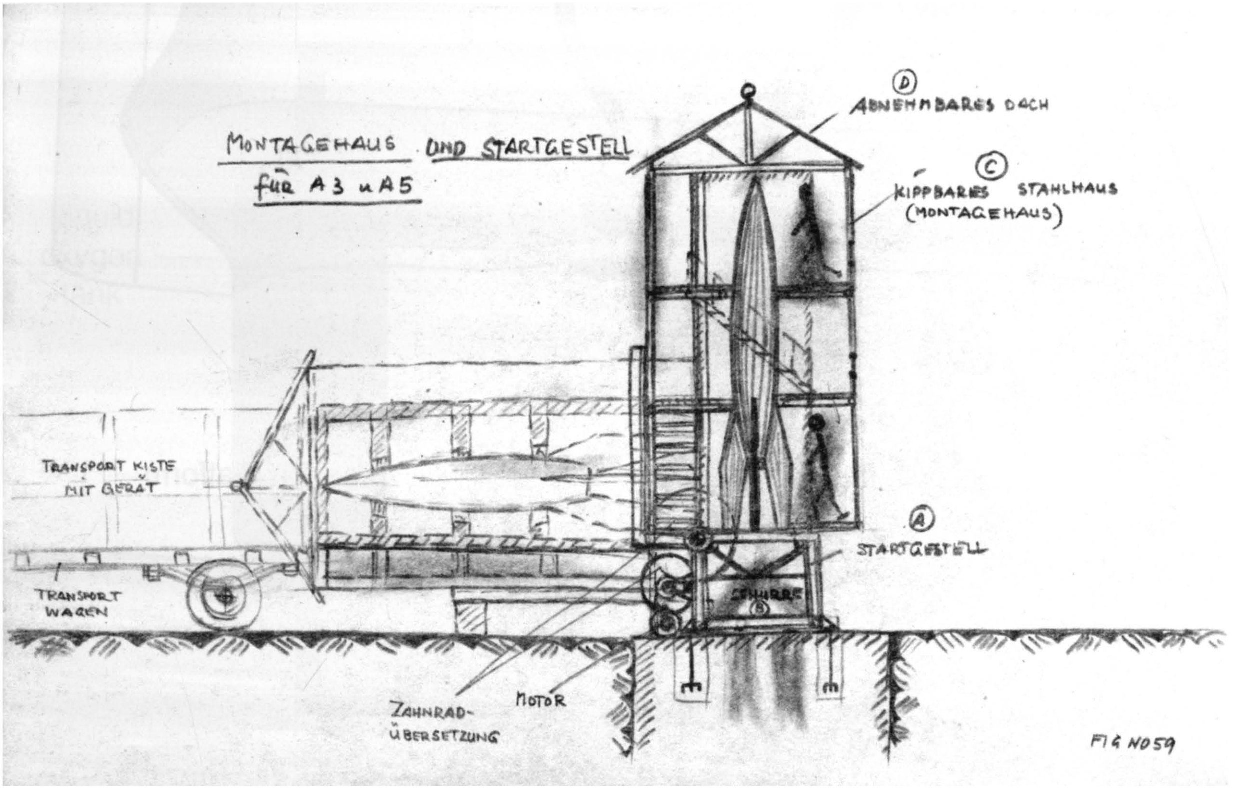


Fig 59: Assembly tower and launch platform for the A3 and A5

abnehmbares Dach	removable roof
kippbares Stahlhaus	tippable steel tower
Montagehaus	assembly tower
Motor	motor
Schurre	chute
Startgestell	launch platform
Transportkiste mit Gerät	transport container with vehicle
Transportwagen	transport lorry
Zahnradübersetzung	gear train

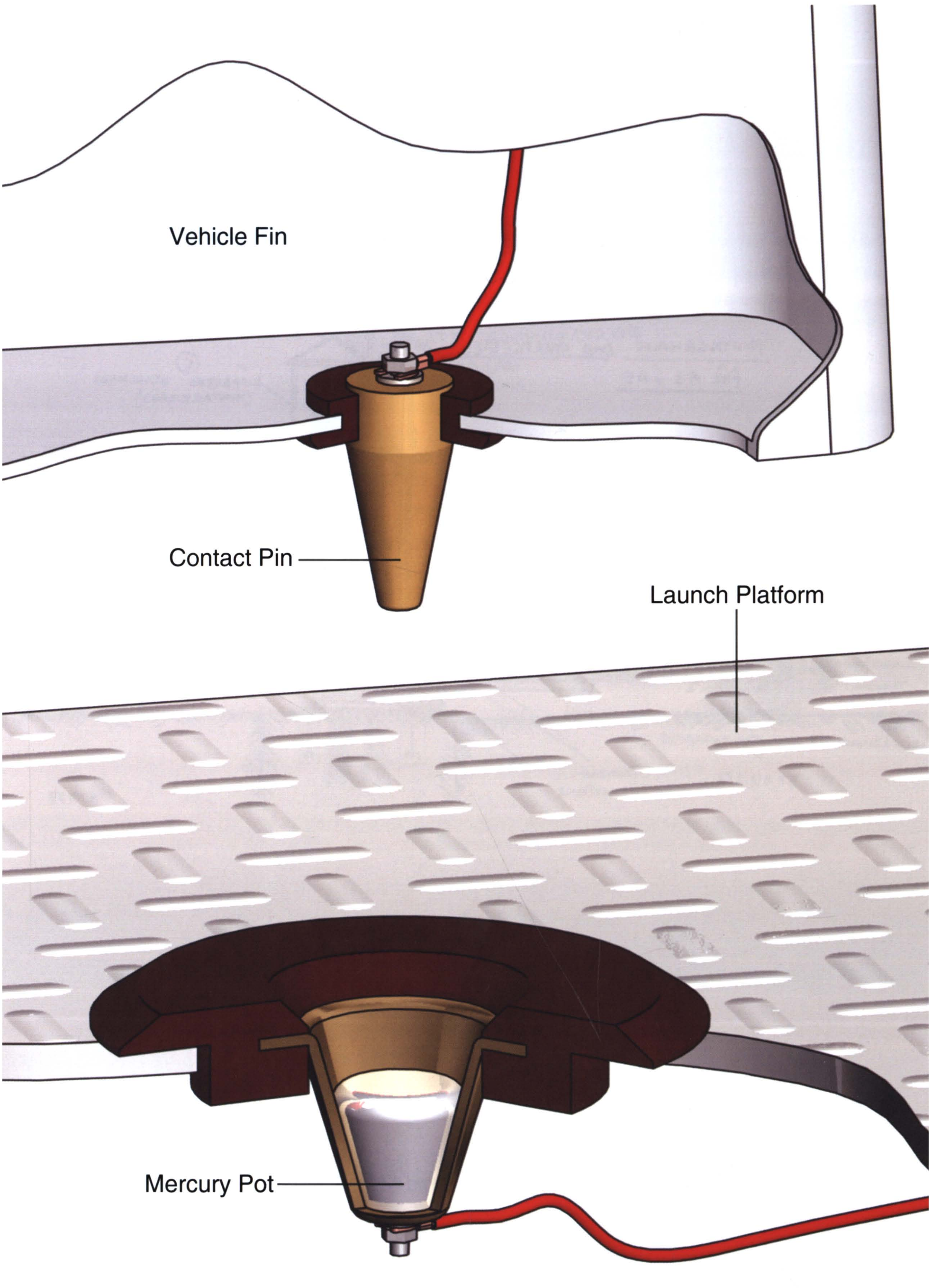


Fig 60: Impression of mercury pot contact system

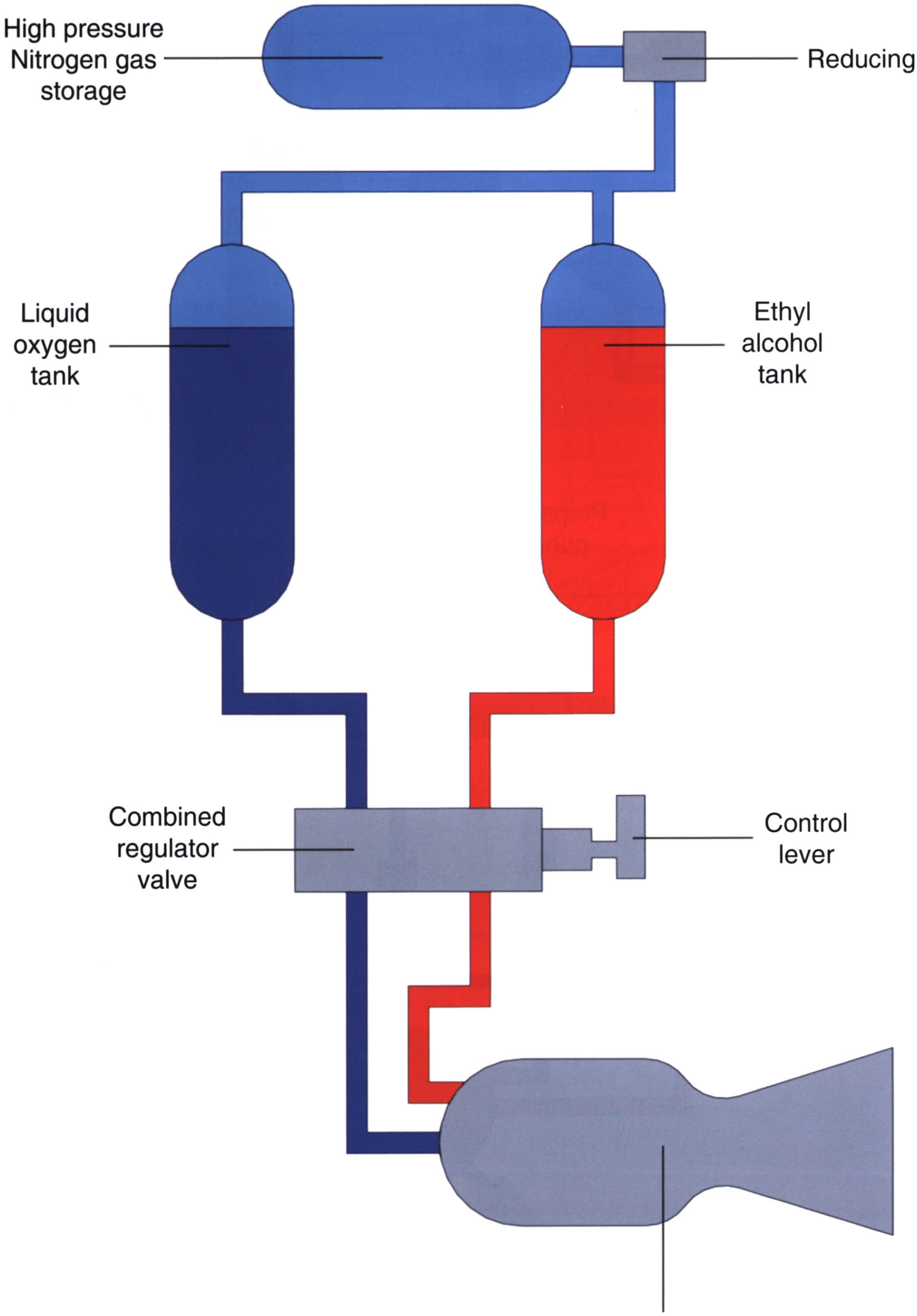


Fig 61: Schematic of pressure-fed system

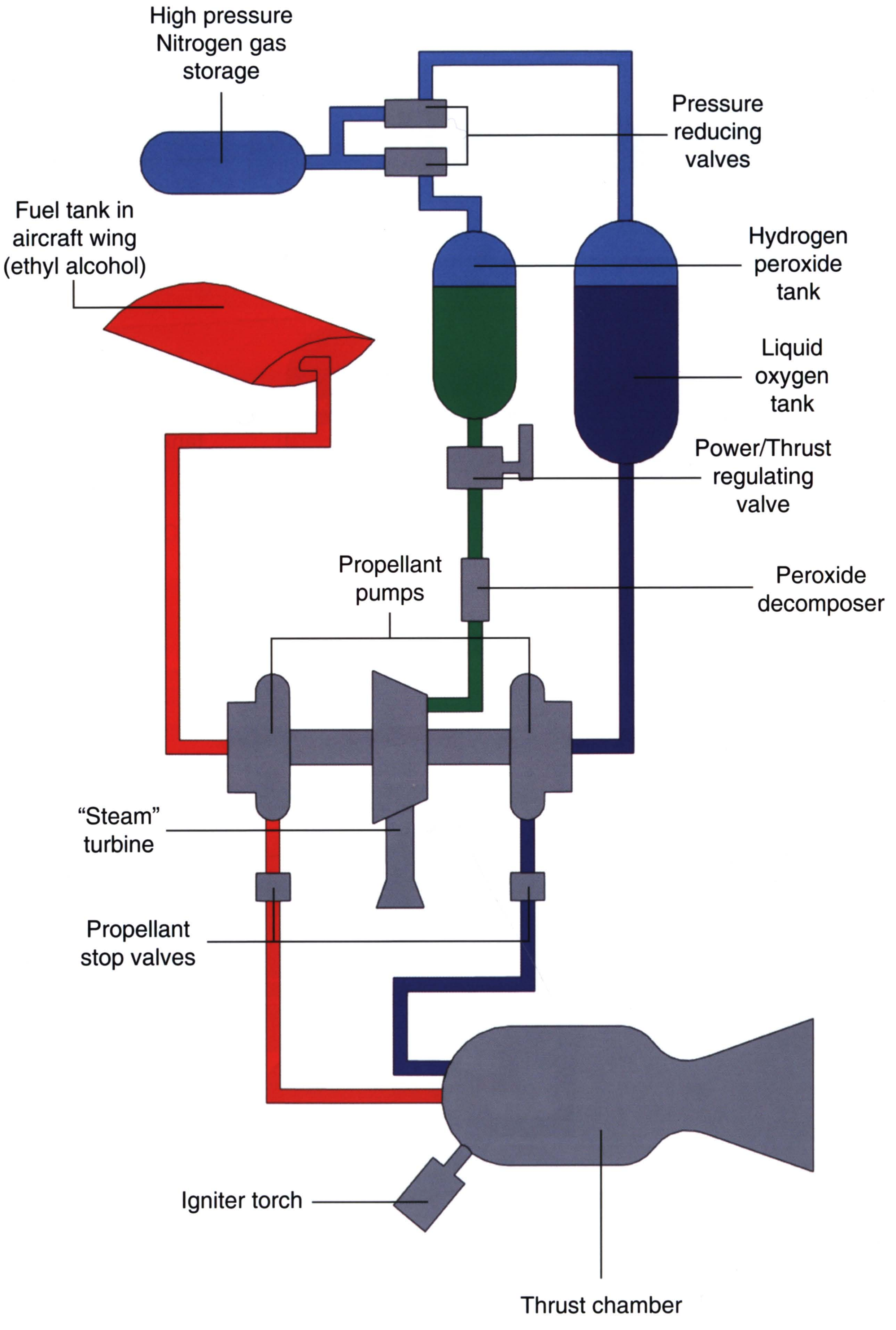


Fig 62: Schematic arrangement of turbo pump-fed thrust chamber

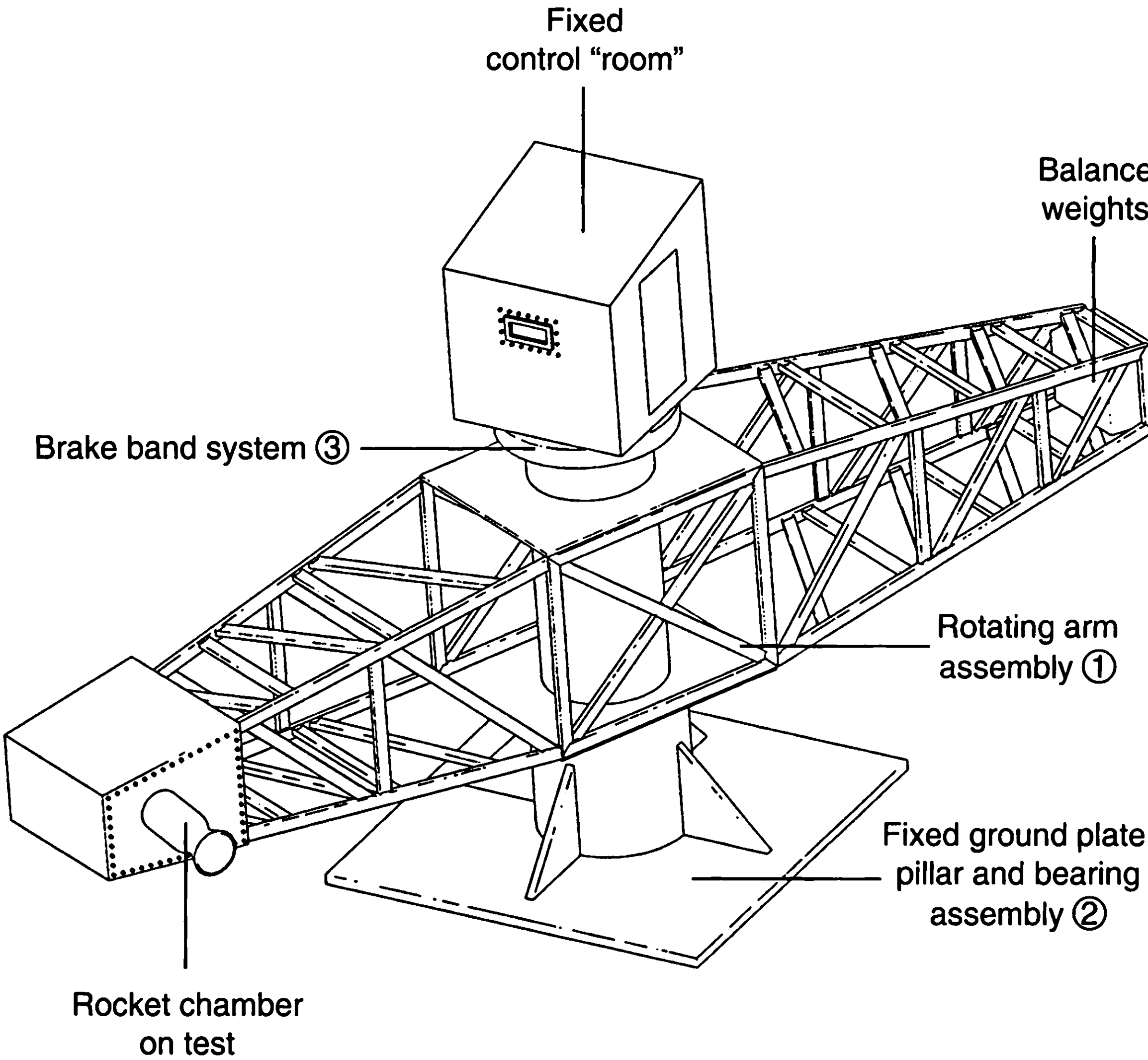


Fig 63: Impression of centrifuge test rig

SPECIFICATION		
Length overall	mm (ft - in)	7,650 (25-1/8)
Maximum body diameter	mm (ft - in)	760 (2-6)
Equipped weight	kg (lb)	750 (1,654)
Thrust	kg (lb)	1,500 (3,308)
Maximum speed	km/h (mph)	1,000 (621)
Thrust duration	sec	45
Maximum altitude	km (miles)	12 (75)

THE A-5

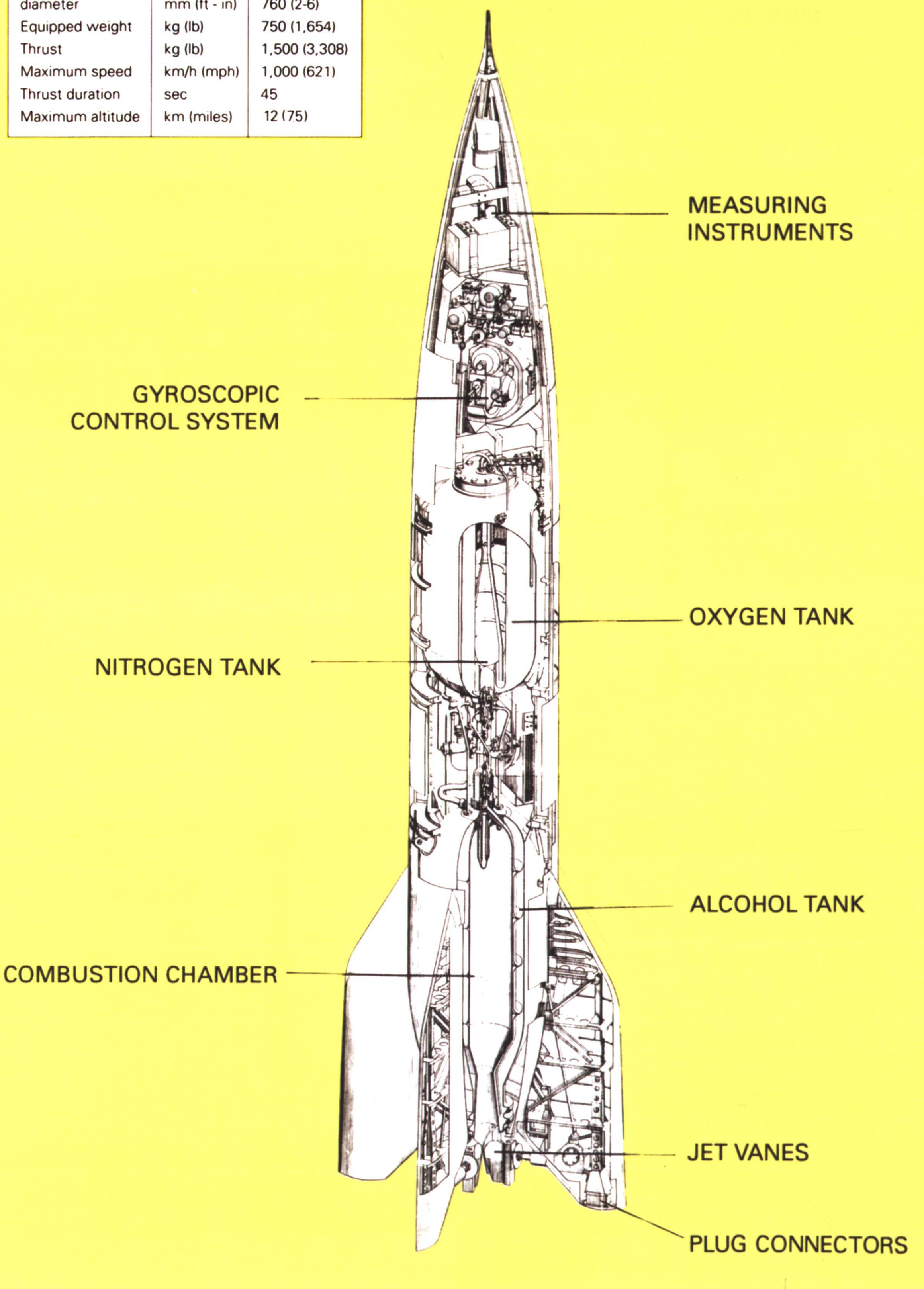


Fig 64: The A-5

CHAPTER THREE

Development activities on long-range rocket-powered guided missiles using liquid propellants at the Peenemünde a/Usedom site of the Army Weapons Department up to completion of the A4 (V2) project (1937 - 1942)

During and after the launch tests of the A3 (1937-1938) on the Greifswalder Oie, construction and fitting out of the test site in Peenemünde was already under way. It had by that time progressed to the point where other departments that were immediately concerned with the work could contribute their own experience and test results to improve the vehicle further. The A3 vehicle was re-designated in turn the A5 - the designation A4 having been already reserved for the vehicle that would go into service.

Fig 64 shows the A5 as it was used in large numbers as a control system test vehicle. The A5 not only tested out different types of control systems, but also other launch equipment of interest.

When comparing the A3 in Fig 54 with the A5 in Fig 64 the following significant development features can be highlighted:

The propulsion system has been adopted in its entirety and has not undergone any significant modifications.

The fuel atomiser for the combustion chamber has been improved insofar as the holes have been replaced by swirl jets. The shape of the vehicle was also retained, but the shape of the fins had to be altered. As can be seen from Fig. 64 the fins have been configured to be wider and shorter. This shape had emerged from the aerodynamic department's deliberations and numerous wind tunnel tests and provided the required stability for all launches. The same shape was also used later for the A4 (V2). For the body of the vehicle the same material and the same profiles were used, however it was now a more stable configuration, the main feature being the division of the vehicle into three sections that were bolted together at the parting faces. As can be seen in Fig 64 the three sections were:

1. The nose section, containing essentially the control system, sequencing circuit, control potentiometers, batteries and thermo barograph,

2. The centre section, containing the complete propulsion system and the two parachutes (braking and gliding parachutes),

3. The tail section, including the hull with fins, the control boxes for movement of the exhaust stream rudder vanes, and at the bottom of the fins the conduits for the electrical and pneumatic lines required by the vehicle while on the launch platform.

Three types of control system were developed and tested in the missile. These systems all had one thing in common - they were three-dimensional gyroscopic control systems. The vehicle deviations $(\varphi, \dot{\varphi}, \ddot{\varphi})$ were used to control the vehicle in two control planes and in the spin plane (rotation of the vehicle about the longitudinal axis).

The control system developed by the Kreisel-Geräte company used a platform suspended in gimbal rings that was gyroscopically stabilised, ie maintained in the null position. On this platform were located velocity and acceleration measurement devices $(\dot{\varphi}, \ddot{\varphi})$ for each control plane. These planes were orthogonal to each other. The device for the measurement of spin deviation was similar. The deviation of the position (φ) of the vehicle was measured by potentiometers that were installed on the axes of the gimbal rings. In contrast to the A3, in which the resultant measurements were fed via motors and linkages with to and fro movement through the spars to the control boxes, the A5 used a rotational movement to amplify and transfer the measurements. This rotational movement of the control linkage was translated in the control boxes via a worm gear into a rotational movement of the exhaust stream rudder vanes. This translation had the advantage that it could be performed without any control drift, which was not always the case for the translation via linkages used in the A3.

The control system developed by Siemens and Askania essentially used gyroscopes that were rigidly attached to the vehicle. The positional gyroscopes that measured the positional deviations of the vehicle () and the 'kymographs' that measured lateral velocity or lateral acceleration were monitored by means of gravitational pendulums and maintained in the null position. In the case of the positional gyroscopes the vehicle deviations were measured using potentiometers attached to the appropriate gimbal axes. 'Kymographs' are gyroscopes suspended in gimbals whose outer ring is spring-constrained. When a lateral velocity or acceleration occurred as a result of vehicle movement, spring forces were generated that produced a torque on the gimbal ring with the result that the gyroscope precessed[16]. The resultant precession angle was a measure of the lateral acceleration or velocity. In conjunction with a potentiometer these values could be extracted as voltage differences and used for control purposes. The electrical signals picked up in each individual plane were measured and amplified and the resultant electrical values used to control the vehicle. Control was achieved via a rotational linkage, which was again fed through the four spars and connected to the rudder vane rams of the exhaust stream rudder vane boxes. Using oil-based hydraulics the exhaust stream rudder vanes could thus be moved.

To produce sufficient turning moments to control the vehicle the surface areas of the rudder vanes in the exhaust gas stream had been significantly increased for the A5 compared with those of the A3. As will be recalled, the A3 launch failures essentially occurred because the exhaust rudder vanes were too small. Further progress was achieved by using graphite as the rudder vane material. This was in place of the molybdenum used in the A3, which was far too expensive and heavy.

The mercury-based power disconnects used on the A3 launch platform (Fig 60) were not wholly successful in practice. The electrical connections were unreliable in wet weather and in other conditions that often caused short circuits and defects. For these reasons the system was abandoned and plug connectors were used instead. Fig 64 shows the plug connectors as used on the launch platform plate and on the vehicle disconnects.

The purposes of most of the components listed under 1 above, such as control potentiometers, batteries and the thermo-barograph, have already been discussed in the previous chapter on the A3 vehicle. The sequencing circuit was a new item. The sequencing circuit acted as a command transmitter for the control system that directed the vehicle into a particular pre-defined flight path. After the vertical climb the vehicle was to follow a curved flight path.

After a vertical climb for three seconds and subsequent transfer of the vehicle into a curved flight path, the centre of gravity of the vehicle at the point of combustion shutdown (30-40 secs) was moving at a certain angle α with the ground. The sequencing circuit was in effect a timing device. At the time of launch it switched on and the first contact was made at 3-4 seconds. At this instant a circuit was closed that set a small motor in motion. In the case of the Kreisel control system this rotated the stabilised platform with its on-board command transmitters around the null position with the same angular velocity. In this manner commands were automatically generated in the position-sensing components of the control system that corresponded to the position of the vehicle. These commands produced deflection of the exhaust stream rudder vanes that steered the vehicle into the desired flight path. In the other types of control system the potentiometer in the horizontal system was adjusted so that voltages were automatically generated in the sensor components as a result of rotation. Via the

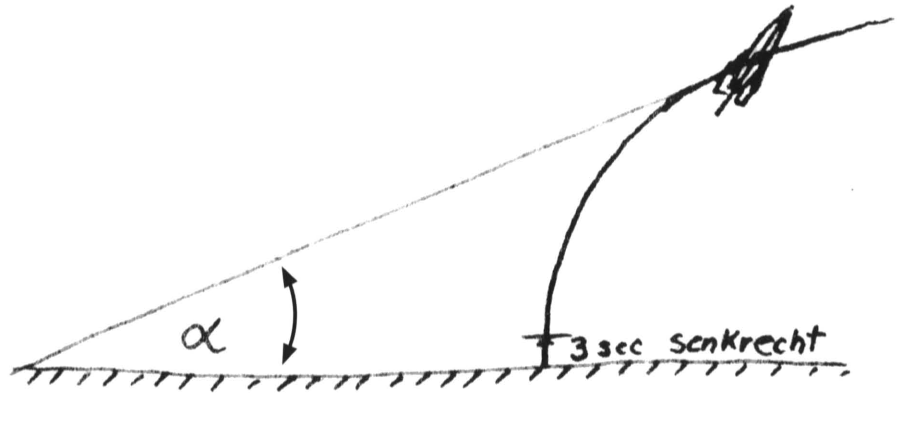


Fig 64A: Missile trajectory

3 sec senkrecht — vertical climb for 3 seconds

[16] *Later, these came to be known as 'rate gyros'.*

actuation components these voltages moved the exhaust rudder vanes in the longitudinal plane. After ~ 30-40 seconds the combustion shutdown contact was made, ie the magnet of the control solenoid valve was energised and moved the valve to the end position, shutting off the propellant valves. The vehicle now flew on without power in the familiar parabolic trajectory.

It was, however, also possible to transmit the combustion shutdown command from the ground. A command receiver was fitted for this purpose. It received the command from the ground station via so-called loop antennae that were insulated in the tail fins. With this arrangement the control solenoid could be energised in a similar manner and combustion shutdown obtained.

If the vehicle passed the intended end of the flight path a command released the braking parachute and a certain time later the gliding parachute was released. The vehicle descended suspended from these two parachutes and in many cases could be recovered without any damage.

The performance data of the A5 vehicle are identical to those for the A3. Launches similarly took place from the Greifswalder Oie in the years 1938 – 1940. The launch site and launch preparation procedures were the same as those for the A3 and have already been described in the previous chapter.

With vertical launches a height of 10-12 km was achieved on average, and when the vehicle was translated into an $\alpha = 45°$[17] flight path the average range was 18-20 km.

With this test series (which included 25-30 vehicles) it was possible to extract all the data required for the proposed development of the A4. The control systems were developed to the point at which a sufficiently large volume of experience was available for the A4.

In January 1939 the first design schemes for the A4 (V2) were generated in the Peenemünde design office. An average range of ~ 300 km was a prime requirement, and the vehicle had to be able to carry a payload of ~ 1 tonne. In the course of time the end product was the vehicle with the shape and performance that is now familiar. The shape used for the A5 was geometrically magnified and also used for the A4.

The vehicle comprised 4 sections:

1. Payload nose section to accommodate the required payload

2. Control system equipment nose section, containing the position-sensing components of the control system, power supply, electrical equipment, etc

3. Centre section with the propellant tanks

4. Tail section with the four fins, containing combustion chamber, propellant feed pump with drive, actuation components of the control system, exhaust stream rudder vanes, antennae, etc.

The vehicle body was of a framework structure with 'top hat'-shaped spars and frames, Ω-shaped stringers of 1 to 1.5 mm made from 1623 steel, and a 0.7 mm thick skin made of the same material and spot-welded to the frame. Access flaps were fitted at the required points of access to the propulsion unit and equipment.

In the original project the plan was to use the wall of the body centre section as a tank wall to save weight. From the technical point of view the reservations were not so serious. Even in the case of the liquid oxygen tank that had almost no internal pressurisation the only reservation would have been that with an average wall temperature during flight of 600-800° C[18] more vaporisation would take place. Likewise the stresses caused by the cold oxygen could perhaps have produced some unpleasant surprises. But with the chosen frame structure configuration the spars would have had to be fed through the floors of the tanks and welded to them to form a seal. At that time such welding could not be performed with any reliability. For this reason the safer path was chosen of using light alloy propellant tanks located separately from the vehicle body.

Here I must make a general point that as a result of entry into the war we had to produce a usable and practical vehicle as quickly as possible. As a result the normal course of development was disrupted in part. Not all possible solutions could be pursued and investigated, and when choosing between development proposals we had to adopt those that were practically possible at the time to avoid risks.

Evaluation of the propulsion unit design revealed that high-pressure tanks could not be used for driver gas supply of propellants if the required vehicle performance was to be achieved. Thus there emerged a propulsion unit that comprised the following modules:

(a) non-pressurised propellant tanks
(b) turbo-pump for supply of propellants
(c) vapour generation plant to drive the turbo-pump

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[17] *This angle is chosen to give the maximum theoretical range.*

[18] *Riedel may have meant to state degrees Kelvin - these values appear to be too high.*

(d) combustion chamber
(e) propulsion unit systems.

(a) Fig 65 shows the thin-walled propellant tanks. An aluminium alloy with the composition Al-Si-Mn-Mg, called Hydronalium, was used as the material. The thickness of the bottom of the tank was ~ 2 mm in both cases, that of the wall of the O_2 tank was similarly 2 mm, and for the conical fuel tank it was 1.2 mm. The bodies of the tanks comprise four parts that are welded together and strengthened by means of 6 internal profile rings. A pipe of ~ 235 mm dia was welded into the O_2 tank, and the main fuel line passed through this pipe.

Weight of the fuel tank ~ 75 kg
Weight of the oxygen tank ~ 120 kg

(b) The propellants supply pump used in the A4 is shown in Fig 66. As can be seen, it differs little from a conventional turbo-pump for the supply of liquids. It features a turbine rotor (Curtis system) that sits on the same shaft as the alcohol pump rotor. The oxygen side of the pump is separate, and the oxygen pump rotor is fitted on a separate shaft that is connected via a coupling to the other side of the pump (with the turbine rotor and alcohol pump rotor). The pump casing is bolted as a sealed block to the turbine casing. Insulation is fitted at the interface. The fuel rotor runs in two conventional ball bearings. The shaft is sealed against the turbine casing by means of a conventional stuffing box and features three cast iron rings tensioned by means of circular springs. On the fuel side of the pump the shaft is sealed by means of a stuffing box with conventional radial packing rings. No problems occurred with these components. However, the plain bearings and stuffing box seal on the oxygen side of the pump required particular attention. Lead-bronze plain bearings proved to be the best. These were configured in four parts and were very durable, with a lack of sensitivity to moisture and low wear. To reduce the wear to a minimum the shaft was hard chromed. The shaft was sealed on the oxygen side of the pump by 3 three-part cast iron rings lying one behind the other and held in position by springs. Lubrication of the bearing was by means of a low mass flow rate of liquid O_2 through a small clearance between shaft and bearing. The small loss of liquid O_2 was led out through a leakage pipe. A clearance of ~ 0.4 mm between shaft and bearing was necessary to accommodate the state of the components when cooled to low temperatures.

An average inlet pressure of ~ 1.5 atm. was required to avoid cavitation at inlet to the liquid oxygen pump rotor.

Four nozzle blocks, each with four nozzles of 7 mm diameter, were fitted at the peroxide vapour inlet to the turbine rotor. The nozzle blocks were fed by two lines from the manifold.

All cast parts of the turbine casing were made of an aluminium alloy Al-Si-Mg-Mn (Hydronalium), the turbine rotor was an alloy of Al-Mg—Mn-Sb (KS-Seewasser), and the turbine blades were made of Al-Si-Mg-Mn (Hydronalium). The shaft and bolts were made from steel with 0.45% C and less than 10% P and S. The turbine nozzle block was of grey cast iron.

The pump supplied on the oxygen side G_{O2} ~ 69 kg/sec

at a delivery pressure p_k ~ 18 atm

Oxygen inlet pressure was p_0 ~ 2 atm

and, on the fuel, side G_{CH} ~ 56 kg/sec

at a delivery pressure p_k ~ 22 atm

fuel inlet pressure was p_0 ~ 1 atm

The number of guide vanes for each pump rotor = 7

The turbo-pump had a power output of N_e ~ 465 HP

and required ~ 2.1 kg/sec vapour (decomposed peroxide)

at an inlet temperature of ~ 400° C

and an inlet pressure p_d ~ 25 atm

The exit pressure was p_{da} ~ 0.75 atm

Number of nozzles = 16

Pump average rotational speed ~ 3800 rpm

Total weight of the pump G_p ~ 160 kg

(c) To generate the vapour that drove the turbo-pump a well-known chemical reaction was used in which hydrogen peroxide (H2O2) is decomposed by the presence of a catalyst (in this case potassium permanganate KMnO4). The reaction proceeds endothermically[19], ie (2H2O2) decomposes into (2H2O + O2) and releases heat (47 kcal/kg) that transforms the liquid into

[19] *Riedel has made an obvious mistake at this point – the reaction must proceed exothermically.*

vapour[20], if the correct conditions of volume and pressure are present.

The schematic in Fig 67 shows how the peroxide vapour generation plant for the A4 vehicle was designed to accommodate this process.

The plant consisted of tank (A) with a capacity of ~ 126 litres of hydrogen peroxide (H_2O_2); tank (B) with a capacity of ~ 11 litres of liquid catalyst ($KMnO_4$); the vapour generator (C) in which the chemical reaction took place, and a number of valves.

The plant functioned in the following manner. As a result of opening the manual shut-off valve (8) high pressure gas (~ 200 atm) flowed out of the N_2 main set of storage bottles (6), up to the reducing valve (17). Adjustment of the reducing valve (17) reduced the pressure to a constant average pressure of ~ 30 atm. The N_2 pressure filled all lines up to the switching valves. When the two tanks (A) + (B) were full and closed, the solenoid shut-off valve (27) was switched open and the ~ 30 atm. pressure was fed through line (x) into tank (A) and through line (y) into tank (B). Potassium permanganate from tank (B) passed through line (z) into the vapour generator (C). At the instant at which the pressure in line (z) reached 1.5 atm the membrane contact (30) switched so as to close a power circuit. The valve (31) opened, as did the pneumatically-controlled main valve (32) (a 25-tonne valve), and the valve (33) (an 8-tonne valve)[21]. H_2O_2 entered the vapour generator (C) and was decomposed by the small amount of KM_nO_4 already present. The vapour generated, consisting of ($H_2O + O_2$) at an average temperature of 400° C, was fed at 25 atm through line (k) to the turbo-pump. If the vapour generation process were to be halted for any reason, all the valves in operation up to that point would close. At the same time valve (24) would be energised and would open the two gas blow-off valves (25 and 26) pneumatically so as to release pressure from the tanks.

Fig 69 outlines how the vapour generation plant functions in conjunction with the whole propulsion system (see under e).

Fig 67a shows the vapour generation plant assembly as used when installed in the propulsion unit. The components can be recognised since they are annotated in accordance with the schematic in Fig 67. For the general arrangement of the vapour generation plant and propulsion unit, see Fig 69a.

(d) When the last elements of the Army Experimental Establishment in Kummersdorf were moved to Peenemünde in 1937, Dr-Ing Thiel took over the Kummersdorf test site with a contract to carry out basic research in the field. Under his direction an atomisation system was developed for a 1.5 tonne combustion chamber that, using alcohol and liquid oxygen as propellants, achieved an $X = w_a/w_{atheor} = 0.95$. This was the best utilisation of the available thermal energy to be achieved up to that point in time. At about the same time (1938) the combustion chamber was being designed for the A4 with ~ 25 tonnes thrust. There was no better course of action, therefore, than to use for this purpose the atomisation system developed by Thiel. Thus emerged the familiar injection system for the A4 combustion chamber, in which 18 of these heads were used[22]. Over time the combustion chamber shown in Fig 68 evolved. Nearly 3 years of development were required to produce a practical design. At that time it was an enormous step to move across from the 1.5 tonne combustion chamber (for the A3 and A5) to one with 25 tonnes of thrust. In the course of development difficulties occurred with the practical details of manufacture and with the high static and thermal loads on individual components. At an average combustion chamber pressure pi ~ 25 atm and a combustion chamber diameter of ~ 900 mm the combustion head had to resist a loading of ~ 100 tonnes. To give a practical appreciation of the stresses and forces occurring it can be stated that when the combustion chamber was in operation the head expanded by 10 to 20 mm, to spring back again into the original position when the burn was complete. The other form of loading was thermal. The gas temperature in the combustion chamber was an average of 3000° K. Maintenance of the integrity of the walls was very difficult and without the use of film cooling would have been impossible. Even so the high wall temperatures caused expansions leading to high stresses in the material and thus to destruction. The stress differences between the inner and outer walls could only be controlled by the location of individual expansion rings in the outer wall.

[20] *Comprising steam and oxygen.*

[21] *In the A4 vehicle, engine shut-down was achieved in two stages, to give more precise control of the final velocity. Thus the full 25 tonne thrust was reduced to 8 tonnes for a short period before final shut-down. Hence the naming of the valves to correspond to their duty.*

[22] *To generate the approx 25 tonnes of thrust*

Nevertheless all these difficulties were overcome in the course of development and by virtue of many tests a combustion chamber of sufficient integrity was developed empirically.

As can be seen from Fig 68, the combustion chamber comprised the head and the nozzle that was connected to it. The head was formed from three stacked sheets of material, forming two chambers into which the 18 pots were welded.

The fuel flowed from the pump, entered by (a) into the pipe manifold (b) of the nozzle, flowed through the cooling jacket (c) of the nozzle and through the cover via (d), thus cooling the inner head plate. When the main fuel valve, which was fitted in the middle of the head, was opened, the fuel flowed through the small holes (e) so as to be evenly distributed into each pot. In the inner wall of each of the pots were fitted 44 cooled swirl jets and 24 holes, whereby the fuel penetrated into the pot interior, either as a jet or in finely atomised form. For the different types of injection using swirl jets see Fig 68a.

Type (1) in Fig 68a possessed two tangentially drilled calibrated holes (c) that rotated the fuel mass flow. The mass flow passed through the larger central drilling (d) to emerge from the hole (e) in a finely distributed cone as a result of the induced swirl. Type (2), in contrast to Type (1), had a larger exit hole (e) so that the atomisation cone was larger. The base of this atomiser possessed a further hole (f) through which the fuel was sprayed as a full jet through the atomisation cone and into the combustion volume. This device had the objective of penetrating into the oxygen zone occurring in the centre of the combustion pot as a result of the oxygen atomiser, so as to react with O_2 from this zone for better combustion. A further four small holes (g) were connected to the central hole (d) and served to cool the atomiser. Type (3) was the same as Type (2) except that here there was no central hole (f). Types (2) and (3) were distributed in the individual rows in the atomiser pot according to combustion quality, with the aim being to optimise combustion as monitored by gas analysis. Type (4) were the cooling nozzles that were installed in the inner wall of the combustion chamber and whose holes were sealed using Woods metal.

The liquid oxygen flowed from the pump via the O_2 main valve, via (f) into each of the 18 O_2 atomiser systems. The O_2 atomiser consisted of a hemispherical-shaped brass body in which holes were drilled in a number of rows at a defined angle to the axis. Oxygen passed through these holes into the interior of the pot. The fuel entering via the swirl jets and the oxygen entering via the O_2 atomiser mixed, ignited and burnt. For the purposes of cooling the nozzle wall numbers of holes were drilled that protected the wall from burn-out by creating a film of fuel. The locations of the holes in the various rows can be seen in Fig 68. Each row was connected to a dedicated manifold that was fitted outside the actual cooling jacket. These manifolds were fed through 4 pipes (g), each pipe being fed from the outer head chamber, see point (L), ie the individual annular chambers were only fed with fuel after the fuel main valve was opened. The one row that had 36 holes was, however, connected directly to the cooling jacket. The holes of the cooling nozzles were plugged with a low melting point metal. When combustion was generated by the first stage of fuel injection the metal melted out and the wall of the combustion chamber exhaust nozzle was cooled by fuel exiting through these 36 cooling nozzles. This was sufficient to cool the wall during the first stage of combustion (~ 2.5 tonnes of thrust).

When the second fuel stage is switched on the main fuel valve opens, so that the individual film cooling manifolds are supplied through pipe (g) and the film cooling required for maximum thrust is brought into operation. The pressure differential between individual manifolds and the combustion chamber across individual rows is on average 0.8 atm. The fuel mass flow rate needed for this type of film cooling is on average 13% of the total fuel mass flow rate.

'1604' steel was used as the material for the highly loaded combustion chamber components and '37.12' steel was used for the others. The combustion chamber weighed on average 425 kg. Hydronalium was also used in the combustion chamber to begin, but this generated integrity problems for the nozzle. For this reason, but also for reasons of manufacture, implementation in steel was preferred. The head continued to be manufactured in Hydronalium for a long time without any difficulties arising. It was only when the nozzle material was changed from Hydronalium to steel that it became essential to change the head to steel to avoid the need for a strong flange joint between head and nozzle.

The following data can be presented regarding combustion chamber performance.

In Fig 68b the temperature T_i (°K) and exhaust velocity w_a (m/sec) are plotted as functions of the mixing ratio m = O_2/fuel for a combustion chamber pressure pi ~ 16 atm. and combustion of 75% ethyl alcohol with liquid oxygen.

From analysis of a large number of combustion chamber tests it was possible to establish how far the test results agreed with theoretical values.

The thrust achieved in the tests corresponds to the calculated theoretical thrust when the losses occurring have been taken into account. In accordance with theory it exhibits practically no dependence upon the mixing ratio m.

In contrast the characteristic velocity also displays an independence of 'm' in contradiction to theoretical predictions, if 'm' remains within the limits as determined approximately from the tests. The explanation for this is to be sought in incomplete mixing between the propellants and the fact that the combustion process was not in accordance with theoretical assumptions. Since it is practically independent of 'm', the characteristic velocity can be represented as a linear function of 'p_i'.

As plotted in Fig 68b, therefore, the actual exhaust velocity w_a, is seen to be independent of mixing ratio within the limits m = 1 to 1.45, in contrast to the theoretical velocity w_{atheor}.

Individual combustion chambers generated different values of thrust, characteristic and exhaust velocity for the same level of combustion chamber pressure. This was the result of non-identical manufacture, particularly of the injection system. In Fig 68b the exhaust velocity w_a that has been plotted is an average obtained from the set of tests. The same is true for the factor X that defines the ratio of actual to theoretical exhaust velocity.

In practice it should have been possible in these tests to achieve a value:

$$X = w_a/w_{atheor} = 0.95$$

if a nozzle loss of 5% is included in the analysis.

As can be seen from Fig 68b a value of X = 0.93 was achieved for a combustion chamber pi ~ 16 atm. and m ~ 1, a figure that approached the best that was practically achievable.

Average combustion chamber pressure ~ 15 atm

Average pressure differential ~ 2.5 atm

Average pressure drop in cooling jacket 4.5 atm

Average mixing ratio M = O_2/fuel 1.25

Average O_2 consumption rate 69 kg/sec

Fuel consumption rate (75% C_2H_5OH + 25% H_2O) ~ 56 kg/sec

Average exhaust velocity w_a ~ 2020 m/sec

Theoretical exhaust velocity w_{atheor} ~ 2300 m/sec

= w_a/w_{atheor} = 2020/2300 ~ 0.88

Expansion ratio for the nozzle 16/0.76 ~ 21

Ratio of combustion volume to cross-sectional area of nozzle throat L* ~ 113 in

Average film cooling rate ~ 13% of fuel

Average burn time t ~ 67 sec

Weight of combustion chamber ~ 425 kg

(f) The propulsion unit consists of:

propellant tanks
turbo-pump with drive
combustion chamber
high-pressure storage bottles
valves and pipework.[23]

Within the confines of this monograph it is not possible to go into great detail concerning the all-important propulsion unit. The propulsion unit modules listed above have to an extent already been described in the previous chapters in general terms. As far as the pipework is concerned there is little to say since we are dealing with conventional and familiar components. Similarly I will stop short of describing each valve in detail. In general it can be said that the liquid valves were pneumatically controlled. From the set of N_2 storage bottles the high pressure of 200 atm was reduced to 30 atm. and fed through electrically-operated solenoid valves to each of the valves. In general the liquid valves were configured so that they were closed when under gas pressure and open in the non-pressurised state. A prime feature of the two propellant valves was that they were configured to supply two stages of mass flow rate. When the system was switched into the

[23] *A more complete description at this point would read: two main propellant tanks, a single-shaft turbo-pump with decomposed peroxide drive, one combustion chamber, one set of high pressure storage bottles, associated valves and pipework.*

first stage of fuelling and combustion a small valve fitted inside the larger valve provided the mass flow for generation of a small flame in the combustion chamber. This flame ignited the full propellant mass flow rates when the valves were switched into the main stage of fuelling and combustion.

All the valves were designed and tested by a dedicated valve group working in a well-equipped laboratory. As a result of this concentration of experience all valves and associated fittings were refined to a level where they exhibited high standards of safety and reliability.

The system schematic for the propulsion unit is shown in Fig 69 and in the following paragraphs I will describe the most essential features concerning launch preparations and mode of operation of the propulsion unit.

Preparations for launch:

Functional check of all solenoid valves and switches.

Tanking up with alcohol through filler pipe(1) approx 3820 kg.

Tanking up with liquid oxygen through filler pipe (2) ~ 4900 kg.

Filling with hydrogen peroxide (82% concentration[24]) through pipe (3) ~ 173 kg.

and potassium permanganate solution (27%) through filler pipe (4) ~ 12 kg.

Charging of the set of high-pressure storage bottles (6) (7 bottles @ 7 litres capacity each) of the vapour generation plant with gaseous N2 up to 200 atm. through line (a), non-return valve (7), and main shut-off valve (8). The pressure was displayed on gauge (9).

Similarly, charging of the set of storage bottles (10) through the connection (11) at approximately 200 atm. N_2 pressure. This pressure was displayed on gauge (12).

Through line (e) the O_2 gas release valve (18) is pressurised from the ground station and vents the O_2 tank during the tanking process. At the same time high pressure N_2 passes via the non-return valve (19) into the distribution line (f). The non-return valve (20) shuts off the ground station pressure line from the pipework of the vapour generation plant.

Solenoid valve (13) is then briefly switched open. Via line (b) the upstream fuel valve (14) is pressurised and opens. Alcohol passes out of the fuel tank through line (c), through the fuel side of the propellant pump (15) into the main pipe and distributor (d) into the cooling jacket of the fuel chamber (16).

Reducing valve (17) is adjusted to reduce the high pressure of 200 atm to 30 atm. Thus all control lines to the pneumatically controlled valves are placed under N_2 pressure. Line (e) is shut off from the ground station pressure source by closure of the non-return valve (19). Gas release valve (18) is vented on its control side and closes. Via line (g) the O_2 tank is placed under N_2 pressure at an average 1.5 atm from the ground station pressure source. (This pressure is necessary to ensure the required liquid oxygen suction conditions on the inlet side of the turbo-pump).

Solenoid valve (13) is switched open thus opening the upstream fuel valve (14). Fuel flows through as far as the main fuel valve on chamber.

1st combustion stage

When the pyrotechnic igniter installed in the combustion chamber is activated the solenoid valve (20) is switched so that N_2 pressure is exerted on to the spring unit of the 1st stage of the O_2 valve (21) and the valve seat opens. A short time later the solenoid valve (22) is switched and feeds pressure into the spring unit of the 1st stage of the fuel valve (23) so that this valve seat also opens. As a result of the pressure in the O_2 tank and the gravitational head of the fluid in the fuel tank a certain flow of the two propellants enters the combustion chamber and is ignited by the ignition flame. Combustion is generated corresponding approximately to a thrust of 2.5 tonnes.

2nd combustion stage

The pressure differential in line (g) to the O_2 tank exerted from the ground station is switched off. By switching solenoid valve (24) the gas release valves (25) and (26) for the two vapour generation plant tanks are closed and by actuation of solenoid valve (27) both tanks are placed under an average pressure of 30 atm. From the potassium permanganate tank (28) fluid passes through line (h) into the vapour generator (29). The

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[24] *The water in the potassium permanganate solution is what causes the temperature to rise to only 400 °C (a basic 82% gives ~ 620 °C)*

pressure-controlled switch (30) in the supply line is closed at ~ 1.5 atm. The current switches the solenoid valve (31) and thus opens both the pneumatically-controlled peroxide valve (32) (for the 25 tonne thrust stage) and the electrically-controlled peroxide valve (33) (for the 8 tonnes thrust stage). In this manner peroxide comes into contact with the fluid catalyst in the vapour generator (29) and chemical decomposition starts to take place. This generates an average pressure of 25 atm, an average temperature of 400 °C, and an average vapour mass flow rate of 2.1 kg per second to drive the turbo-pump (15) via line (k). The pump thus supplies liquid oxygen via the O_2 valve (21) whose main valve cone opens fully as a result of the pressure, and then via the O_2 distributor line (l) into the atomiser systems of the 18 combustion pots. At almost exactly the same time fuel is similarly fed through line (d) and valve (23) into the atomiser systems of the 18 combustion pots. Here too the main valve cone of the fuel valve opens fully as a result of the rise in turbo-pump supply pressure. The exhaust gases from the pump progress through a vaporiser (34) and two exhaust lines fitted with nozzles out of the vehicle and into the surrounding atmosphere. The objective behind installation of these nozzles was to avoid any increase in pump rotational speed and hence in supply of propellants that might occur at greater altitudes as a result of the fall in atmospheric pressure. It is well-known that if a suitable nozzle is fitted the pressure ahead of the throat and in the throat plane does not fall as the external pressure decreases once the nozzle chokes. With the full propellant mass flow rates the required combustion chamber pressure of an average p_1 ~ 15 atm. is generated, corresponding to an average thrust S of 25.4 tonnes. The vehicle then lifts off from the launch platform and the flight begins.

Operations during flight

A small amount of liquid oxygen is extracted from the main line at valve (21) and passes through line (n) via a non-return valve (35) and a pipe coil (36) to be vaporised in the oxygen vaporiser (34). The vapour passes via line (o) into the oxygen tank and holds the pressure constant at an average of ~ 1.5 atm. The valve (18) is configured such that on average a tank pressure of 2 atm. is not exceeded. During flight the fuel tank obtains its pressure differential by means of a stagnation pressure line from the nose, solenoid valve (37) maintaining open the stagnation pressure valve (38).

Combustion shutdown

Approximately 3 seconds before the actual combustion shutdown the 25 tonne valve (32) is closed by actuation of solenoid valve (33). As a result the thrust reduces from 25 tonnes to ~ 8 tonnes, so that by means of a lower acceleration in this phase of the flight a more exact combustion shutdown can be obtained at the desired point in the flight path. This means that the vehicle has a more exact final velocity. The correct combustion shutdown point is defined by the integration unit. This is equipment that measures the velocity over the trajectory and at a particular value of final velocity switches and closes the 8 tonne valve (31).

At the combustion shutdown point the alcohol upstream valve (14), main valve (23), oxygen main valve (21) and pressure differential valve (27) of the vaporisation plant are all closed. All gas venting valves remain closed.

During the last section of the flight path the stagnation pressure valve (38) is closed by means of the solenoid valve (37). The high-pressure solenoid valve (39) opens and N_2 pressure is fed via a restrictor to the fuel tank. This measure prevents the collapse of the fuel tanks when the vehicle re-enters the atmosphere during its descent.

The complete propulsion unit, without propellant tanks, as it is actually assembled and installed in the tail section, is shown in Fig 69a. The most important components, insofar as they can be discerned in this figure, have been annotated so that the fundamentals can be extracted.

To conclude this section a listing of weights can again be provided:

Combustion chamber	~ 425 kg
Turbo-pump	~ 160 kg
High-pressure storage bottle	~ 75 kg
Vaporising plant	~ 73 kg
Thrust frame	~ 57 kg
Pipework and valves	~ 140 kg
Total	~ 930 kg
Fuel tank	~ 75 kg
Oxygen tank	~ 120 kg
	~ 195 kg
Complete engine unit	~ 1125 kg

This produces 25.4 tonnes of thrust for 1.125 tonnes of machinery, ie ~ 22.6 tonnes thrust / per tonne of propulsion unit weight. Alternatively this can be expressed as 1 / 22.6 = 0.044 tonnes / tonnes thrust or 44 kg of propulsion unit weight / per 1000 kg thrust.

Control system

The control system used in the A4 (V2) was not the result of a simple self-contained system development by one company. Rather it was developed by the control systems department of the Army Test Establishment at Peenemünde under the direction of Dr Steinhoff and assembled using individual items of equipment developed both internally and by companies.

In overall terms the control system comprised:

2 batteries (on-board and command transmitter batteries)

2 converters with three-phase frequency regulation

2 gyroscope systems (horizontal and vertical)

1 signal mixing unit and amplifier

4 rudder vane units with potentiometers and exhaust stream vanes

2 trimming motors

1 timing system.

A schematic for the control system can be seen in Fig 70.

A lead accumulator with a rating of 32 volts and 100 amps with ~ 5 minutes power extraction was used as the on-board battery, and a nickel-cadmium accumulator with a rating of 50 V and 300 mA with the same period for power extraction was used as the command transmitter battery.

Control of the rocket was effected by means of 2 gyroscope systems (horizontal and vertical) driven by a 3-phase converter with a regulated frequency of 500 cycles per second. The gyroscope system potentiometers were fed from the command transmitter battery. The control signals from the potentiometers were converted and amplified by a signal-mixing unit into resultant voltages that were supplied to the rudder vane units.

A sketch of the configuration of the vane units with their linkages to the carbon and trimming vanes, and also the trimming motors, can be seen in Fig 71.

The outer aerodynamic trimming vanes in plane (1 + 3) are directly connected to the carbon vanes via chains and levers. The outer trimming vanes in plane (2 + 4) (the longitudinal plane) are not coupled directly to the carbon vanes. The trimming vanes in plane (2 + 4) are driven by separate trimming motors. They are activated if the trimming vanes in plane (1 + 3) (the lateral plane) are no longer operating in synchronisation. In this event the trimming vanes in plane (2 + 4) (the longitudinal plane) can be called upon to provide the control to remove spin. In general these outer trimming vanes were only used for this purpose of controlling spin.

The timing system has the task of providing certain commands, and actuating valves. In particulars it provides the control commands that, with the help of a unit in the horizontal gyroscope system, control the vehicle into the flight path.

The vertical gyroscope system monitors spin and lateral control (plane (1 + 3)) and the horizontal gyroscope system monitors altitude control (plane (2 + 4)). The two systems are driven by the on-board battery via the converter with frequency regulation (500 cycles per sec), the rotational speed of the gyroscopes being approximately 30,000 rpm.

The sketches in Fig 72 show the two gyroscope systems (vertical and horizontal). The gyroscope axes are monitored by a gravitational pendulum and held in their null positions. For this purpose servomotors (a) and (b) are provided at the ends of the axes. The ends of the axes are fitted with rotors surrounded by windings (stators). In the event of a deviation of a gyroscopic system from the null location a current controlled by the gravitational pendulum passes through the windings. This produces an electrical field and hence a torque on the rotor whose effect is to oppose the deviation of the gyroscopic axis.

Each movement of the vehicle from this null location represents a deviation by the gyroscopic axes and is registered by the corresponding potentiometer. The voltage differentials that arise are converted in a signal mixing unit and amplifier into signals that can be used for control purposes. The resultant voltages thus obtained are fed to the rudder vane units. The signal mixing unit and amplifier is a purpose-built circuit of resistances, condensers, transformers, amplifying valves, etc, in which monitoring and amplification of the pulses from the potentiometers is undertaken.

For the vehicle's turning schedule a disk was fitted on the horizontal axis of the gimbal ring of the horizontal gyroscope system. This disk carried a potentiometer. By means of a small motor the potentiometer was rotated via a worm gear under the pick-up. This generated a voltage in the potentiometer that was fed via the mixing unit to the vane unit for plane (2 + 4), and thus turned the vehicle into its flight path. In practice turning was completed after an average of 45 seconds.

A functional schematic of the vane unit can be seen in Fig 73. The vane unit consisted essentially of the small electric motor on whose axis sat a gear pump. The gear pump had two contra-rotating gears so that two supply paths were formed. The motor was located above the oil tank. Two passages lead to the gear pump. Each divides behind the gear pump into a return circuit via a small control valve (1) and (2), and into a passage that leads directly to a piston connected to the drive to the exhaust stream vane. In each of the supply lines is fitted a safety valve that opens at about 40 atm and redirects oil back to the tank. The stroke of the piston is about 55 mm, corresponding to a rotation of the exhaust stream rudder vane of about 90°. The control valves (1) and (2) are connected via a pivoted lever to a coil-magnet system.

In the null setting of the vanes this lever is held in a position that means the oil pump is supplying to both sides evenly, because on either side the oil is led back at equal rates to the oil tank (see Fig 73).

If the vehicle deviates from the prescribed flight path, then the resulting current pulse from the signal-mixing unit is sent to the magnet coil of the vane unit. The position of the pivoted lever is altered and thus the settings of valves (1) and (2) (see Fig 73 [lower] – setting providing movement of the vanes). As can be seen in this example, valve (1) closes the return line so that the amount of oil supplied impinges on the one side of the piston more strongly. The amount of oil displaced on the other side of the piston is directed back through the open valve (2) to the oil tank, as is the oil supplied on this side of the pump. In this manner movement of the exhaust stream vane is produced. In very general terms it can be said in summary that using small control pulses small, pilot, control valves can be moved. The latter control an oil power circuit enabling the exhaust stream vanes to execute defined movements to correct the orientation of the vehicle during flight.

As can also be seen in Fig 71, a potentiometer sits at each end of the exhaust stream vane bearing arrangement. The potentiometers in the plane (2 + 4) (the longitudinal plane) monitor via the signal mixing unit and amplifier the synchronisation of the two exhaust stream vanes for the altitude control system.

In plane (1 + 3) (lateral plane) the potentiometers monitor any deviations from synchronisation of the rudder vanes in this plane. They also provide a command via the signal-mixing unit to the trimming motors in plane (2 + 4). This is to off-load the movements to counteract spin by the trimming vanes and exhaust stream vanes in plane (1 + 3), if a more pronounced vehicle spinning motion occurs. The trimming motors with gear ratios of 3000 : 1 are only fitted in plane (2 + 4) and drive the trimming rudder vanes in this plane via a chain drive.

With these general remarks I will conclude my descriptions of the main individual modules of the A4 vehicle.

Fig 74 shows an assembly drawing of the A4 (V2) vehicle, including the main dimensions and the distribution of the vehicle into its modules with approximate weights. A short performance summary completes the general data.

At locations (a) on the vehicle (see Fig 74) insulation inserts (Turbax) were installed in the tail fins. These held the receiver antennae for the command receiver. The command receiver was fitted in the control system nose section (see Fig 74 - electrical equipment sector). This received electrical signal pulses from the ground transmitter. In this manner it was possible to transmit a combustion shutdown command from the ground. In situations in which the vehicle was threatening to break away from the defined flight path the propulsion system could be shut down by transmission of this command from the ground.

In the section on the propulsion unit I have already mentioned that the final velocity of the vehicle at the combustion shutdown point in the flight path could be determined by means of an integration unit. The unit was able to give the combustion shutdown command at the correct point in time for the 8 tonnes stage. Two types of integration unit, IG1 and IG2, were used.

IG1 used a heavy gyroscope in which the moments occurring as a result of the longitudinal accelerations lead to precession. The relationship is such that the precession velocity corresponds to the moment, and the rocket velocity corresponds to the angle of rotation of the gyroscope caused by the precession. The final velocity required for the particular range in question can thus be pre-defined by means of a contact that switches when the correct precession angle has been achieved. In practice the device was fitted with two contacts, where one switched off the main stage, and the other the primary stage.

IG2 used an acceleration-sensitive mass system with an electro-thermal integration utilising the change in potential of a polarised cell that defined the desired switch off point in time.

For the purposes of improving the lateral control of the vehicle a technique using directional electromagnetic radiation was developed. This generated an electromagnetic plane of symmetry, perpendicular to the earth and passing through the launch site and target, in which the path of the rocket could be maintained. A signal transmitted from the ground using suitable aerials was received via the rod or loop antennae in the tail of the vehicle and passed to the on-board receiver that transmitted the pulses or signals onward as a control voltage to the signal-mixing unit. From here the amplified pulses were passed to the vane units of plane (1 + 3). As a result of appropriate settings of the exhaust stream vanes the vehicle could be maintained in the plane of the directional radiation.

To measure the velocity of the vehicle during flight a direct velocity measurement technique was developed based on use of the Doppler effect. The technical principle is outlined as follows. A frequency transmitted from the ground was doubled on board the vehicle in a frequency doubling unit and transmitted back to the ground. On the ground it was compared with a frequency that had similarly been doubled and a difference tone was generated. The frequency of this difference tone was a direct measure for the velocity of the rocket relative to the ground transmitter.

Fig 74 shows a cross-section through the control equipment nose section, from which it can be seen in which sectors the individual devices and items of electrical equipment were installed.

Movement of the A4 (V2) vehicle was by means of a Meiler transporter – see Fig 76. The Meiler transporter (known as a 'Meilerwagen') consisted of a strong frame structure with a solid axle at the tractor unit end. The rear end was configured as a twin-axle bogie. A pivoting jib was positioned above the frame. The rocket vehicle was attached to the jib at two locations using clamps. The pivoting jib together with the rocket vehicle could be moved from the horizontal to the vertical position. This movement was performed using an oil-based hydraulic system. A petrol engine was coupled to an oil pump that circulated the oil. By means of a hand-wheel valves were actuated to direct the circulating oil into a telescopic system of pistons that executed the jib movement. During transport the jib and the rocket vehicle were located in the horizontal position.

The total length of the truck was approx 14.45 m

The total width of the truck was approx 2.75 m

The total height of the truck was approx 3.25 m

and the weight of the truck was approx 11.3 tonnes

The transporter had no drive unit of its own and was moved by means of a tractor unit.

The launch of the vehicle took place from a platform, see Fig 76 [inset]. The platform consisted of four strong columns with footplates. Each column could be moved vertically up or down to adjust its height and hence the horizontal orientation of the plate fitted above the columns. On this plate was a ring in which were located the supporting surfaces of the four vehicle fins. This ring was supported on a ball bearing race and could by rotated by means of a hand lever via gearing. At the base of the platform there was another boiler-plate structure configured as the deflection chute for the exhaust gas stream. On the rotating ring were fitted the electrical cable mast, the five pipe connectors (for operation of the propulsion unit before launch as described with reference to Fig 69), and the oxygen tanking shut-off valve. A valve chest was also located on the fixed plate. This contained a operating console with valves that enabled a check to be made on the operation of the vehicle's propulsion control system before the launch.

The launch platform was not moved on the Meiler transporter. To move the platform a single-axle chassis could be pushed underneath and used for this purpose.

When the launch site had been selected the Meiler transporter with the rocket vehicle was driven to the site, as was the platform. The latter was unloaded and erected at the tractor unit end of the Meiler transporter. Using the oil hydraulics system the rocket vehicle was raised into the vertical position (see Fig 76). After releasing the rocket vehicle clamps, which was carried out on the ground by rotating the linkage via a hand wheel, the rocket vehicle was set down on the support surfaces of the rotating ring on the platform and prepared for launch.

There followed the checking of the propulsion unit, the control system and all the electrical components. Two platforms on the jib of the Meiler transporter enabled work to be done on the vehicle, the lower platform providing access to the propulsion unit and the upper to the control system module.

The launch of the vehicle was directed from a tank, which was fitted with one operation console for the propulsion unit and another for the control system. From the launch control tank two cables led via the cable mast and two connectors in the plane 2 fins into the control equipment nose section (see also Fig 74). The two connectors included all the cables that were necessary for checking and operation of all equipment before launch. The two connectors were retained electromagnetically, and at the appropriate point in time ahead of launch they were separated from the vehicle by spring forces after the electromagnetic field had been switched off. Power for the checks and for spinning up the gyroscopes ahead of launch was provided by a ground power source and only shortly before launch was the switch made to the on-board battery. Shortly before launch the Meiler transporter was driven away so that at the launch site there remained only the rocket vehicle, standing on its platform; and at some distance the launch control tank that was connected to the rocket vehicle by electrical cables. It would be excessive to describe in more detail all the preparations and checks that were necessary for the launch within the compass of this monograph, since this would require many more pages. To conclude this section I can just state that preparation activities including the loading of the propellants etc required an average of 20 – 30 minutes.

At this point I should return briefly to the ignition of the propellants in the combustion chamber.

Four pyrotechnic igniters were used to form the ignition system. As shown in Fig 77b these were installed tangentially into a star-shaped body formed out of plastic. This star-shaped body had a bore into which was inserted the holder for the igniters. The holder was a tube through which the ignition cables were led from the igniters to the valve chest (see Fig 77a).

When the ignition system was switched on current flowed through the four ignition cables to the firing unit in each of the igniters. Ignition took place and the powder charge was set alight. The combustion gases generated left the igniter through a hole in the cap. As a result of the tangential configuration the ignition system was set in rotation so that a disk of hot combustion gases was generated[25]. This filled the diameter of the combustion chamber. To be sure that all four igniters burnt without fail a spiral spring was fitted around the igniter star. At one end this was connected to a thin wire and at the other end to the rotating cross by a peg. The thin wire was used as a current bridge. When the igniters were set alight and started to rotate the spiral spring was placed under tension until the force generated fractured the thin wire (current bridge). This triggered a contact that indicated that the igniter was working and that the first stage of combustion could be switched in. If one or two of the igniters failed in the ignition process the tangential forces generated by the exhausting gases from the remaining two or three igniters were insufficient to fracture the thin wire (current bridge). Thus no command was given to indicate that the vehicle's propulsion system could be switched on.

The weight of the ignition system was ~ 1.5 kg. The burn time was on average 10 seconds and the time from start of combustion to fracture of the thin wire (current bridge) was ~ 2.5 seconds. The rotational speed of the ignition system was ~ 400 rpm and the flame temperature of the combustion gases ~ 1400 °C.

On the 6 July 1942 the first A4 was ready for launch. It lifted up a short way from the ground, fell back and was destroyed. Four weeks later launch No 2 took place. On this occasion the propulsion system operated for 45 seconds, then a fault developed and the vehicle broke apart.

On the 3 October 1942 the first successful launch took place with combustion shutdown after 63 seconds. The flight path was along the Pomeranian coast and the vehicle achieved a range of 190 km. The apogee was at a height of approximately ~ 85 km.

The next vehicle was also a success but its point of impact could not be traced. There followed a number of vehicles that were unsuccessful. Of a further 80 test vehicles launched there were only 30 failures.

In Fig 78 are shown a number of photographs of A4 launches from test facility 7.

This monograph cannot be said to be complete without some comments concerning the test facilities that we had at our disposal. For testing of the A4 vehicle two test facilities, (I) and (VII), were available

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[25] *This device can be likened to a Catherine wheel.*

whose structure and size were unparalleled in the whole world in the field of rocketry. With reference to personnel safety in the vicinity of the test facilities, the functionality of the buildings and regulations as planned and provided also demonstrated the correctness of the measures adopted. During the whole development programme not a single death was recorded that could be traced back to an accident during development activities. This is a very remarkable result when one remembers that in an extensive test programme involving the handling of large quantities of propellants and thousands of tests the potential for danger was present on each occasion. During the same development programme countless explosions and destructions of rocket vehicles were recorded.

In the following paragraphs I must now give a short overview of the test facilities that existed at Peenemünde, with some brief details concerning the purposes to which they were put. I will go into greater detail concerning the two important test facilities, I and VII, to provide interested parties with an indication of their structure and size.

Test facility I:
Testing of the 25 tonne combustion chambers and complete A4 vehicles.

Test facility II:
Testing of combustion chambers and propulsion units for the A5. For its layout and structure see Fig 55.

Test facility IIa:
Tower-shaped structure for the supply of propellants by means of a pump to the A4 propulsion unit. In the structure the propellant tanks were vertically positioned one above the other so as to reproduce the conditions that would later be present in the A4 vehicle.

Test facility III:
Testing of combustion chambers developed by the Ministry of Aviation. Horizontal firing of combustion chambers. (Fig 78a)

Test facility IV:
Testing of propulsion units for development in the Ministry of Aviation sector, such as units for the V 112 and take-off auxiliary units for aircraft.

Test facility V:
Propellant supply system testing (including injection system testing) on complete A4 propulsion units including combustion chambers. The testing was focussed on determining propellant mass flow rates required.Test facilities for testing of the turbo-pump and the peroxide vapour generation plant.The test facility comprised a tall building in which 2 or 3 A4 vehicles could be suspended vertically. From individual floors access was possible to the particular vehicle components of interest in the propellant supply tests. The operation and observation cells were installed in adjacent rooms together with the necessary measurement equipment.

Test facility VI:
Testing of complete A5 vehicles with reference to propulsion units and control systems. See Fig 56 for the layout and structure.

Test facility VII:
Testing of complete A4 vehicles with reference to propulsion and control systems. Launch site for testing of firing sequence.

Test facility VIII:
Testing of combustion chambers, in general up to 25 tonnes thrust with turbo-pump supply. This was in contrast to Test facility I, in which the supply of propellants was generated by N_2 driver gas from large pressure vessels. The test facility consisted of a rigid firing scaffold, of solid iron construction, for reception of the combustion chambers. The firing stand had a water-cooled gas deflection chute followed by a walled gas exhaust passage of fireproof stonework. The observation and operation cell was located some distance away. This was a concrete building with 2 floors. In the lower floor was located the measurement cell and above it the observation and operation cell. In front of this building was located the pump house with all the pipework and valves. During assembly activities on the firing stand a mobile housing of appropriate size was driven on to the firing stand. This was removed during the actual testing so that the firing stand was free standing.

Test facility IX:
Testing of the propulsion systems and equipment for the Ministry of Aviation C2 development (Wasserfall) using hydrocarbon and nitric acid propellants.

Test facility I
This test facility was built for testing of the 25 tonnes thrust combustion chambers and complete A4 vehicles. Fig 79 shows the test facility in cross-section. Fig 79a shows the ground plan view and in Fig 79b one can see a photograph of the test facility.

The test facility was built on a large concrete base (35 x 30 x 20 m). At the front was located the water-cooled exhaust stream deflection chute (A). This featured a system of water pipes with inlets and outlets supplied by a dedicated pump house. The extension of this chute was in the form of an open gas exhaust channel (B) made of fireproof stonework. This channel possessed a fluid collection pit in which any fuel flowing out of the combustion chamber could be collected. This gas exhaust system also featured a foam extinguisher facility (P) for safety reasons in the event of fires occurring as a result of combustion chamber explosions. The fluid chemicals and driver pressure provided by a set of N_2 storage bottles required by this extinguisher facility were installed in the so-called fire extinguisher cell (D). Above the deflection chute (A) stood the firing scaffold (E) on to which the combustion chamber (F) was attached by means of a suspension system. The higher frame (G) standing adjacent to the firing scaffold served to receive the complete rocket vehicle suspended in gimbal rings. The firing scaffold stood in a test house (E) that was configured so that all 3 side walls (I) could be lowered into shafts (K). The front wall (L) was lifted upwards like a roller shutter. The objective of this design feature was that during combustion tests the firing scaffold would be left free-standing on the concrete block. Thus in the event of an explosion no great amount of destruction would occur and no build up of pressure would be generated. Above the test house was located a travelling crane track (M) along which a crane platform (N) and, separately, a protective housing (O) could both be driven. When preparation activities were in progress on the test facility the side walls of the test house were in the up position and the crane platform (N) and protective housing were located above the test house (H) so that the personnel could work while protected from the weather. The crane platform (N) was equipped such that a complete combustion chamber unit could be transferred from a railway wagon in front of the test facility and transported to and suspended from the firing scaffold (E). A mobile assembly platform (EF) enabled all necessary activities to be conducted on the combustion chamber.

Inside the concrete block, behind the combustion test rig there was a cell (Q) in which a large number of N_2 high-pressure bottles were installed. This set of high-pressure storage bottles supplied the nitrogen to drive the fluids out of the propellant tanks. Immediately behind a strong concrete wall was located the observation cell (R) and below this the measurement cell (S). In these observation and operations bunkers were installed the manually operated valves (T), the control consoles (U) and the observation periscopes (V). In front of the observation bunker (R), in other words in the high-pressure bottles cell, were located all valves and associated fittings (W), these being accessible via a ladder and platform (WP).

On the one side, near the observation bunker (R), was located the liquid oxygen cell (X) with the O_2 tank (XB), mounted on a railway wagon. This stood on a weighbridge (XC) with a gauge display (XD) by means of which the O_2 rate of consumption could be measured.

On the opposite side, near the observation bunker (R) was located the fuel tank cell (Y) with the fuel tank (YB) on a railway wagon. The rate of fuel consumption was, as for the oxygen, measured by means of a weighbridge and gauge display. The capacity of the tanks was on average 10 cubic metres. The fluid lines (~ 125 mm internal diameter) were connected by jointed pipes to the propellant tanks to enable the weight measurements to take place. In spite of these propellant supply configurations, with large propellant tanks mounted on railway wagons and long supply lines with various joints, the errors made in propellant rates of consumption were no larger than ~ 1 %[26].

Thrust measurement was similarly achieved using a measurement wagon system and a gauge display (Z) of approximately the same type as for the quantities measurements.

In combustion chamber tests the observation and operations cell (R) was used. When testing complete vehicles on the other hand the use of the cell was no longer permitted for safety reasons. For this reason a further observation and operations bunker was located at a distance of ~ 90 m in the direction indicated by the arrow in Fig 79a. This bunker featured six movable periscopes, and the whole of the propulsion system facility was operated and observed from here. On account of the simplicity of its structure this bunker is not shown separately.

Test facility VII

Test facility VII was built exclusively for the testing of complete vehicles and anticipated the possibility of investigating vehicles of up to 100 tonnes thrust.

The layout and extent of the test facility are shown in Figs. 80, 80a and 80b. It included a firing stand (A) with an open water-cooled gas deflection chute. The firing scaffold (B) was configured to be mobile. Around the firing stand was located a massive sand embankment (12 m high) that shut off the danger zone (C) from the rest of the site. At a distance of ~ 100 m from the firing stand the observation and operations station (B) was installed in the sand embankment. It included the actual observation and operations cell (Da), from which observation took place through periscopes. In this cell were installed all the control consoles and equipment necessary for operation of the complete rocket vehicle, including the testing of the control

[26] *This represents a considerable refinement of technique – values such as this are not readily obtained with cryogenic propellant feed systems.*

system on the stand. From this bunker there was access through a sealable double door (Db) into the testing zone (C). Near the observation and operations bunker (Da) was the measurement bunker (Dc). Here stood the measurement panels with all instruments and electrical equipment that were necessary for measurements during testing. It also featured three periscopes from which the vehicle could similarly be observed during testing. (Dd) was the welfare room, (De) the storage room, (Df) the room for the test facility engineers, (Dg) the workshop, and (Dh) a passage that enabled heavy equipment and test units or similar to be brought into the testing zone (C) on trucks.

The observation and operations bunker (D) was connected with the firing stand (A) by means of a cable conduit (E). Similarly a cable conduit (F) led to the N_2 high-pressure storage bottles room (G) and to the assembly hall (H). In the vicinity of the firing stand, built into the sand embankment, was located the pumping station (I) with a number of water collection tanks, from which was supplied the cooling water for the gas deflection chute on the firing stand.

The sand embankment had at one point an opening, through which the firing scaffold (B) could be driven on a mobile platform (K) into the hall (H).

Fig 80a shows test facility VII as seen in direction (A), Fig 80. Two firing scaffolds (B) could be driven into the assembly hall (H) to carry out preparation activities on the vehicle for the firing tests. After these activities had been completed the prepared vehicle, suspended in the firing scaffold, was driven onto a mobile platform (K). The mobile platform (K), which was fitted with an electric drive, brought the firing scaffold (B) with the vehicle up to the entrance into the testing zone (C). From this point the firing scaffold (B) travelled using its own electric drive from the mobile platform down to the firing stand.

In the assembly hall (H) assembly frames (L) were fixed on to one of the long walls. In these the complete rocket vehicles arriving from the workshop were made ready for testing. In the buildings adjacent to the assembly hall were located workshop, store and accommodation for employees in the test facility area.

Fig 80b shows the firing stand and the firing scaffold. The firing stand consisted of a massive concrete block that contained the exhaust gas channel (a) (7.7 x 40 m). In the middle of the firing stand was located the water-cooled gas deflection chute (b). Near the firing stand on both sides were the cable and pipework conduits (c) in concrete with cross sections of 4 x 5 m. In these conduits were located the water supply and removal pipes, that connected the exhaust deflection chute (b) with the pumping station, and all electrical cables.

The movable firing scaffold (B) consisted of a strong framework structure (16 x 17 m) made of steel. The main profile of the framework was ~ 2 m high, and served to receive the eight wheels. The load on each wheel was ~ 12.5 tonnes. On the framework stood 4 strong columns of iron construction that were approximately 13 m high. The ends of these columns formed a rigid platform, in the centre of which it was possible to suspend the rocket vehicle via gimbal rings (d). The attachment and stiffening structures were configured to be strong enough to accommodate a thrust of 100 tonnes with the vehicle in either a vertical or a horizontal orientation. On the platform stood the assembly housing (e) providing weather protection for the personnel. Doors were fitted at the sides to allow the vehicle to be introduced and suspended. Similarly movable flaps (f) were fitted in the platform that when opened provided sufficient space for rotation of the vehicle into the horizontal position. (Simulation of the turning of the vehicle into a flight path with a 45° angle was also possible on this stand). Between the lower frame (g) and the upper platform an assembly lift (h) could be moved upwards and downwards for the purposes of accessing each section of the vehicle when preparing for testing. In this lift (h) ran an assembly platform (k) that could be moved to from side to side by a hand-crank operated drive. On one column of the firing scaffold there was also a lift (M) that could transport 5 people, enabling the movable platform (k) or the upper platform in the assembly housing (e) to be reached. It was however also possible to reach the platforms via a ladder (N).

The weight of the total mobile firing scaffold (B) amounted to ~ 100 tonnes. The drive was provided by an electric motor of ~ 90 HP and the driven speed was an average of 35 m/min.

The main dimensions entered in the figures give a measure of the size of the test facility.

In conclusion to my descriptions of the two test facilities I and VII I must add that I have attempted to give the reader a certain overview of the extent and size of the test facilities. This has been with the aid of a number of figures with main dimensions annotated, but these figures are not able to provide a true representation of the actual size and dimensions of the facilities. The actual size and magnitude of these test facilities can only be truly appreciated by someone who has actually seen them.

In conclusion Fig 81 shows the location of the Peenemünde site in Northern Germany with data regarding the launch sites and measurement sites for tracking of the vehicle during flight.

In Fig 82 the Army Test Establishment at Peenemünde can be seen on a larger scale with individual areas annotated. There follows a list of the most important buildings and development areas as well as the test facilities:

1	Administration building	
2	Wind tunnel	
3	Component building	
4	Assembly building	
5	Large measurement house	
6	Test facility workshop	
7	Material testing	
8	0_2 plant	
12	Canteen	
11		
13	Overnight accommodation for salaried staff	
14		
15	Central entrance with security and garages	
10	Commandant's headquarters	
17	Living accommodation and garages	
18	Storage area	
19	Small measurement house	
20	Test facility I	A4 combustion chamber
21	Test facility II and IIa	
22	Test facility III	Take-off assistance
23	Test facility IV	Rocket propulsion for aircraft
24	Test facility V	A4 test facility
25	Test facility VI	A3 test facility
26	Test facility VII	
27	Test facility VIII	
28	Test facility IX	
29	A4 (V2) launch site	

With this my description of rocket development from the beginnings with Max Valier up to the A4 (V2) vehicle can be concluded.

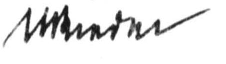
Approximately 12 years of development were necessary, beginning with the tests with the blowlamp, to develop the A4 vehicle into a practical vehicle. This was without question the greatest success in the technical development of German rocketry, and nothing similar could be claimed by any other nation. It is, however, also without question that this success was not achieved without a certain cost.

This monograph has been kept brief, in accordance with the nature of the task, and describes only the fundamentals. In the course of this writing it has not been possible to describe the many related activities that only when brought together would truly reproduce the extent of the designs and developments that took place. Perhaps we will have to wait until a later date when Dr Wernher von Braun may be able to report on the complete technical story in a more detailed format.

In the Foreword to this monograph I dedicated the remarks I have made here to the memory of Max Valier. I cannot conclude without naming two men who brought to fruition that which was denied to Max Valier. These are Dr Walter Dornberger, Head of the Army Test Establishment and a most enthusiastic patron of rocket development, and Dr Wernher von Braun, as the Technical Leader of the Peenemünde project.

The team of colleagues at Peenemünde brought to fruition the first guided, long range, rocket powered by liquid propellants. They thus undertook a step that now makes it seem possible to think of space travel by means of projectiles driven by propulsive thrust.

If the path followed is considered with hindsight, then it can be said: *"If it has been trouble and hard work, it has also been hugely enjoyable,"* and all those who have contributed to this activity, the many unnamed, beginning with the simplest craftsman and moving up to the scientists, can look back with a certain pride and satisfaction on their achievements. They have all through their working capabilities contributed to bringing to fruition this unique technical achievement.



Westcott, near Aylesbury den 9. Okt. 1950

Walter Riedel
Westcott, near Aylesbury
9 October 1950

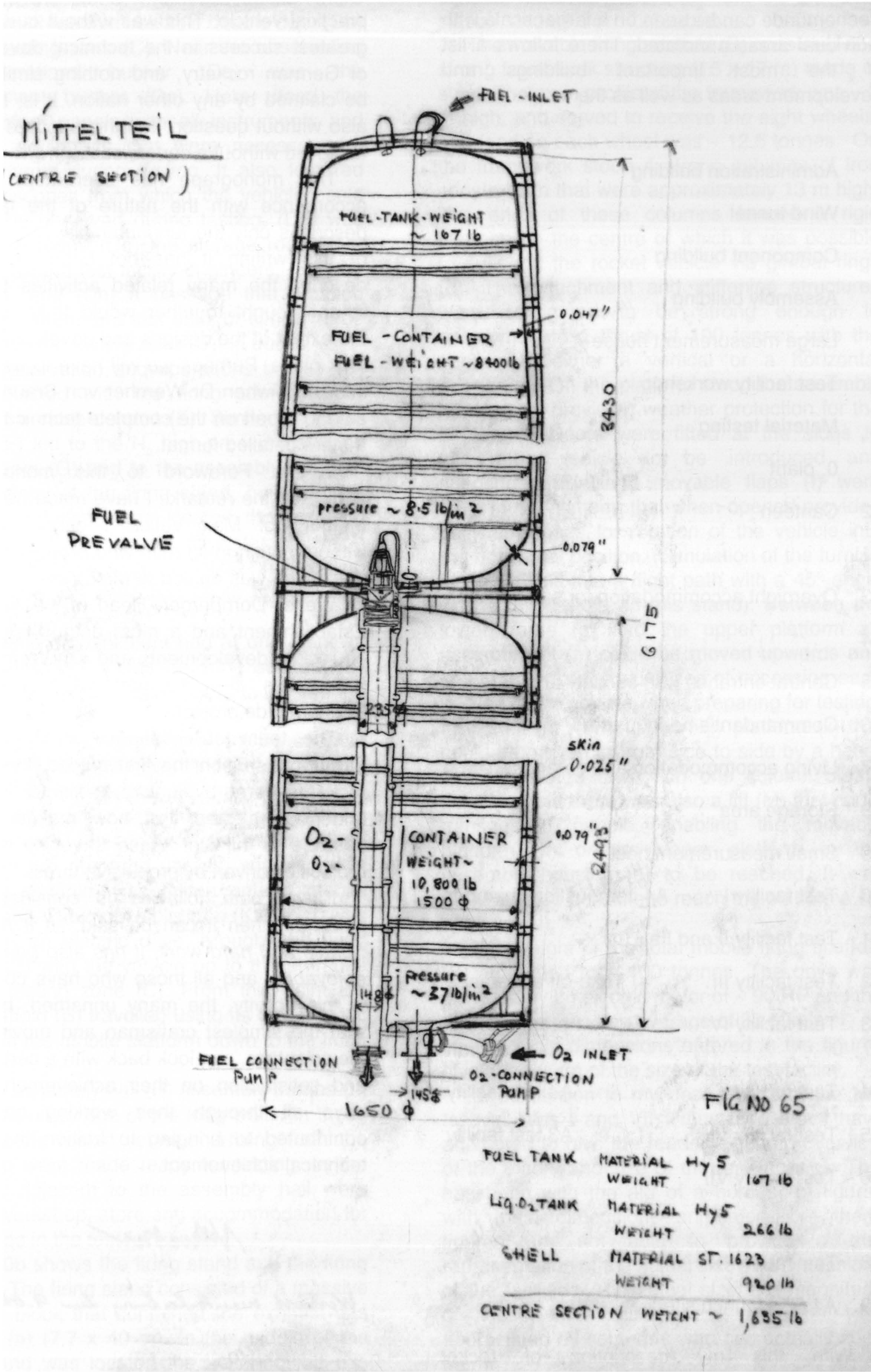


Fig 65: Centre section (Thin-walled propellant tanks)

Fig 66: A4 turbopump assembly

Abdampf-Kasten	exhaust steam chest
Alkohol-Pumpenrad	alcohol pump rotor
Austritt Alkohol	exit for alcohol
Austritt flüss. O_2	exit for liquid oxygen
Dampf-Eintritt Verteiler	inlet steam distributor
Eintritt Alkohol	inlet for alcohol
Eintritt Dampf	inlet for steam
Eintritt flüss. O_2	inlet for liquid oxygen
Leckleitung	leakage line
Pumpen-Schnellschluss	fast-acting pump shut-off valve
Sauerstoff-Pumpenrad	oxygen pump rotor
Turbinenrad	turbine rotor
Wellen-Kupplung	shaft coupling

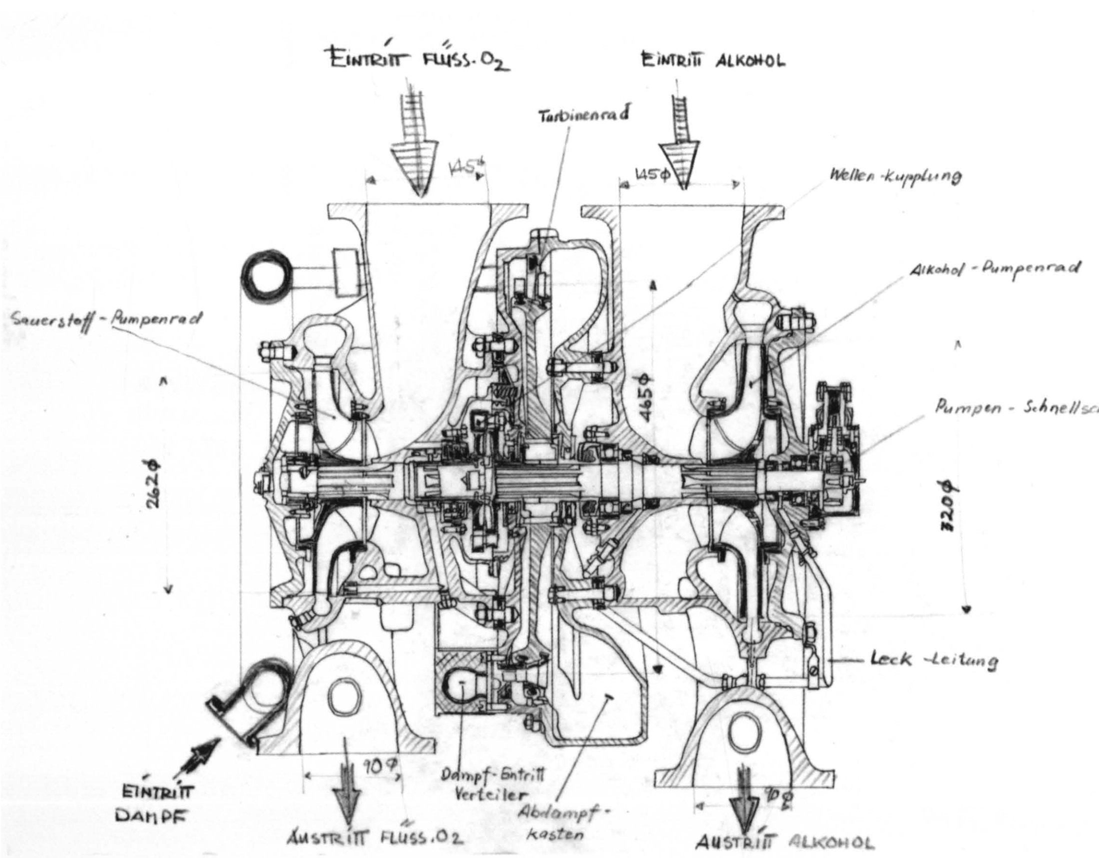


FIG NO 66

Fig 67

27% Kalium-Permanganat Tank	27% potassium permanganate tank
7 Flaschen a 7 Ltr.	7 bottles, each of 7 litres capacity
82% H_2O_2-Tank	82% H_2O_2 tank
Auswaschanschluss	washing connector
Auswaschanschluss u. Ltg.	washing connector and line
Dampferzeuger	steam generator
Dampf zur Pumpe	steam to the pump
Entlüftung H_2O_2 Tank	vent for H_2O_2 tank
Entlüftung Kal-Permanganat Tank	vent for potassium permanganate tank
Filter	filter
Füllung ~11 Ltr.	capacity ~11 litres
Füllung ~126 Ltr.	capacity ~126 litres
Füllung N_2-Gas v. d. Boden-station	N_2 gas filler line from the ground station
Füllstutzen	filler pipe
Gasablassventile	gas release valves
Hand-Absperrventil	manual shut-off valve
Haupt-Peroxyd valve (25 to)	main peroxide valve (25 metric tons)
Ltg K	line K
Membrancontakt	membrane contact
Neben-Peroxyd valve (8 to)	auxiliary peroxide valve (8 metric tons)
Reduzierventil	reducing valve
Sicherheitsventil	safety valve
v. d. Hauptbatterie	from the main bottle bank
z. d. Hauptbatterie	to the main bottle bank
zur Triebwerkseinheit	to the engine

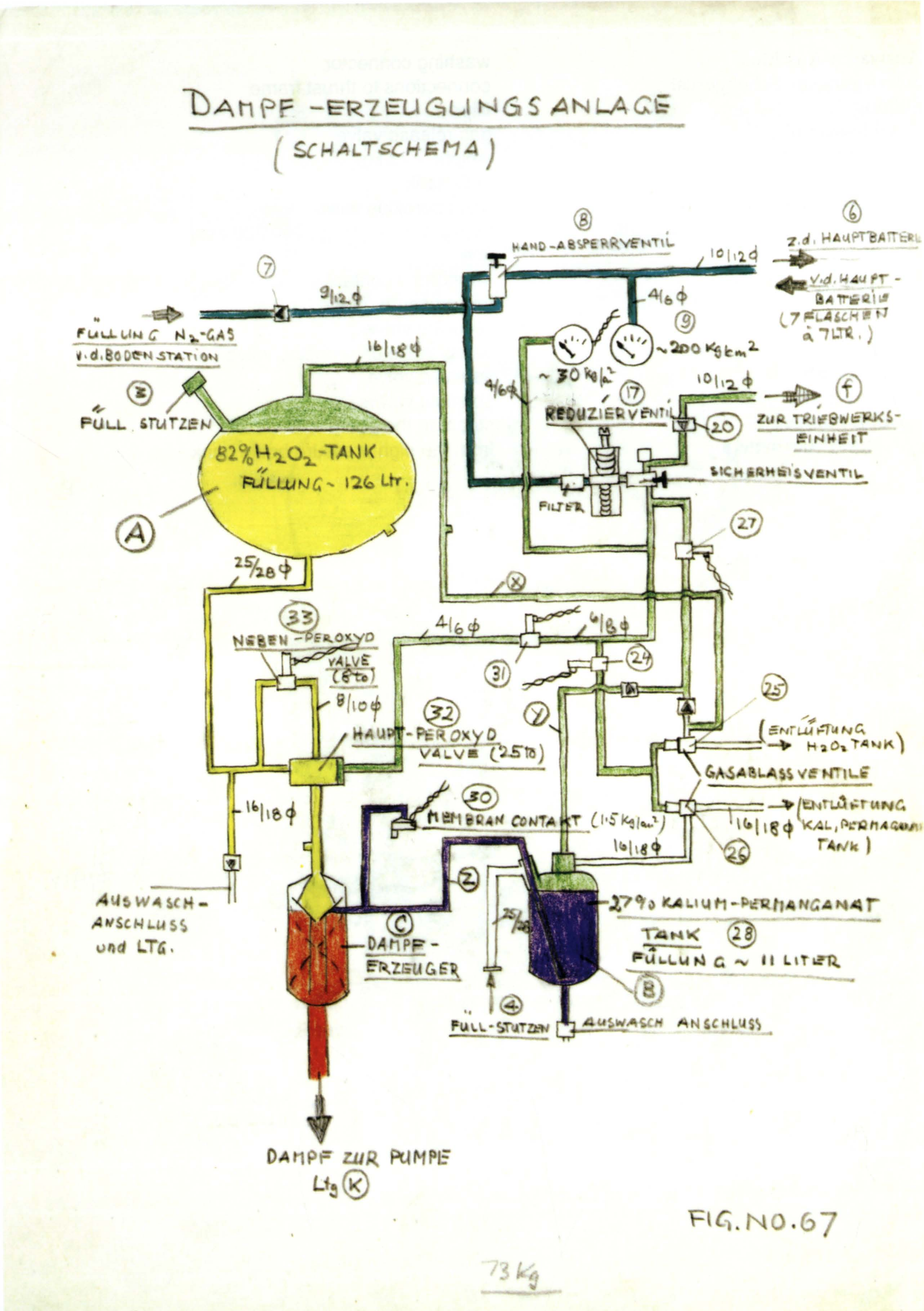


Fig 67: Steam generation equipment (schematic)

Fig 67A

Auswasch-Anschluss	washing connector
Befestigung am Schubgerüst	connections to thrust frame
Füllung	filler
Gasablassventil	gas release valve
Gewicht ~ 73 kg	weight ~ 73 kg
H_2O_2-Tank	H_2O_2 tank
Haupt-Peroxyd valve	main peroxide valve
Hochdruckmanometer 200/220 atü	high pressure gauge 200/220 atm
Ltg.	line
Membran-Contakt	membrane contact
Niederdruckmanometer 0-60 atü	low pressure gauge 0-60 atm
Reduzierventil	reducing valve
Sicherheitsventil am Reduzier-ventil	safety valve on reducing valve
Solenoidventil	solenoid valve
Solenoidventile	solenoid valves
Steam z. Pumpe	steam to the pump
v. d. Hochdruckbatterie	from the high pressure bottle bank

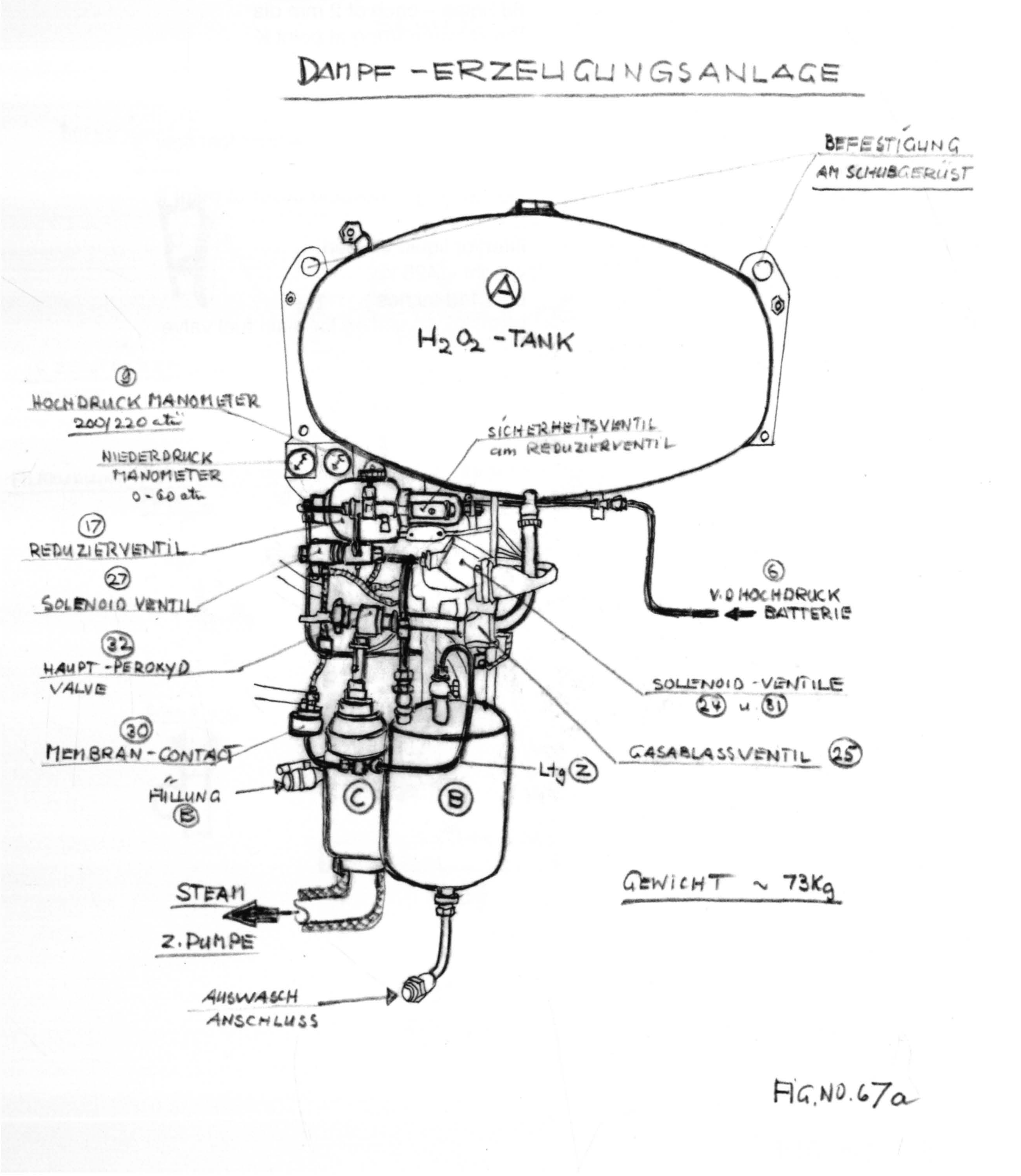


Fig 67A: Steam generation equipment

Fig 68

1 Reihe à 12 swirl jets	1 row of 12 swirl jets
2 Reihen à 12 Löcher	2 rows with 12 holes in each
2 Reihen à 16 swirl jets	2 rows with 16 swirl jets in each
18 Zerstäuber Topfe	18 atomiser heads
86 Löcher à 0.8 φ	86 holes – each of 0.8 mm dia
88 Löcher à 2 φ	88 holes – each of 2 mm dia
Befestigung Schubgerüst Punkt K	thrust frame fixing at point K
Eintritt Brennstoff v. d. Turbopumpe	inlet for fuel from the turbopump
Filmkühlung ~ 13% der gesamt Brennstoffmenge	film cooling ~ 13% of the total fuel flow
Filmkühlung-Abnahme Deckel Punkt L	film cooling removable cover at point L
Fl. Sauerstoff-Eintriit	inlet for liquid oxygen
Gewicht ~ 425 kg.	weight ~ 425 kg
L* ~ 113 in.	L* ~ 113 inches
Platz für Einbau Haupt Brennstoffventil	installation location for main fuel valve
Schnitt a-b	section a-b
Zuleitung Filmkühlung	film cooling supply pipe

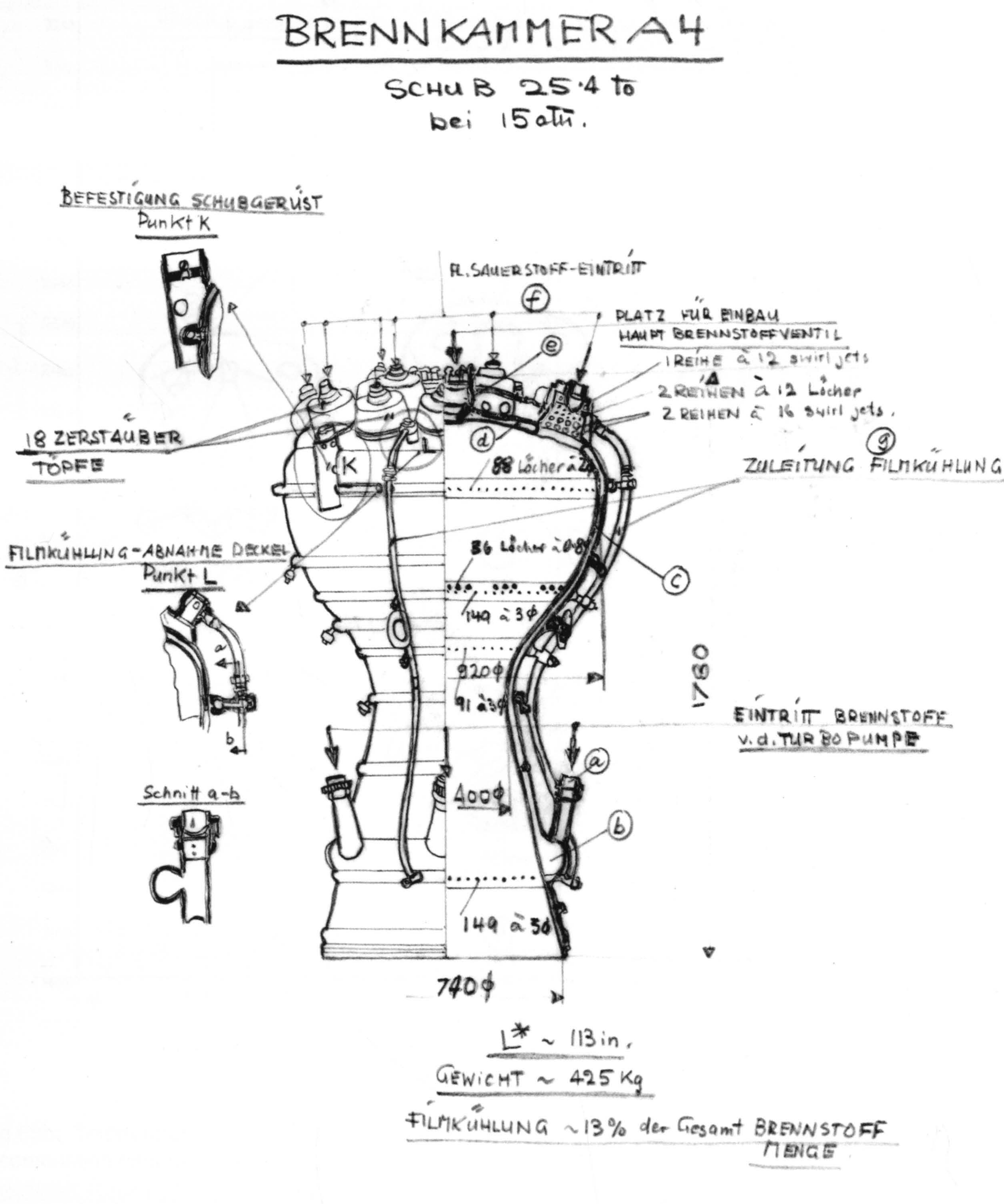


Fig 68: A4 combustion chamber, 25.4 metric tons of thrust at 15 atm.

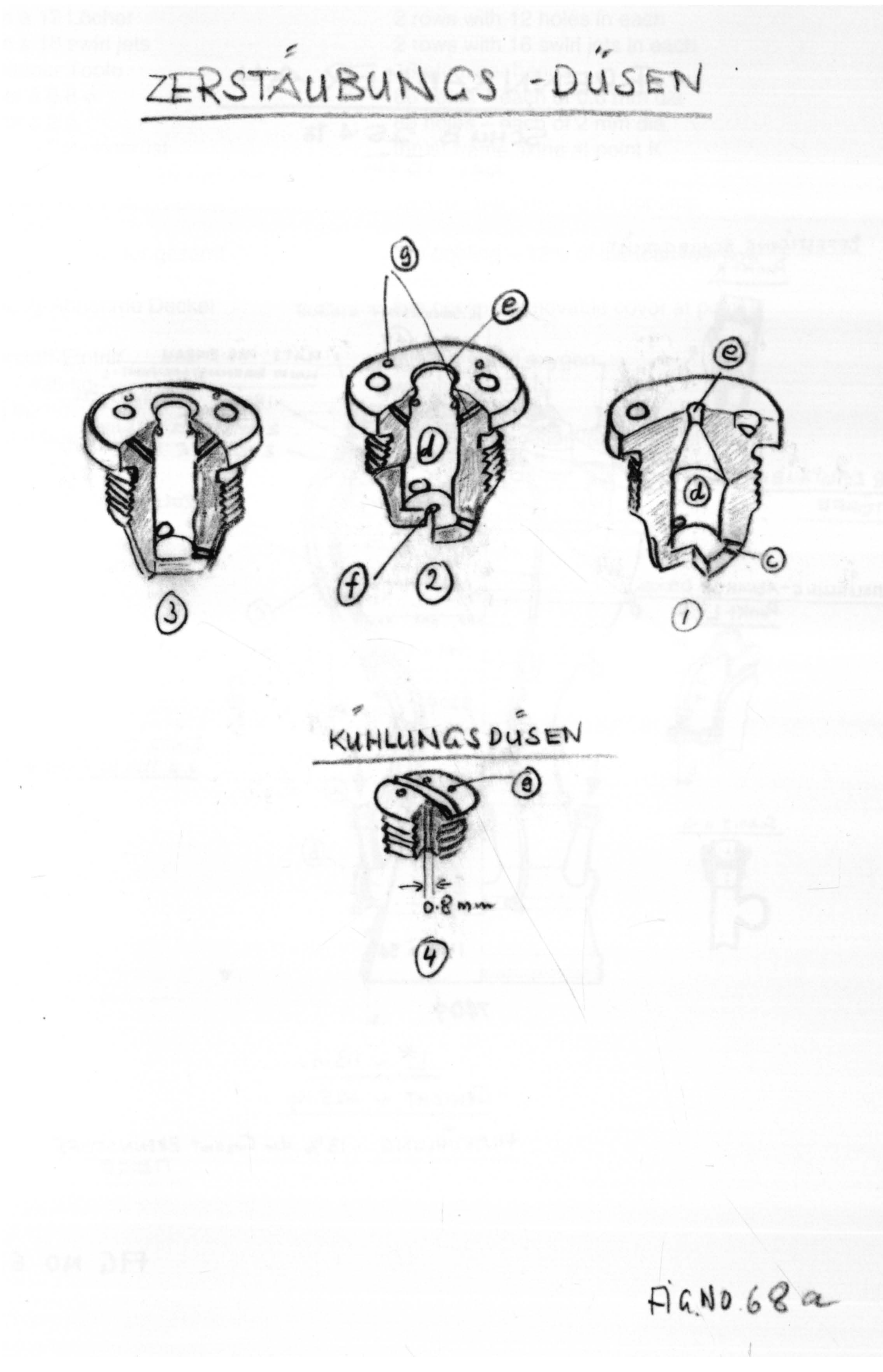


Fig 68a: Atomiser nozzles

Kühlungsdüsen cooling nozzles

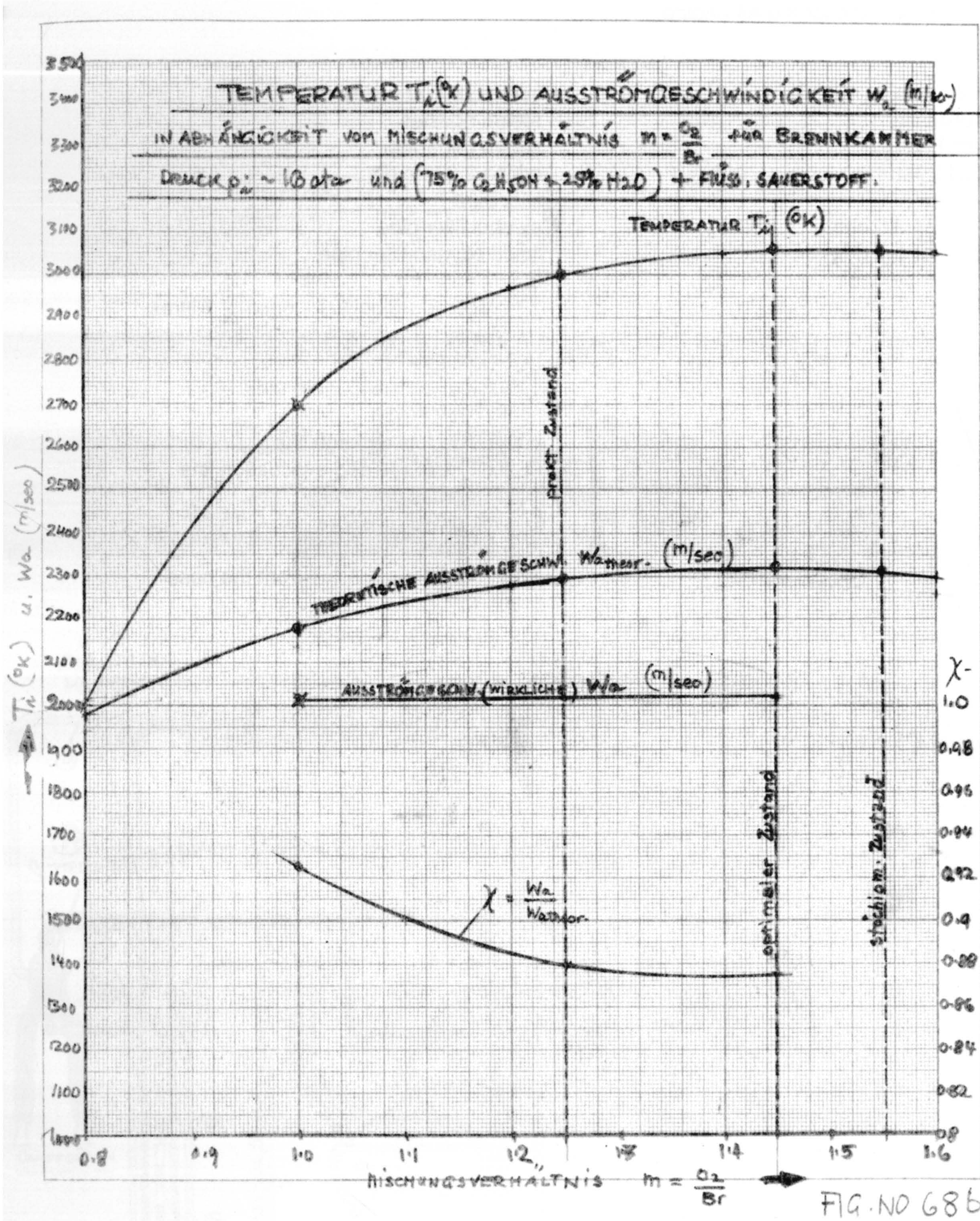


Fig 68b: Temperature T_i (°K) and exhaust velocity W_a (m/sec) as functions of mixing ratio m = O_2/fuel for a combustion chamber pressure p_a ~ 16 atm. and (75% C_2H_5OH + 25%H_2O) + liquid oxygen

Ausströmgeschw. (wirkliche) W_a (m/sec)	actual exist velocity W_a (m/sec)
Mischungsverhältnis m = O_2/Br	mixing ratio m = O_2/fuel
optimaler Zustand	optimum operating state
prakt. Zustand	practical operating state
stöchiom. Zustand	stoichiometric operating conditions
T_a (°K) u. W_a (m/sec)	T_a (°K) and W_a (m/sec)
Temperatur T_i (°K)	temperature T_i (°K)
theoretische Ausströmgeschw.	theoretical exhaust velocity
W_{atheor} (m/sec)	W_{atheor} (m/sec)

Fig 69: Schematic for the A4 engine

Brennkammer	combustion chamber
Dampfdüsen	steam nozzles
Dampf-Erzeuger	steam generator
Drossel 2.3 mm φ	orifice 2.3 mm dia.
Füll-Stutz	filler pipe
Füllstutzen Alkohol	alcohol filler pipe
Füllstutzen liq. Oxygen	liquid oxygen filler pipe
Gasablass-O_2-Tank	gas release from O_2 tank
Hochdruck Flaschen 7 à 7 Ltr.	7 high pressure bottles – each of 7 litres capacity
Hochdruck N_2	high pressure N_2
Kalium-Permanganat-Tank	potassium permanganate tank
Kontroll-Druck	control pressure
Leck-Ltg. Fuel Pumpenseite	pump-side fuel leakage line
O_2-Nachfüllung und Entleerung	O_2 tank recharge and evacuation line
O_2-Tank-Druck	O_2 tank pressure
O_2-Tank-Druckzusatz	O_2 tank driver pressure
O_2-Verdampfer	O_2 vaporiser
Staudruck-Ltg. von der Spitze	stagnation pressure line from the nose
Treibstoffpumpe	propellant pump
Ventil-Mitteldruck	average valve pressure

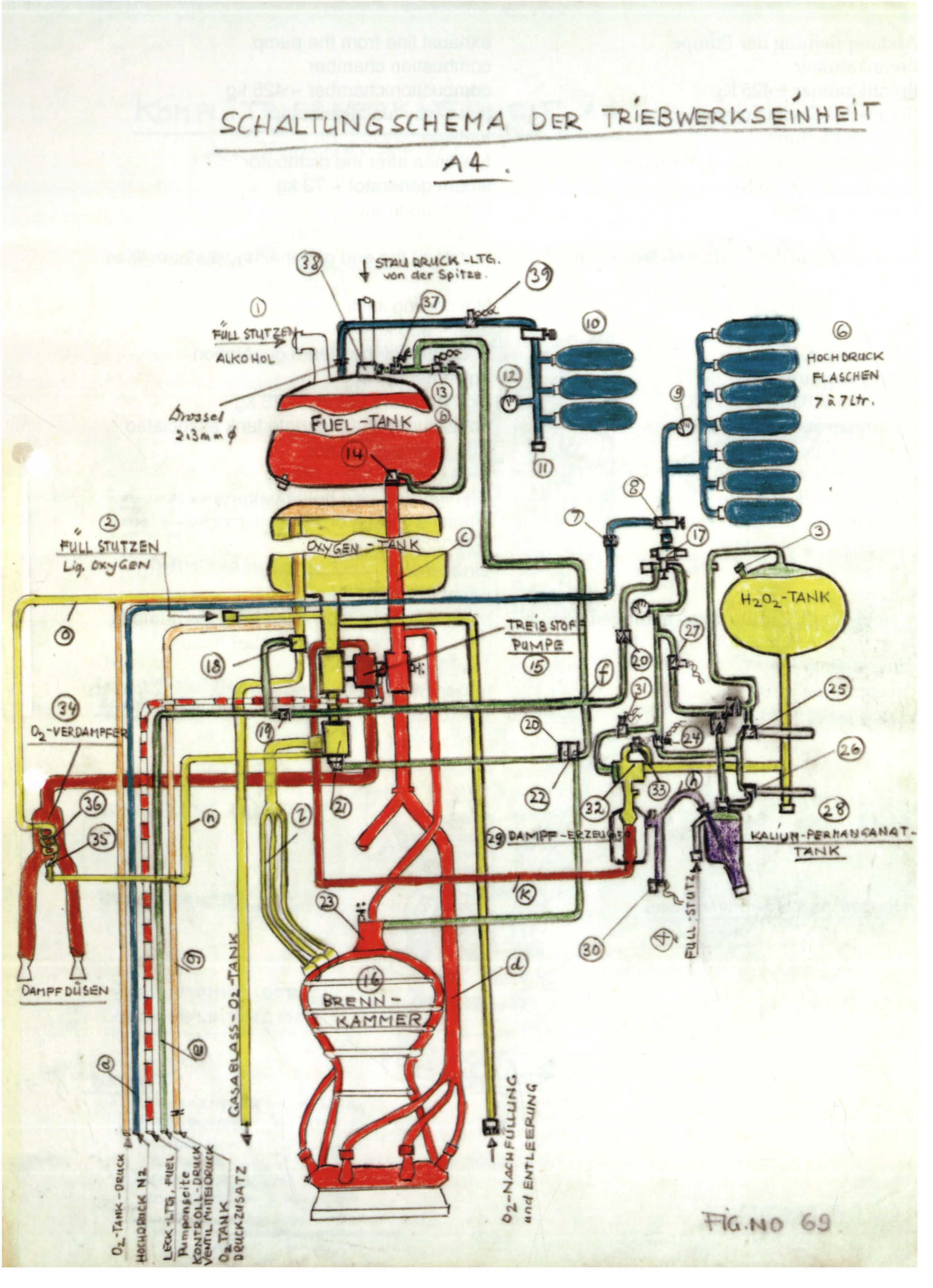


Fig 69: Schematic for the A4 engine

Fig 69a

Abdampfleitung der Pumpe	exhaust line from the pump
Brennkammer	combustion chamber
Brennkammer ~ 425 Kg	combustion chamber ~ 425 kg
Brennstoff-Dreifachverteiler	three-way fuel distributor
Brennstoffleitung	fuel line
Brennstoffleitungen n. d. Verteiler	fuel lines after the distributor
Dampfanlage ~ 73 Kg	steam generator ~ 73 kg
Dampferzeuger	steam generator
Dampfleitung zur Pumpe	steam line to the pump
Düse am Ende der Abdampf- leitungen	nozzle at the end of the exhaust steam lines
Filmkühlungen Zuleitungen	film cooling lines
Gesamt ~ 930 Kg	total ~ 930 kg
H_2O_2-Tank d. Dampf-Erzeugungsanlage	H_2O_2 tank of the steam generation equipment
Hochdruck-Batterie ~ 75 Kg	high pressure battery ~ 75 kg
Kaliumpermanganat Tank z. Dampfanlage	potassium permanganate tank associated with steam generator
Ltg., Ventile, usw ~ 140 Kg	lines, valves, etc ~ 140 kg
N_2 Hochdruck-Batterie	N2 high pressure bottle battery
7 à 7 Ltr. 200/220 atü.	7 bottles – each of 7 litres capacity – 200/220 atm.
Schubgerüst	thrust frame
Schubgerüst ~ 57 Kg	thrust frame ~ 57 kg
System der O_2 Zuführungs- leitungen von der Pumpe zu den 18 Topfen der Brennkammer	system of O2 supply lines from the pump to the 18 combustion chamber heads
Turbopumpe ~ 160 Kg	turbopump ~ 160 kg

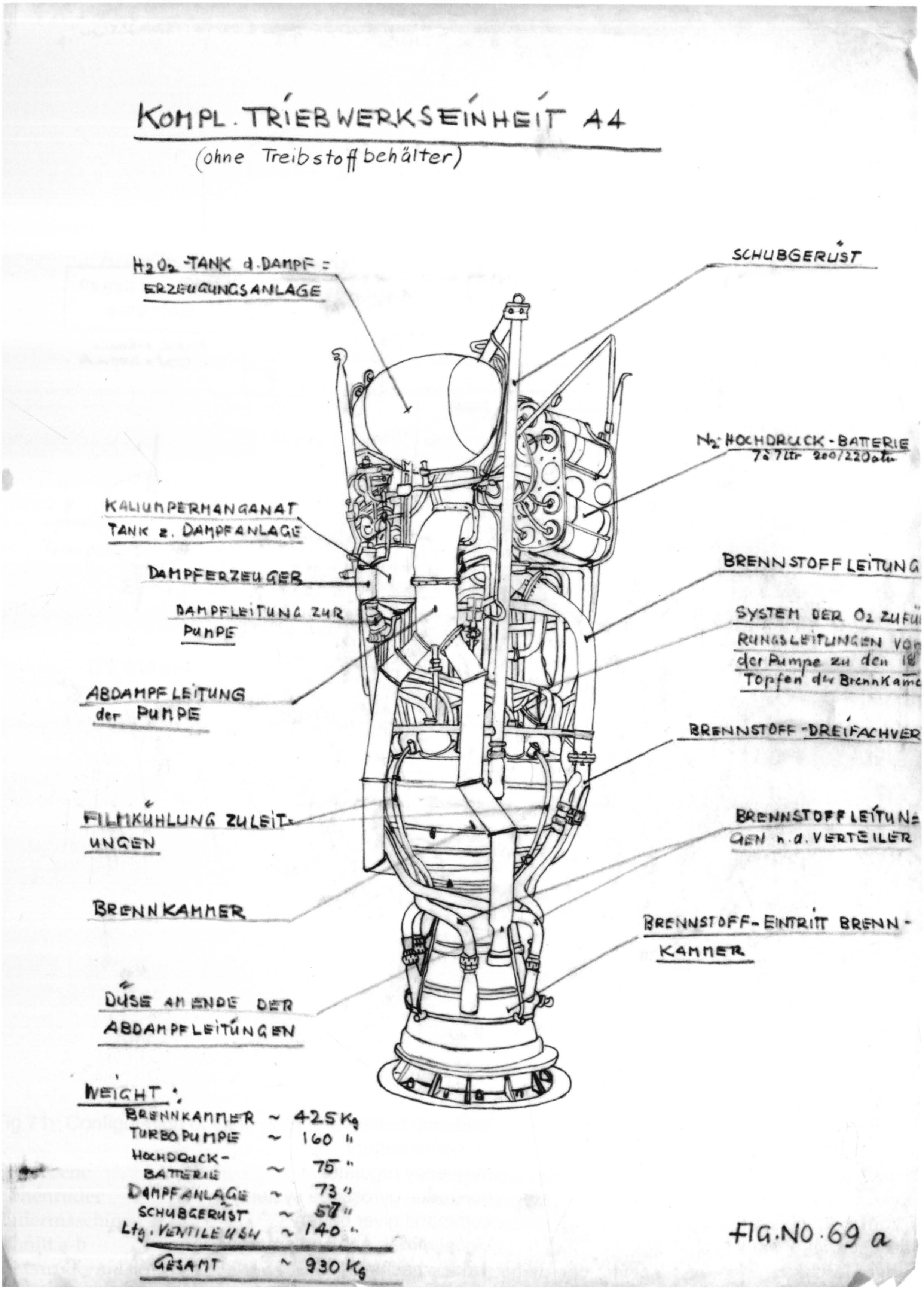


Fig 69a: Complete A4 engine (without propellant tanks)

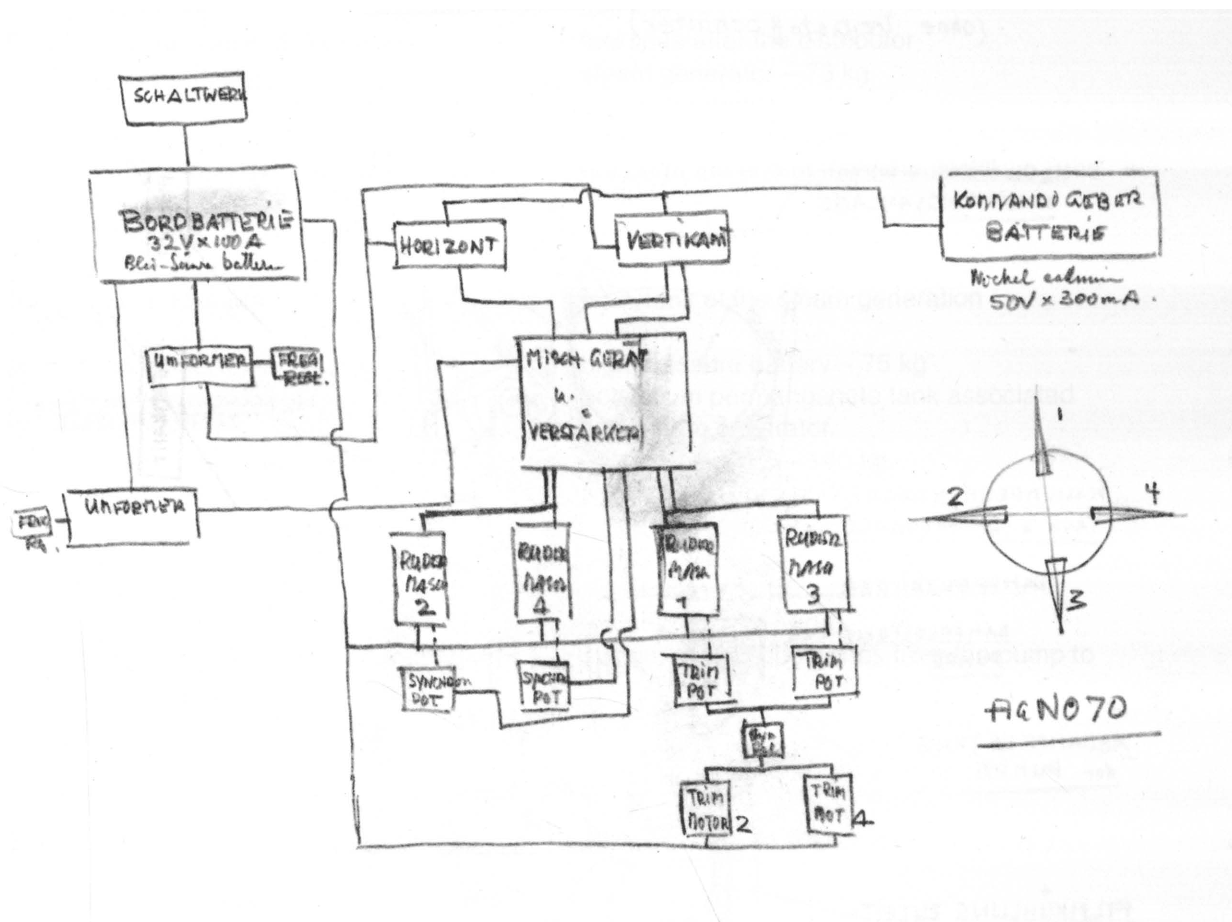


Fig 70: Schematic of vehicle control system

Blei-Säure Batterie	lead-acid battery
Bordbatterie	on-board battery
Freq. Regl.	frequency regulator
Horizont	horizontal gyroscope system
Kommandogeberbatterie	command giver battery
Mischgerät u. Verstärker	signal mixing unit and amplifier
Ruder Masch.	rudder machinery
Schaltwerk	circuitry
Synchro Pot	synchronous potentiometer
Trim Motor	trim motor
Trim Pot	trim potentiometer
Umformer	transformer
Vertikant	vertical gyroscope system

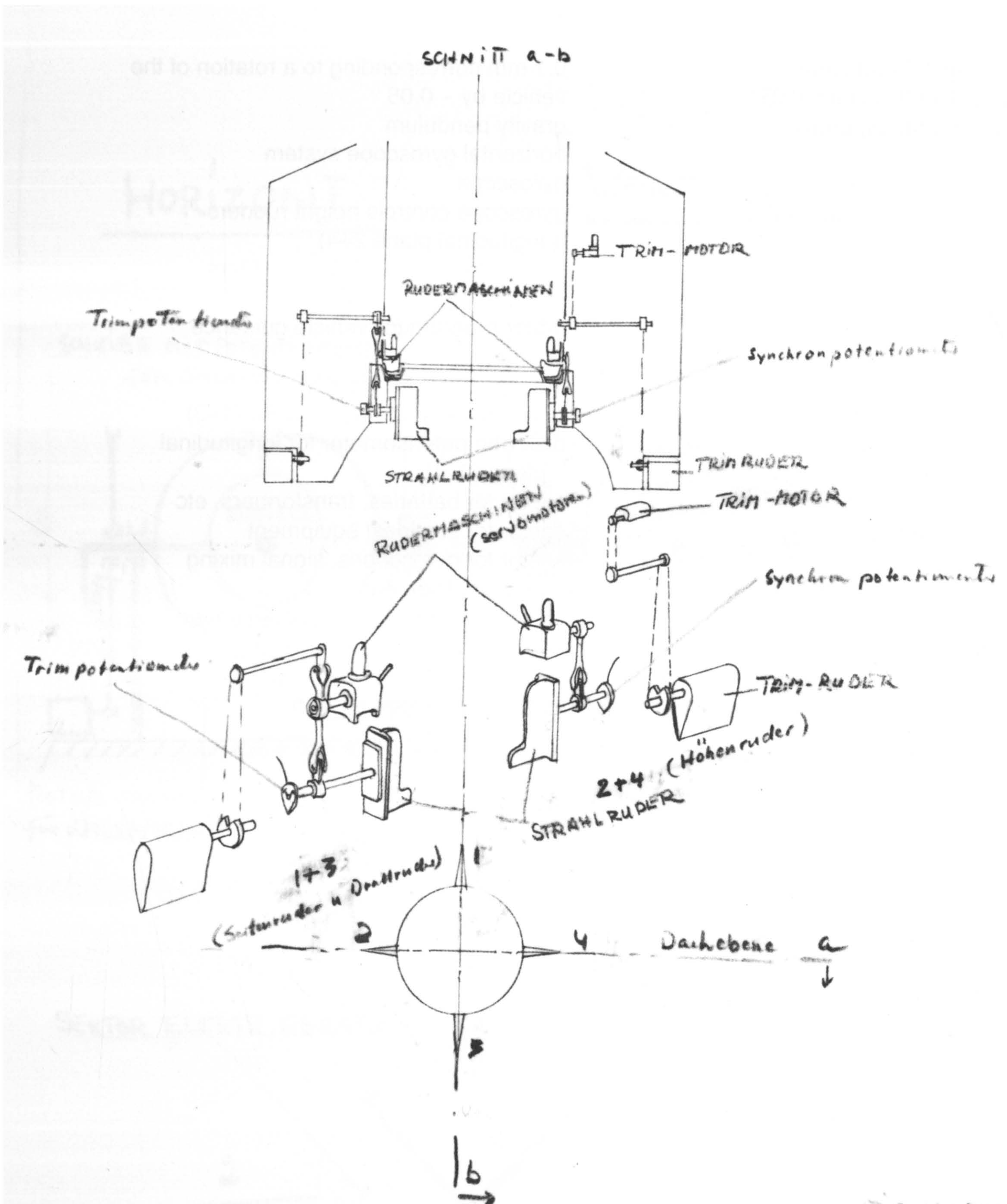


FIG NO 71

Fig 71: Configuration of vane units and trimming motors

Dachebene	longitudinal plane
Höhenruder	height rudders
Rudermaschinen	rudder machinery
Schnitt a-b	section a-b
Seitenruder u Drallruder	lateral rudders and rotation rudders
Servomotoren	servo motors
Strahlruder	exhaust stream rudders
Synchronpotentiometer	synchronous potentiometer
Trim Motor	trim motor
Trim Potentiometer	trim potentiometer
Trim-Ruder	trim rudders

Fig 72

0.1 mm entsprechend einer Drehung d. Gerätes von ~ 0.05 °	0.1 mm corresponding to a rotation of the vehicle by ~ 0.05 °
Erdbeschleunigungspendel	gravity pendulum
Horizont	horizontal gyroscope system
Kreisel	gyroscope
Kreisel kontrolliert Höhenruder (Dachebene 2+4)	gyroscope controls height rudders (longitudinal plane 2+4)
Kreisel kontrolliert Seitenruder (Ebene 1+3) and Drall	gyroscope controls lateral rudders (plane 1+3) and rotation
Motor-Programm für Umlenkung	motor program for vehicle guidance
Pendel	pendulum
Potentiometer für Drall	potentiometer for rotation
Potentiometer für Seitenebene (1+3)	potentiometer for lateral plane (1+3)
Scheibe mit Potentiometer für Dachebene (2+4)	disk with potentiometer for longitudinal plane (2+4)
Sektor Batterien, Umformer usw	sector for batteries, transformers, etc
Sektor elektr. Geräte	sector for electrical equipment
Sektor für Kreisel, Mischgerät- Verstärker, unit usw	sector for gyroscopes, signal mixing and amplifier, etc
Sektor für N2 Flaschen	sector for N2 bottles providing driver
Druckzusatz Br. Behälter	pressure for fuel tank
Stützmotoren	servomotors
Vertikant	vertical gyroscope system

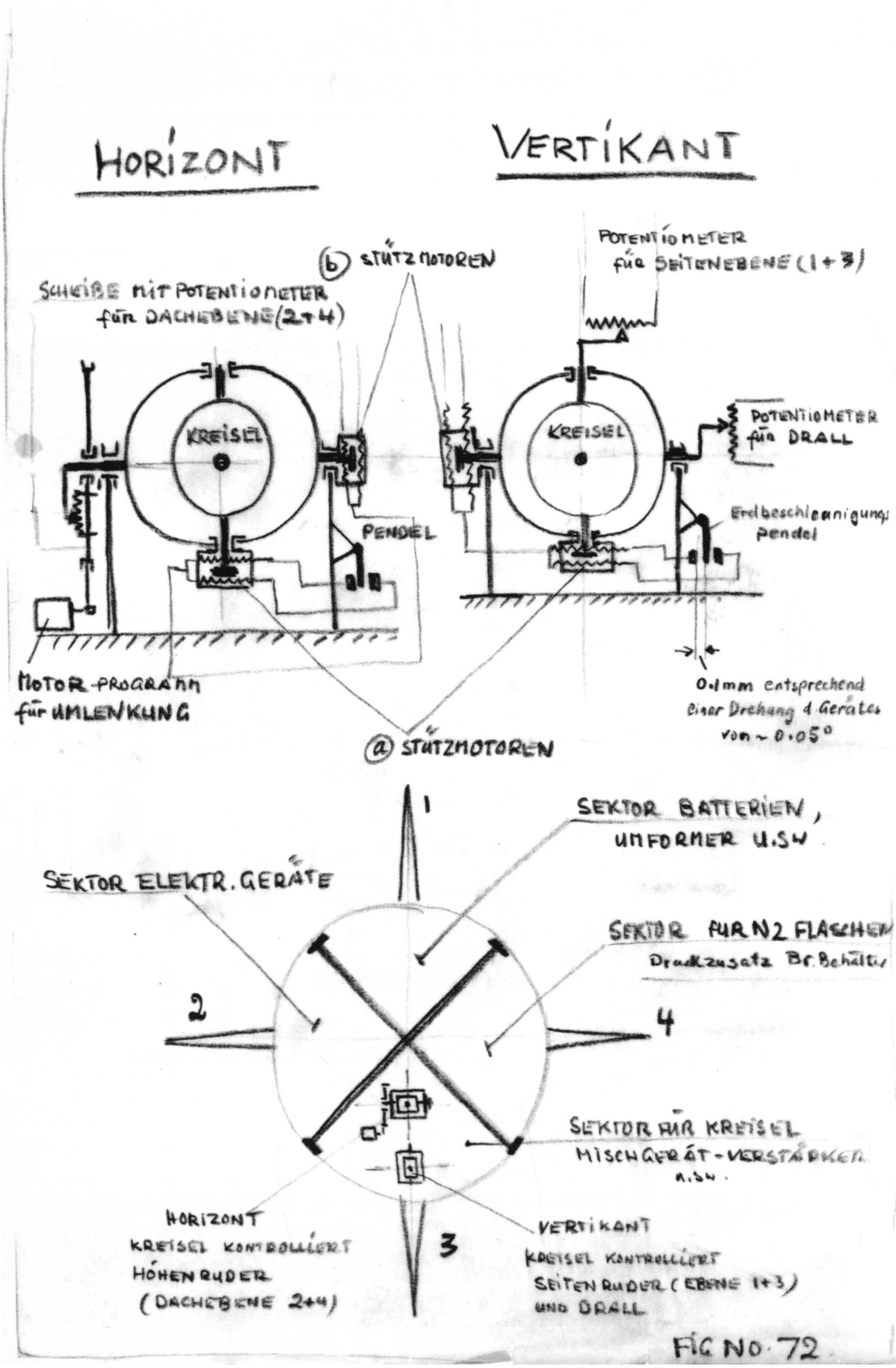


Fig 72: Gyroscopic systems

Fig 74

I Payload

1. charge ~ 750 kg
2. casing ~ 250 kg = 1000 kg

II. Nose section (control)

1. Control system
2. Power supply
3. Electrical equipment
4. N_2 battery
5. Flaps and framework = 480 kg

III. Centre section

1. Framework and skin ~ 420 kg
2. O_2 tank ~ 120 kg
3. Fuel tank ~ 75 kg
4. Valves. Cables, etc ~ 125 kg = 740 kg

IV. Rocket engine

1. Combustion chamber ~ 425 kg
2. Turbopump ~ 160 kg
3. N_2 battery ~ 75 kg
4. Steam generator ~ 73 kg
5. Thrust frame ~ 57 kg
6. Valves, lines, cabling, etc. ~ 140 kg = 930 kg

V. Tail section

1. Framework and casing ~ 480 kg
2. Servomotors ~ 160 kg
3. Exhaust stream rudders ~ 60 kg
4. Cabling, ancillary equipment, etc ~ 160 kg = 860 kg

Total weight empty	~ 4010 kg
O2 tank capacity	~ 4900 kg
Fuel tank capacity	~ 3820 kg
H2O2 tank capacity	~ 173 kg
	~ 12 kg
Total weight when tanks charged	~ 12915 kg

Brennkammerdruck	combustion chamber pressure (15 atm)
Brennzeit	burn time (67 secs)
Schub	thrust (254 tonnes)

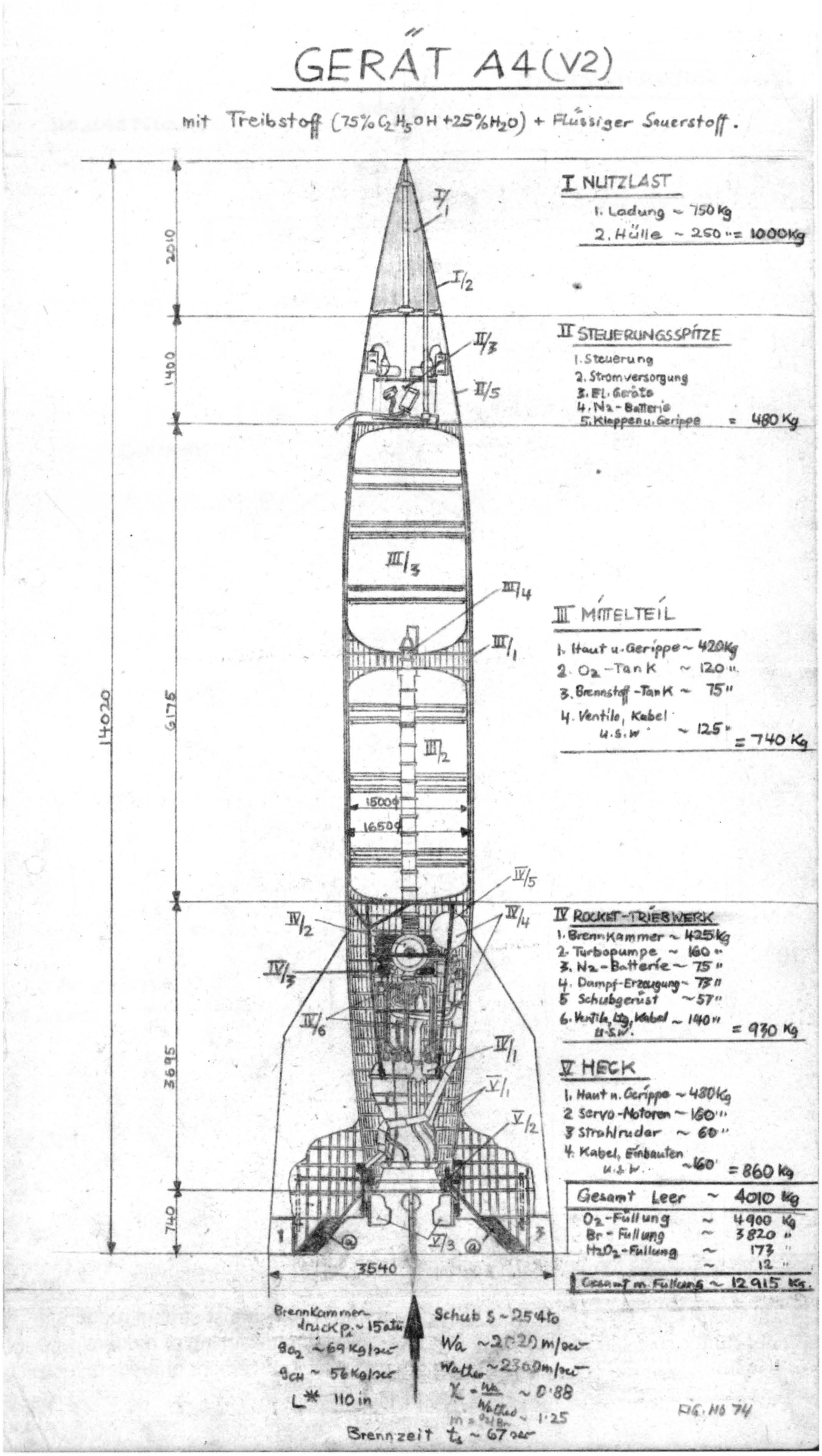


Fig 74: A4 (V2) vehicle with propellant (75% C_2H_5OH + 25% H_2O) + liquid oxygen

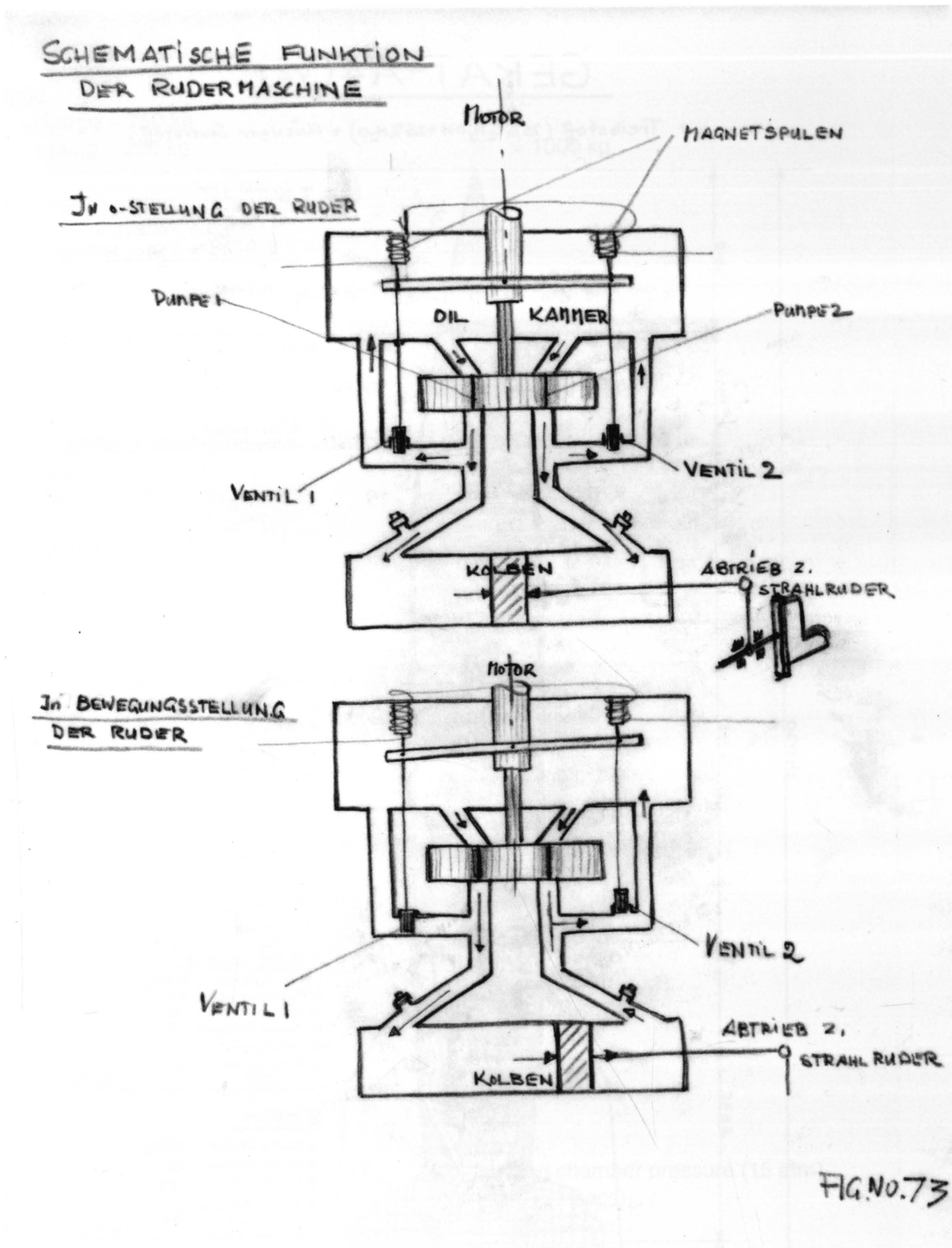


Fig 73: Functional schematic for the rudder system

Abtrieb z. Strahlruder	power off-take to exhaust stream rudders
Jn. 0-stellung der Ruder	system state for null setting of rudders
Jn. Bewegungsstellung der Ruder	system state for movement of rudders
Kolben	piston
Magnetspulen	magnet coils
Motor	motor
Oil Kammer	oil chamber
Pumpe	pump
Ventil	valve

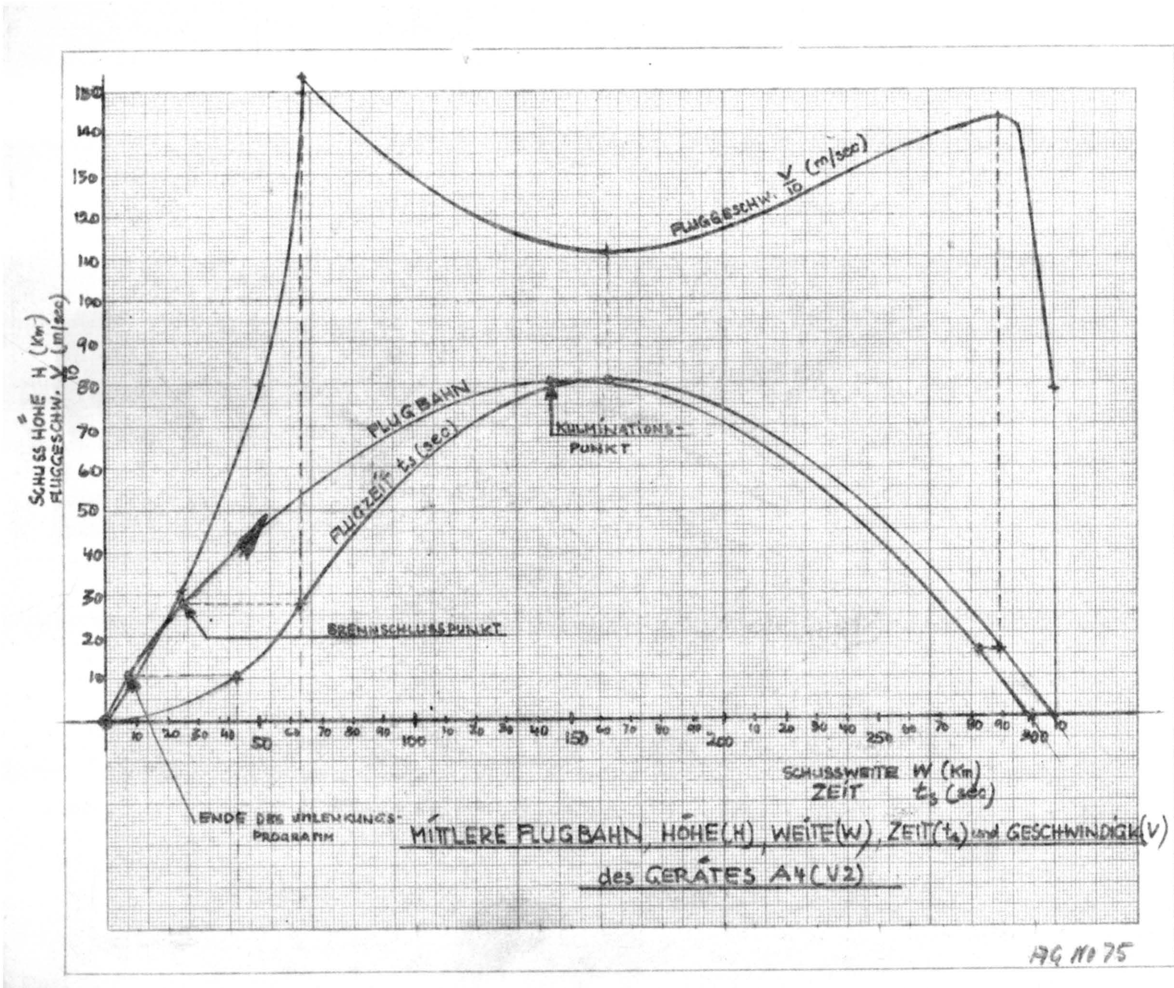


Fig 75: Average flight path, height (H), range (W), time (t_s) and velocity (V) for the A4 (V2) vehicle

Brennschlusspunkt	combustion shut-down point
Ende des Umlenkungsprogram	end of vehicle guidance program
Flugbahn	flight path
Fluggeschw.	flight velocity
Flugzeit	flight time
Kulminations-Punkt	apogee
Schusshöhe	height of flightpath
Schussweite	range of flightpath
Zeit	time

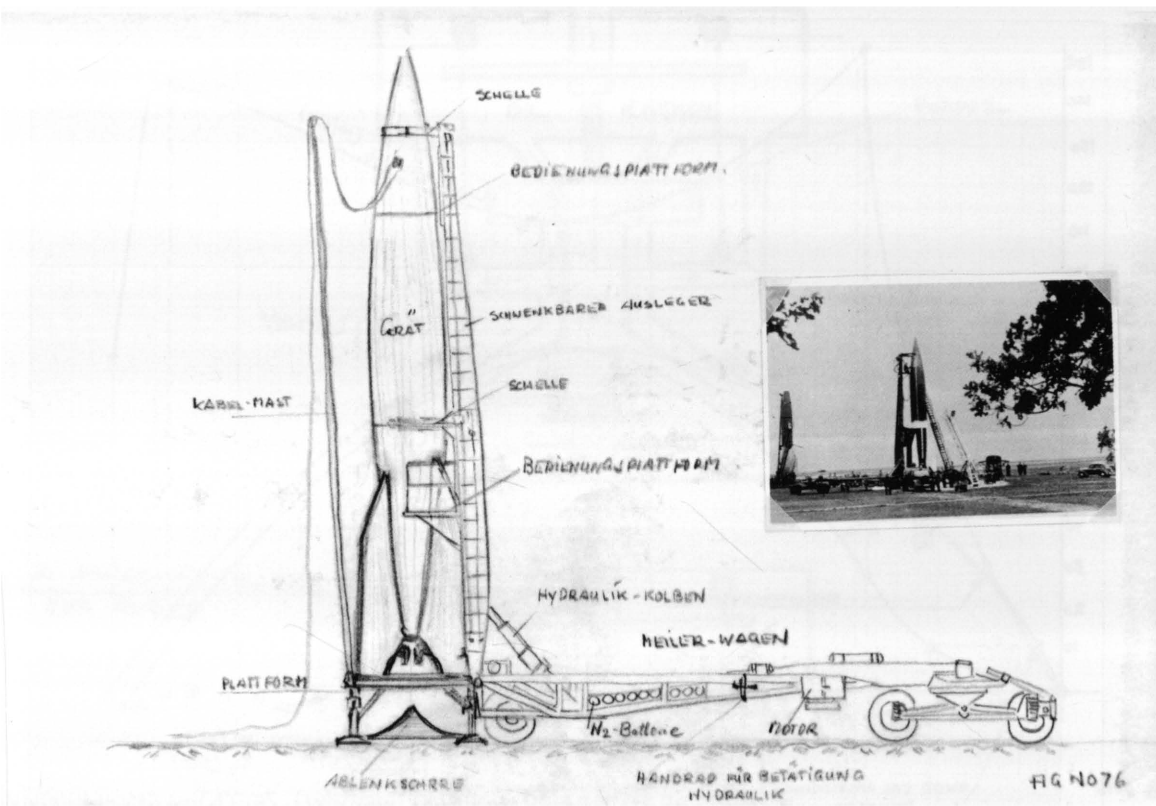


Fig 76: Arrangement of Meilerwagen

Ablenkschurre	deflection chute
Bedienungsplattform	operations platform
Gerät	vehicle
Handrad für Betätigung Hydraulik	handwheel for actuation of the hydraulics
Hydraulik-Kolben	hydraulic piston
Kabelmast	cabling mast
Meilerwagen	Meiler vehicle
Motor	motor
N_2 batterie	N_2 battery
Plattform	platform
Schelle	clamping strap
schwenkbarer Ausleger	swivelling jib

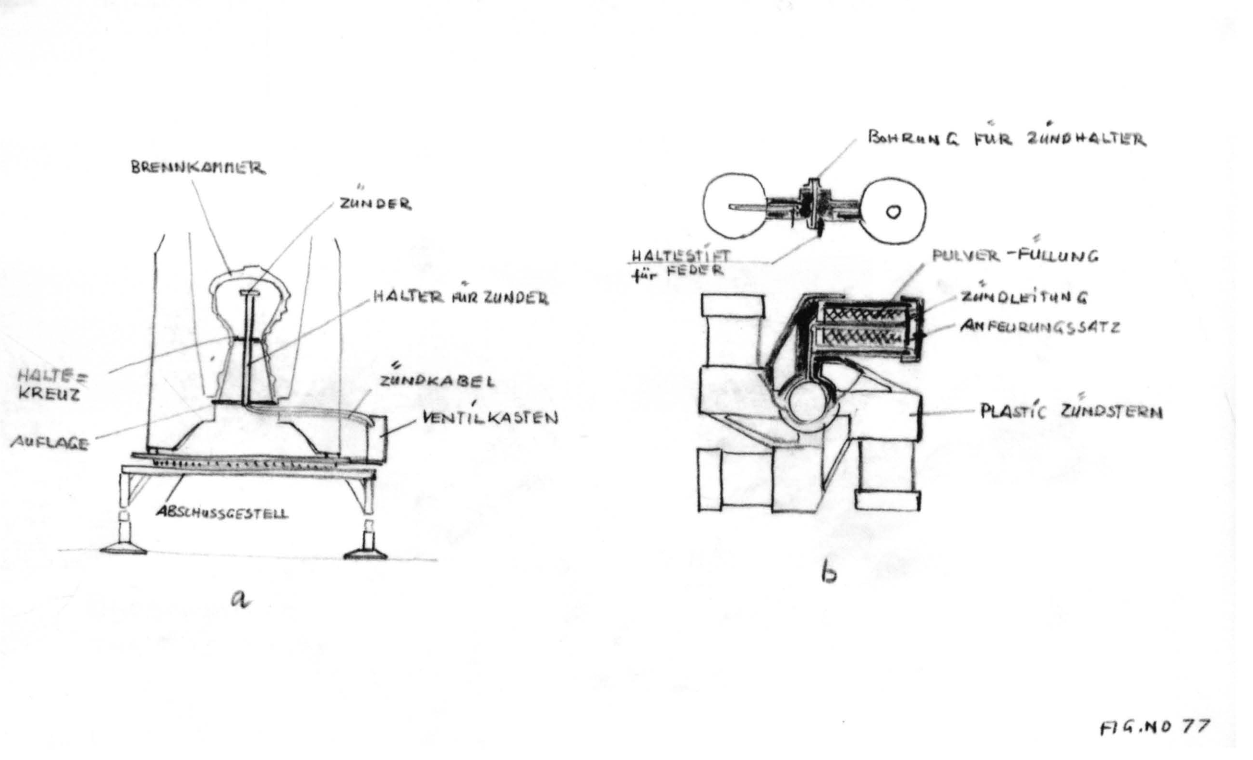


Fig 77: A4 pyrotechnic ignition system

Abschussgestell	launch platform
Anfeuerungssatz	firing system
Auflage	supporting surface
Bohrung für Zündhalter	drilling for igniter holder
Brennkammer	combustion chamber
Haltekreuz	cruciform stay
Halter für Zünder	holder for igniter
Haltestift für Feder	retention pin for spring
plastic Zündstern	plastic ignition star
Pulver-Füllung	powder charge
Ventilkasten	valve chest
Zünder	igniter
Zündkabel	igniter cable
Zündleitung	ignition line

Fig 78: Three photographs of A4 (V2) launches

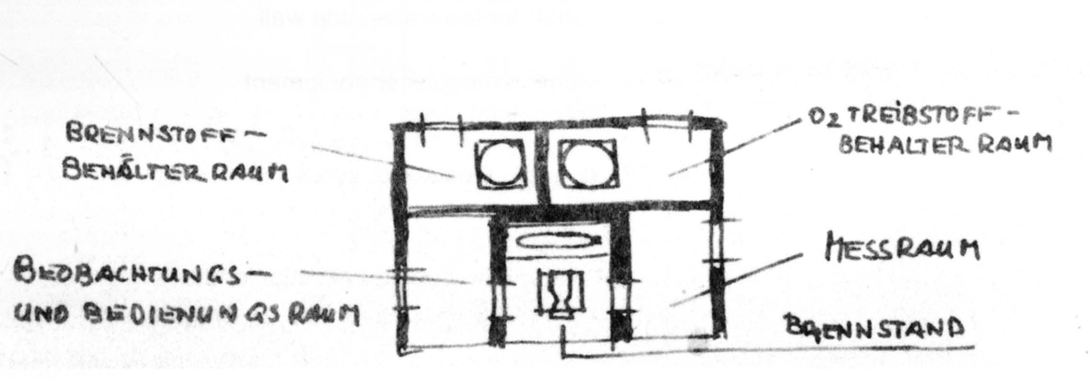


Fig 78a: Test facility III (horizontal firing)

Beobachtungs- und Bedienungsraum	observation and operations room
Brennstand	firing stand
Brennstoff-Behälterraum	fuel tank cell
Messraum	measurement cell
O_2 Treibstoffbehälterraum	O_2 propellant tank cell

Fig 79

Beobachtungsperiskop	observation periscope
Beobachtungsraum, darunter liegend Messraum	observation cell, with the easurement cell below
Brenngerüst	firing scaffold
Brennkammer mit Aufhängung	combustion chamber with suspension
fahrbares Kranschutzhaus	mobile crane protective housing
fahrbare Montagebühne	mobile assembly platform
Fluessigkeit Sammelgrube	liquid collection pit
Gasabzug-Kanal	gas exhaust channel
Jalousie vor der Wand	shutter in front of the wall
Kranbahn	crane track
Messanzeige Schub	thrust measurement display
Messwaage	measuring scales
N_2 Hochdruck-Batterie	N_2 high pressure battery
Pruefstandhaus	test stand housing
Schacht für versenkbare Seitenwand	shaft for lowerable side wall
Schaumlösch-Anlage	foam extinguisher equipment
Treibstoff-Behälter	propellant tanks
Treibstoff-Verbrauch Anzeige	propellant consumption display
Ventil-Stand Buhne	valve display platform
verfahrbare Kranbühne	mobile crane platform
versenkbare Seitenwände	lowerable side walls
Wasserrohr-Ablenk-Schurre	water tube cooled deflection chute

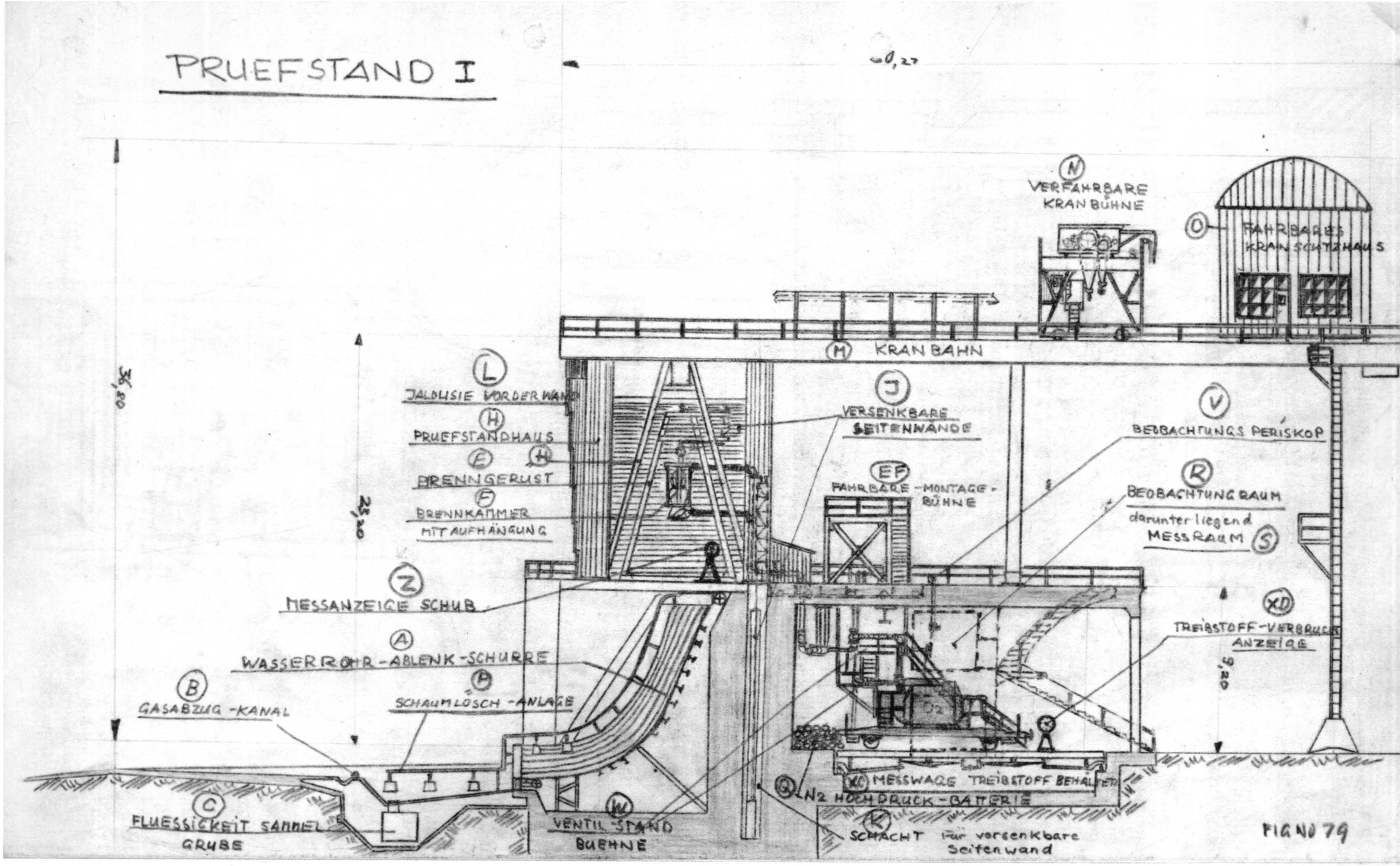


Fig 79: Test stand I

Fig 79a

Aufgang z. Podest	way up to the platform
Beobachtungsbunker	observation bunker
Brennstoff	fuel
Brennstoff Behälter auf Eisen-bahnwaggon montiert	fuel tanks mounted on railway wagon
Druckzusatzltg.	driver pressure line
Eingang z. Beobachtungsbunker	entry to observation bunker
Feuerlöschraum, darüber liegend Werkstatträume	fire extinguisher cell, with workshops above
Fluessig-Sauerstoff-Raum	liquid oxygen cell
Gasabzug-Kanal mit feuer-festen Steinen gemauert	gas exhaust channel faced with fireproof masonry
Handventile	manually-operated valves
N_2-Fuell. Station	N_2 charging station
N_2 Hochdruck-Batterie	N_2 high pressure battery
Nebenräume Flur u. 2 Etagen	extra cells, ground floor and 2 upper floors
O_2-Behälter	O_2 tanks
Podest	platform
Podest z. d. Ventilen	valves platform
Pruefstandhaus	test stand housing
Schaltpulte	control desks
Schaumlösch-Anlage	foam extinguisher equipment
versenkbare Seitenwände d. Pruefstandhauses	lowerable side walls of the test stand housing
Wasserrohrschurre	water tube cooled chute

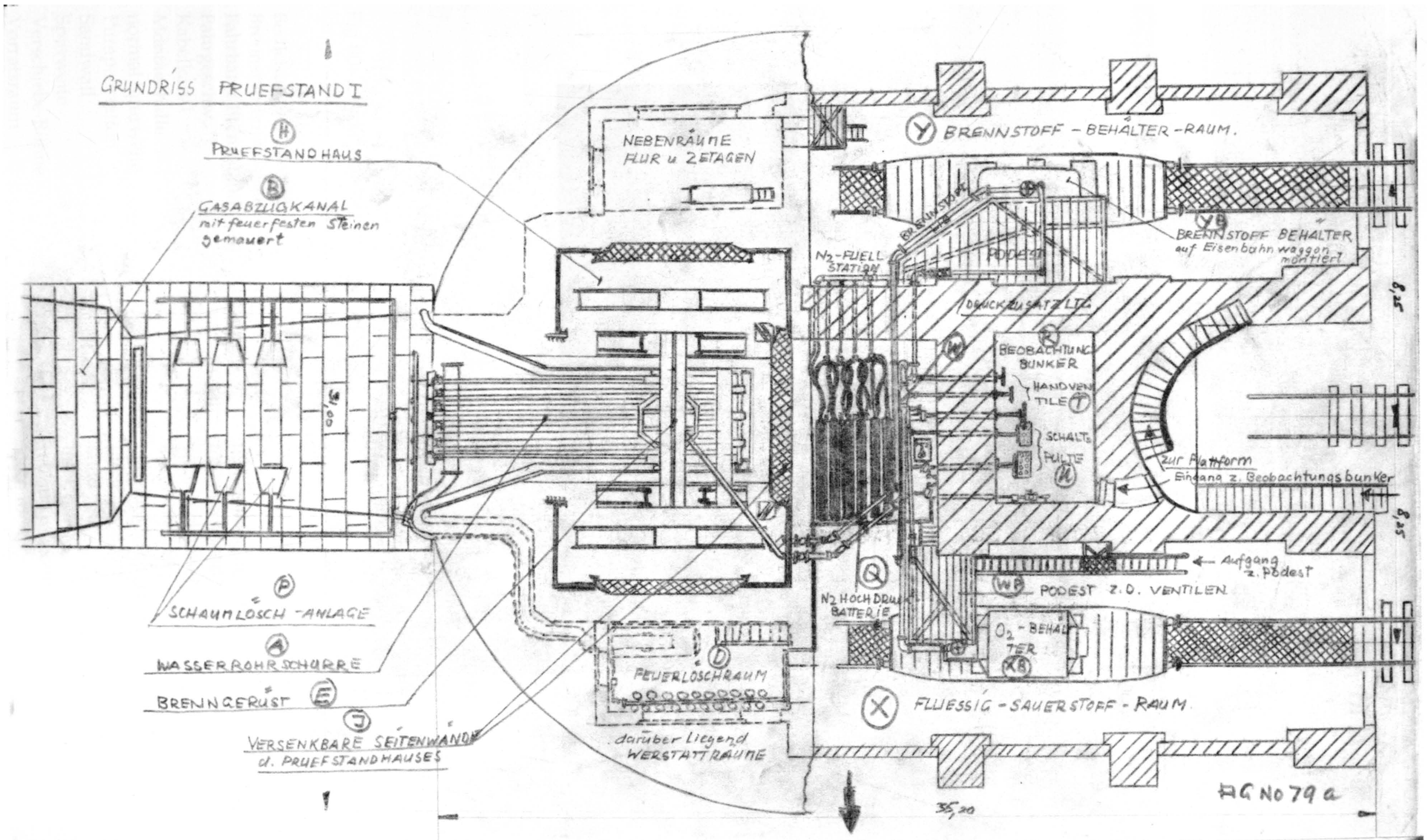


Fig 79a: Ground plan of test stand I

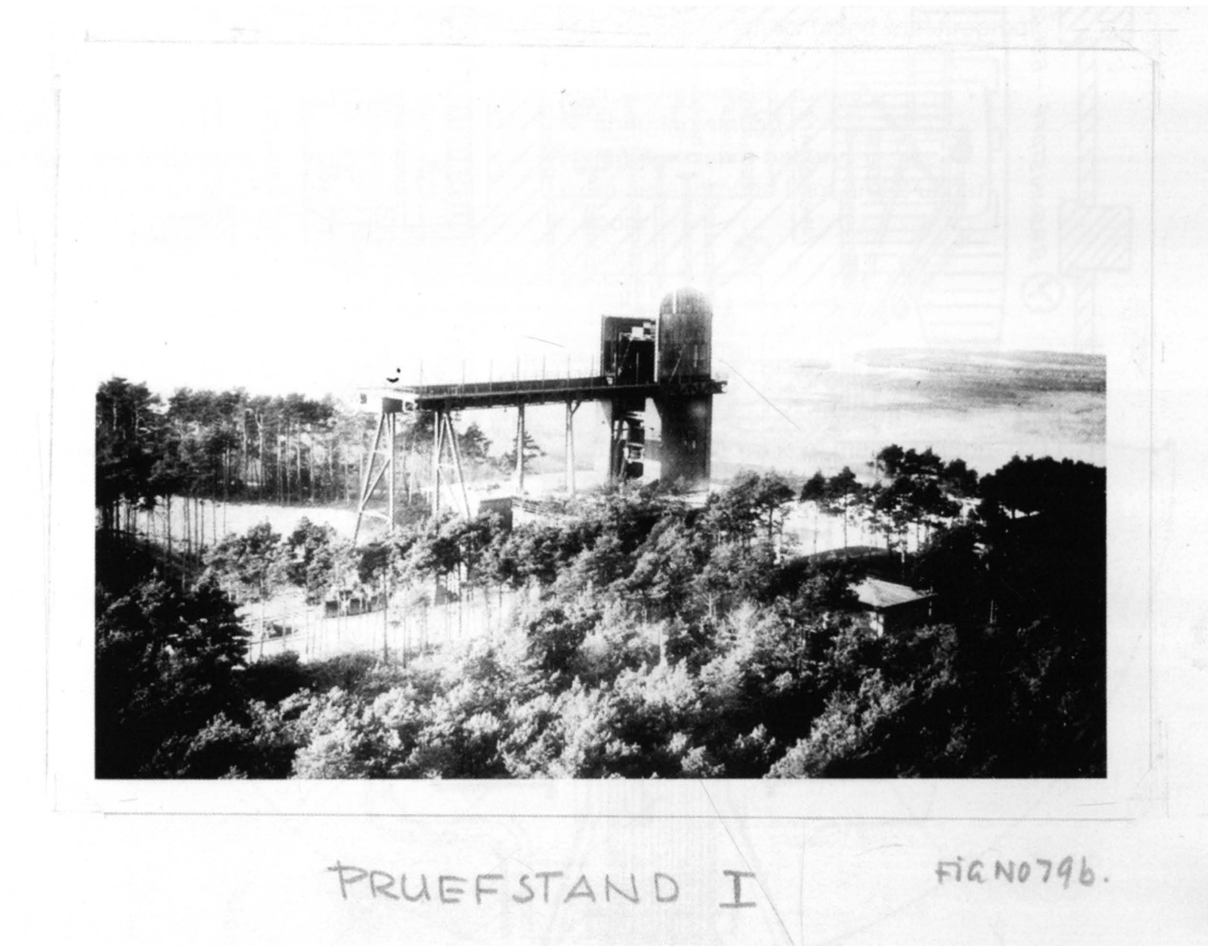


Fig 79b: Test stand I

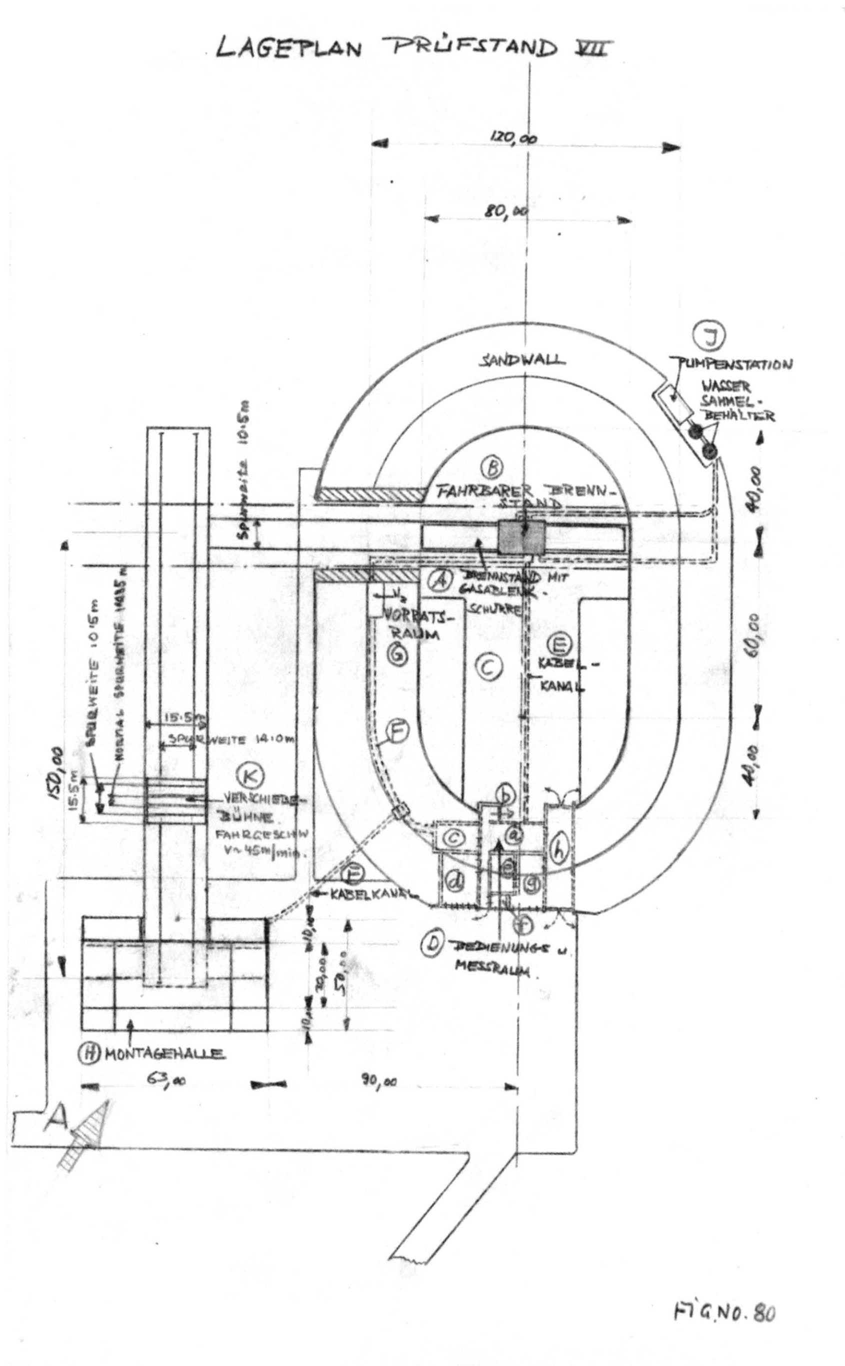


Fig 80: Layout plan of test stand VII

Bedienungs u. Messraum	operations and measurements cell
Brennstand mit Gasablenkschurre	firing stand with gas deflection chute
Fahrbarer Brennstand	mobile firing stand
Fahrgeschw.	traverse speed
Kabelkanal	cabling channel
Montagehalle	assembly hall
normal Spurweite	standard track gauge
Pumpenstation	pumping station
Sandwall	sand wall
Spurweite	track gauge
Verschiebe-Bühne	moving platform
Vorratsraum	store room
Wassersammelbehälter	water collection tanks

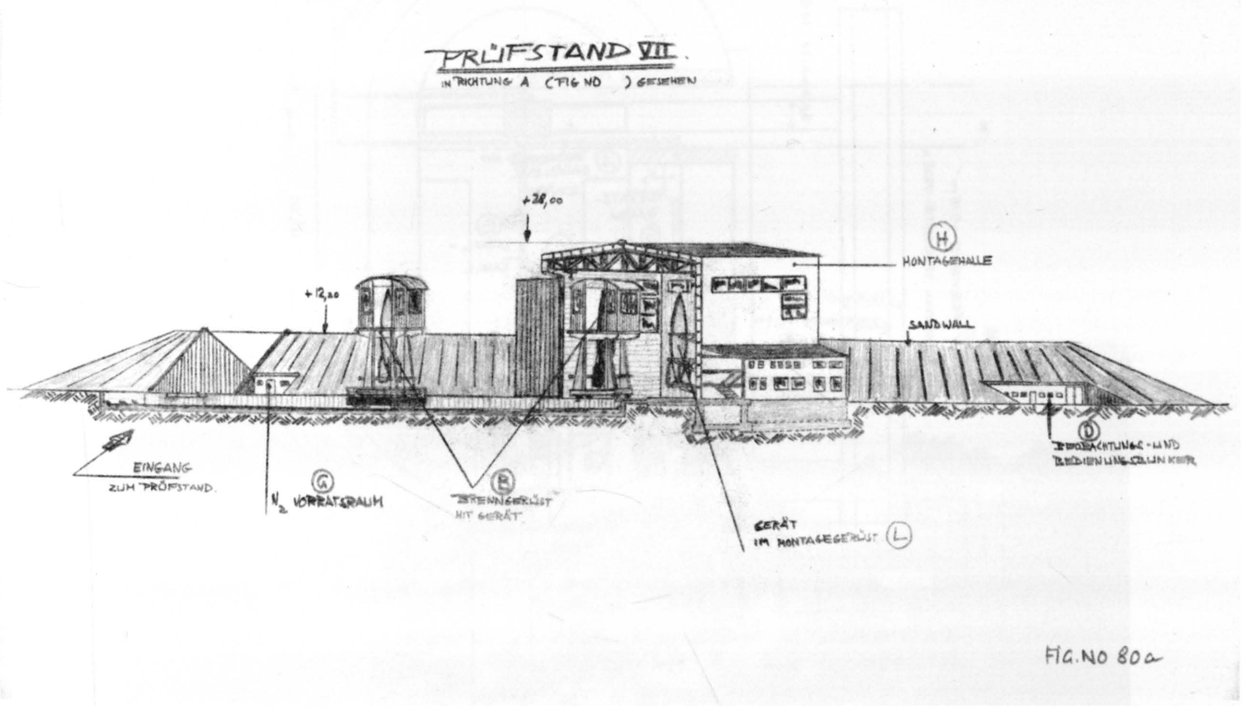


Fig 80a: Test stand VII as seen in direction A (Figure 80)

Beobachtungs u. Bedienungsbunker	observation and operations bunker
Brenngerüst mit Gerät	firing scaffold with vehicle
Eingang zum Prüfstand	entry to test stand
Gerät im Montagegerüst	vehicle in assembly tower
Montagehalle	assembly hall
N_2 Vorratsraum	N_2 store room
Sandwall	sand wall

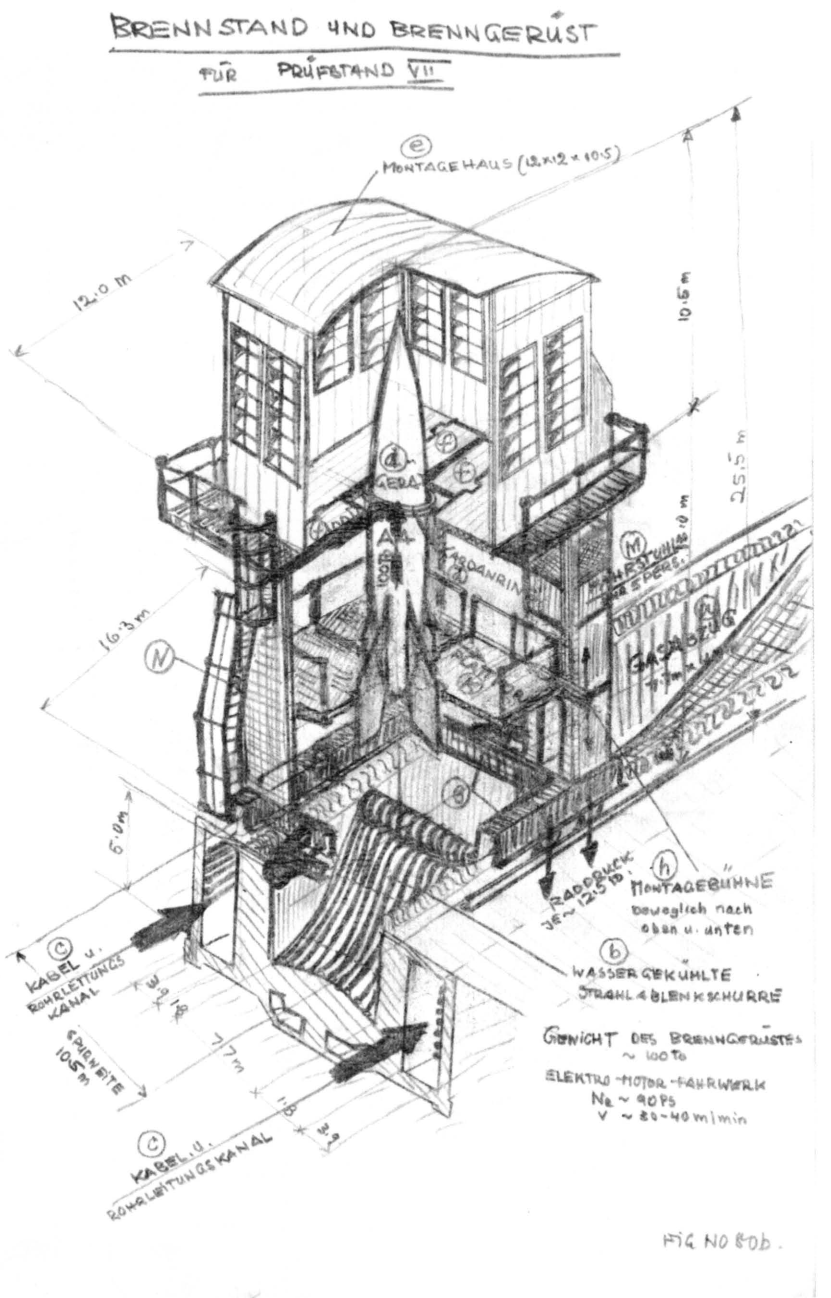


Fig 80b: Firing stand and firing scaffold for test stand VII

Elektro-Motor-Fahrwerk	electric motor drive
Fahrstuhl für 5 Pers.	lift for 5 people
Gasabzug	gas exhaust
Gerät A4	A4 vehicle
Gewicht des Brenngerüstes	weight of the firing scaffold
Kabel- u. Rohrleitungskanal	cabling and pipework channel
Kardanring	gimbal
Montagebühne beweglich nach oben u. unten	assembly platform – movable upwards and downwards
Montagehaus	assembly tower
Plattform	platform
Raddruck je ~ 12.5 to.	load on each wheel ~ 12.5 metric tons
Spurweite	track gauge
wassergekühlte Strahlablenkschurre	water-cooled exhaust stream deflection chute

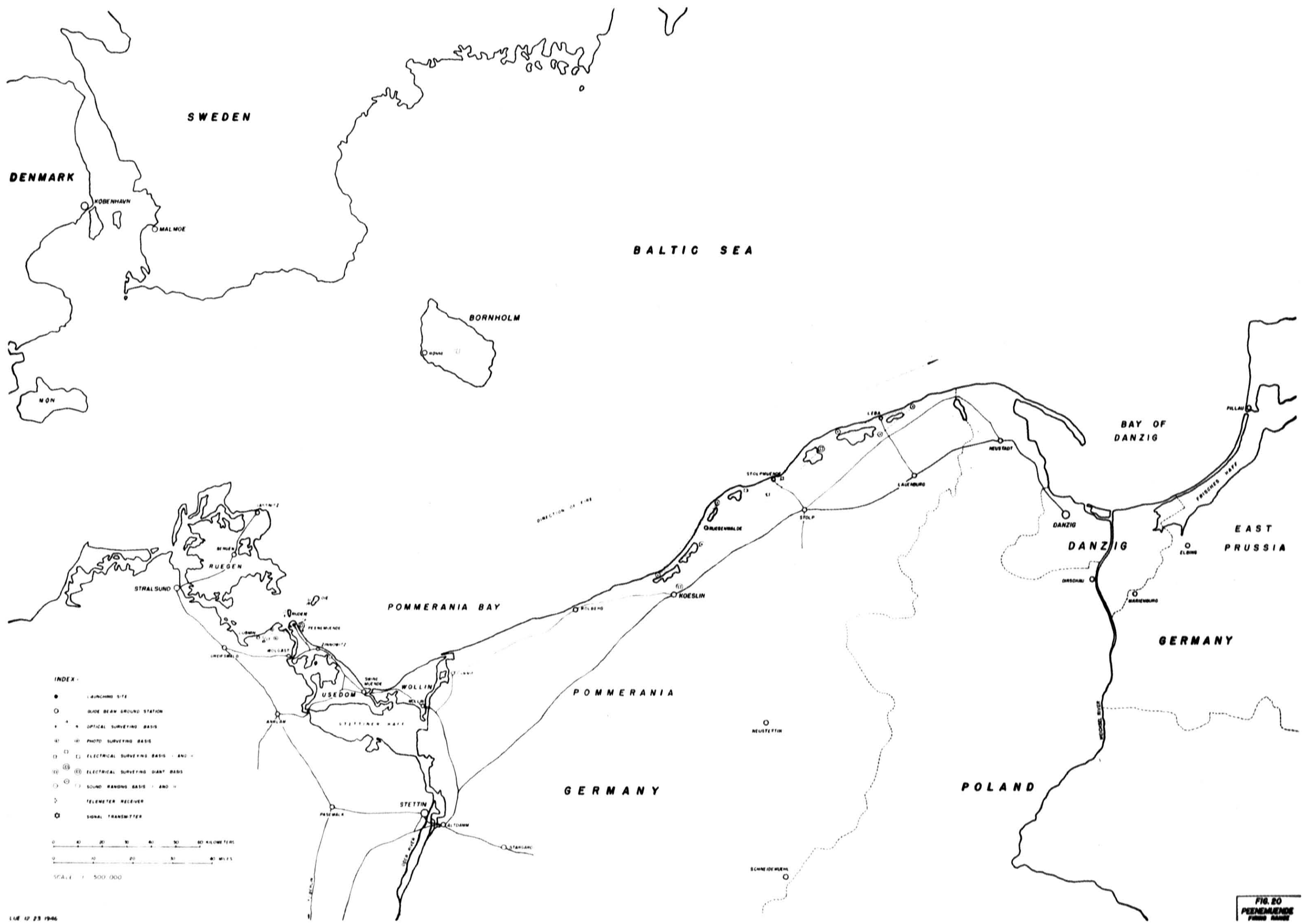


Fig 81: Map of Baltic coastline

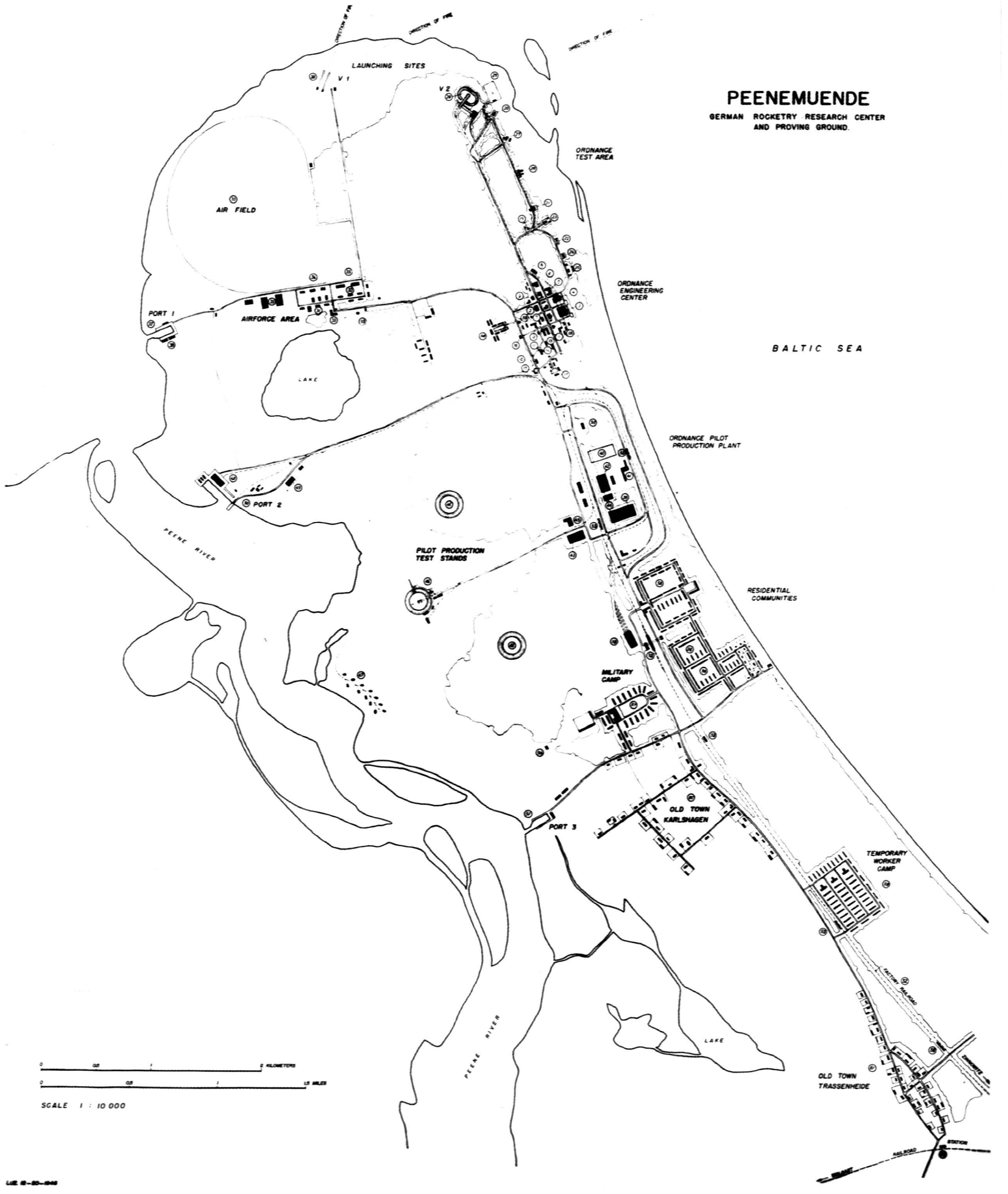
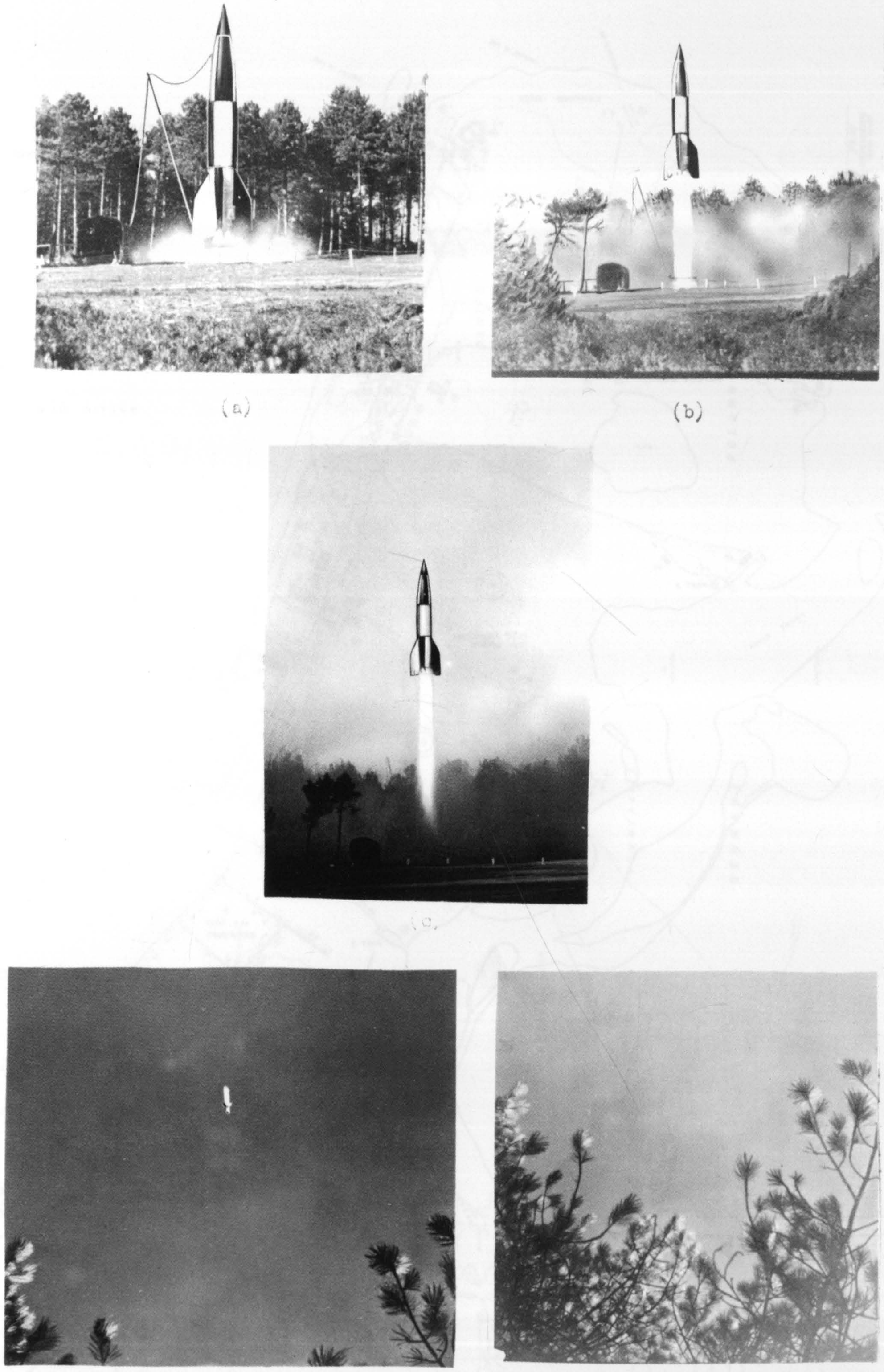


Fig 82: Peenemuende – German rocketry research centre and proving ground



(a) (b)

(c)

(d)

Plate 47. Five stages in the take-off of the V.2.

Fig 84: Five stages in the take-off of the V2.

WALTER RIEDEL, A BIOGRAPHY

Walter Riedel was, as his fifties approached, working at the British Rocket Propulsion Establishment at Westcott, Buckinghamshire, to the north of London. In this era, six years after the 1939-45 war, he brought together his recollection and images of aspects of his experience in rocketry. He dedicated his story to the memory of Max Valier, who had introduced him to the field of liquid oxygen systems.

Riedel's life had been an exciting one in support of new technology born along by the incentive of power and speed, directed to pursuit of military advantage for his native Germany.

To all involved the promise of Space was beckoning in allowing a pleasing rationalisation of purpose and interest as between aggressive and peaceful purpose. Willy Ley paved the way in English language popular technical authorship with *Rockets and Space Travel* in 1948, supplemented as *Rockets, Missiles, and Space Travel* in 1951. Arthur C Clarke with Interplanetary Flight from London, and GP. Sutton with his *Rocket Propulsion Elements* from New York in 1949. Walter Riedel reacted in preparing his monograph presenting a differing and practical viewpoint, and sought publication in association with the British Interplanetary Society. This was not found possible due to the costs of translation and handling of the large collection of diagrams, all of which were hand-drawn by Riedel.

In now bringing this work to publication it is found that there is a shortage of details of Riedel's biography and, therefore, what follows is to be regarded as a basic outline of his life. Most of the facts come from his own monograph; accessible records have been used to add material where possible.

1902

Walter Riedel born in Germany. Educated to Technical College standard.

1929

Employed by the Heylandt Company at Berlin-Britz, specialising in liquid oxygen processes. Due to the association of the Heylandt Company with Max Valier, Riedel enthusiastically worked on demonstration rocket-driven cars, initially powered by CO_2, later on entering the field of liquid oxygen-alcohol rockets.

1930

In May, Riedel was a witness to the unfortunate death of Max Valier, when attempting to operate a rocket chamber with a kerosene/water emulsion instead of the mutually soluble water/alcohol system. This left Riedel as the prime exponent within the Heylandt project group.
Thus, he proceeded with the LOX-alcohol combination demonstrated in the NAG-Templehof car.

1932

Riedel joins Dornberger at Kummersdorf, Berlin, adapting the propellant system for the A-3 project and also carrying out research work on nozzles and chambers.

1934

In association with Dornberger and von Braun at Kummersdorf, Riedel was party to the planned move to Peenemunde, with all its implications for both facilities and staff.

Note: To place our thoughts in authentic historic context for the period, we should best quote Major-General Dr Walter R Dornberger, as speaking at the *Third Symposium on Space Travel* at the American Museum, Hayden Planetarium, New York, in May 1954:

> *" When we started we were four men. The first one was a young student, 19 years of age, who later became Technical Director at Peenemunde, Professor Wernher von Braun, now Division Chief at the Army Guided Missile Centre, Huntsville, Alabama. A second one, a young technician, fired by Heylandt, with some experience in liquid fuel rocket power plants, later Chief Designer at Peenemunde, Walter Riedel, now at Westcott, England. The third, a very skilled foreman, later Chief of the Experimental Shop at Peenemunde, Heinrich Gruenow, now in Moscow. The fourth, myself, at that time Captain in the German Board of Ordnance."*

One could choose to interpret Dornberger's 'fired' as 'fired with enthusiasm'.

1939

Riedel was then Chief Designer at Peenemunde, working on the A4/V-2 project. Due to his 'relative' maturity in a young, expanding team, he acquired the nickname 'Papa', which stayed with him even to his time in England after the war.

1943

Riedel detached from Peenemunde, following some differences between the Design and Development teams. He was sent to Austria to establish a new Design centre. Details of this era are still relatively unexplored, running into the war-end activities and 'Operation Paperclip'.

1945

Riedel worked with the British team at Traune on 'Operation Backfire', which involved the documented firing of several V-2 rockets, so that the British could observe and record the complete process of the launching operations involved in large ballistic missiles.

1946

Walter Riedel transferred to the Rocket Establishment at Westcott, near Aylesbury, as part of the 'imported' German team. This included Dr Schmidt, who – with several others – tragically lost his life in a test bed accident in 1947, involving the running of a German assisted take-off rocket pack.

Riedel worked on a variety of projects, constructively helping in the 'blending' of the British and German teams. During this period, the families of the German engineers had also come to Westcott, resulting in an increasingly pleasant integration of the cultures.

1950

Whilst still at Westcott, Walter Riedel completed the monograph which is the subject of this book. Also, at this time, records show that he travelled to the USA for a meeting at Fort Bliss, where he met again von Braun and many of his former wartime colleagues.

1957

Riedel gained British citizenship, still believed to be living in the Westcott area.

1968

Riedel died aged 66 years.

Peter Stokes, May 2005

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