The foundations of HCCI and petrol engine pre-chamber combustion systems for military aero-engine applications in Second World War Germany

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With kind thanks to combustion research specialist Graham Conway for proofing

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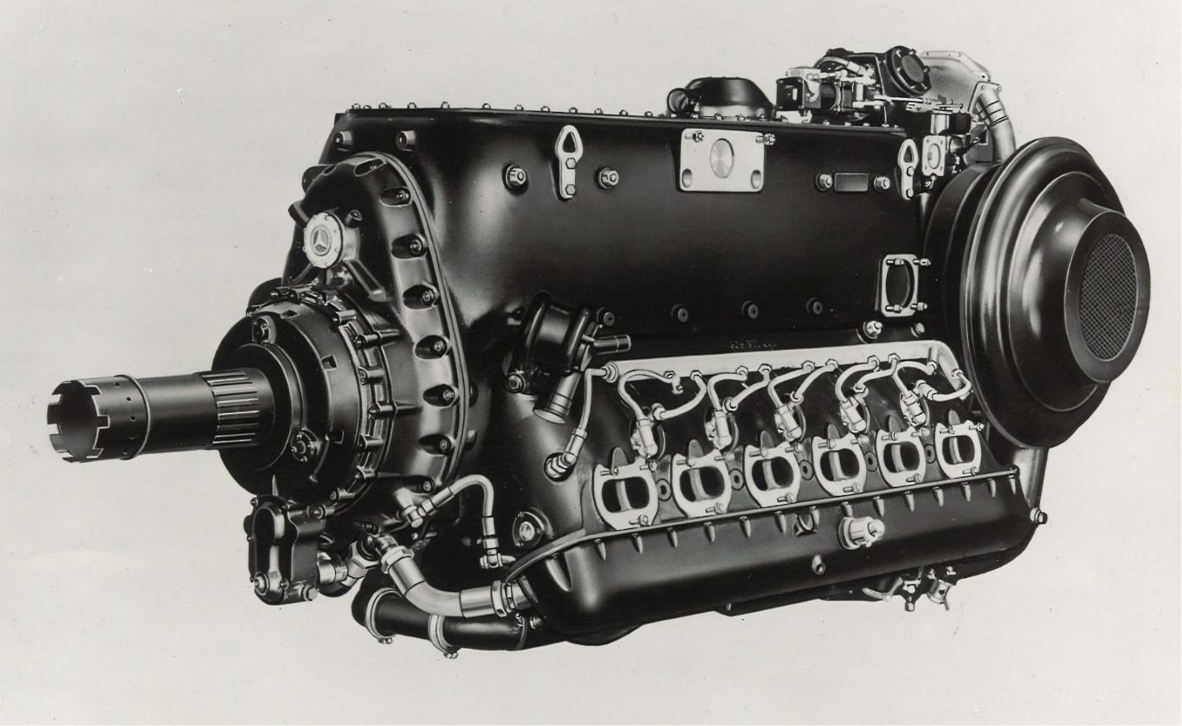

Figure 1: Daimler-Benz V12 aero engine, 1942[1].

1 Synopsis

The diesel engine is controlled by fuel flow, and thus does not require a mechanical throttle to limit the mass of air inducted as it can operated on a wide range of air-fuel ratios. In most situations the petrol engine is controlled by air-flow regulation with some form of mechanical throttle. The fuel introduced is metered to control the air/fuel ratio within some predefined limits, targetting best efficiency, power or EGT. Lean running provides high efficiency however in a boosted engine where MAP is greater than 1Bar it is very difficult to ignite mixtures leaner than lambda 1.3 by spark ignition alone (A-F 19:1), this difficulty increases as manifold air pressure rises.

This paper studies the first time that the operational area between diesel and petrol processes, which is to say spark and compression ignition was bridged. Seventy five years ago prototype engines were manufactured and successfully physically tested, both in test cells and in aircraft test flights at altitudes in excess of 40,000feet (12km). Reference will be made to how such techniques are applied now and the connection between the early developments and modern technique – by comparing the motivations for the development of such different systems at the time and now. The first contemporary use of the technology in automotive use was developed by Toyota Motor Corporation in 1976[2], and also the dual-fuel concept of using a separate ignition-fuel has been tried where it is now referred to as micro-pilot ignition[3].

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[1] Family archive of Dr-Ing. Kollmann, with kind permission.

[2] Development of Toyota Lean Burn Engine. Tech, Noguchi, M., Sanda, S., and Nakamura, N. SAE Technical Paper 1976.

[3] Development of High Density Gas Engine 28AG, GOTO Satoru, Niigata Power Systems Co., Ltd. IHI Engineering Review, Vol. 40 No.1 February 2007.

2 Historical Beginnings

The patents which lay out the basic theoretical possibilities of running a petrol engine along diesel principles were taken out by Rudolf Diesel during his time of employment at M.A.N. in Germany[4]. However these remained on paper, until 1938, when Dipl.-Ing Wolfram Eisenlohr independently proposed a similar system to the diesel patent for use on piston aero engines by the German military[5]. Around the same time, engineers at I.G. Farben fuel laboratories in Ludwigshafen, Germany; also began to work on what they termed the "Otto-Diesel Process". The bulk of this work was conceived, orchestrated and recorded by the chief engineer of the Ludwigshalfen works, Dipl-Ing F. Penzig[6].

The initial motivation for converting the spark-ignition petrol engine to the compression-ignition process was not, as it is now, predominantly for reasons of achieving combustion of ultra-lean mixtures. The motivation was to cure four unique difficulties in the high-energy spark ignition systems of military aircraft operating at very high altitudes. In some cases these piston engine aircraft were flown above the altitudes currently operated at by commercial jet airliners, and in the case of "spy-aircraft" equipped with cameras, it was desired to reach an operating level of 50,000 ft (15 km). The military engines in service at the time, for example those made by Daimler-Benz, Figure 1.could not achieve the desired operating level

The first difficulty faced by high-altitude operation, had been predicted,by the German physicist Friedrich Paschen. Paschen's study on the relationship between pressure and dielectric strength of air showed the wild variation in the ability of air to act as an insulator from sea level upwards towards the outer limits of the earth's atmosphere. Paschen`s Law shows that at sea level it required 30 kV to jump between two electrodes spaced 1 cm apart, at 47,000 feet this had fallen to 1.3 kV (see Figure 2). This presents a difficulty as the aircraft engine magneto ignition system typically produces peak voltages around 24 kV[7], as a result the ignition system experiences catastrophic "flashover" and ceases to run once the dielectric strength of the surrounding air drops significantly below the sparking voltage.

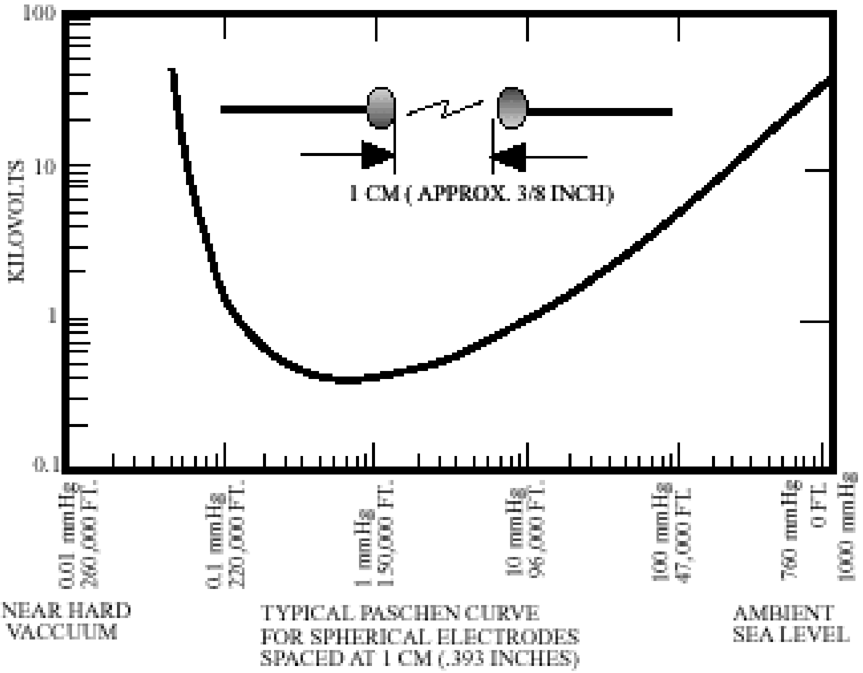

Figure 2: Paschens Law, dielectric strength of air vs altitude[8]

This is manifested in both electric shorting inside the magneto itself, and along the multiple high tension leads from the magneto to the spark plugs. The effect of this was reduced considerably by feeding high-density air from the supercharger or turbocharger compressor outlet into the ignition system via small feed tubes, which attempted to promote the atmospheric conditions equivalent to sea level inside the ignition system assemblies whilst flying at high

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[4] DRP 109-186 MAN & KRUPP, 27th January 1898 (Diesels original patent was DRP 86-633 on 30th March 1895)

[5] Around the same time, he became head of Piston Aero Engine Development at the German Air Ministry.

[6] GDC-FD-2866-46-35T_004

[7] Publication IGN51 – Continental Motors Inc. "The Aircraft Engine Magneto" August 2011

[8] http://catalog.teledynereynolds.com/asset/1431-2.gif

altitudes. This was a partial success but not a cure to the difficulty as sealing the various assemblies is extremely difficult[9].

The second challenge faced was of a more rudimentary nature, in that the electrical screening technology of the time was not particularly advanced and the very high energy pulses in the magneto system produced electromagnetic noise which interfered with other aircraft electrical systems[10].

> "In addition, the whole ignition system must be very carefully screened in order to avoid interference with radio communications, the desire to produce the ignition in another manner is understandable"

A third difficulty was specific to the German engine strategy, which was to boost military engine output as high as possible. To permit high levels of boost, the fuel contained high amounts of tetraethyllead which caused extreme operational reliability problems for the German spark plugs and engine valves. The metallurgical composition of German valves and sparking plugs was highly compromised from the preferred alloys due to chronic shortages of Nickel, Cobalt and Chromium in the case of valves, and by Platinum, Rhodium and Palladium in the case of the spark plug electrodes. Thus, a solution to ignition which did not require a spark plug with such metallic elements was operationally desirable[11].

The final reason was the high incidence of fire in military flights, as crash landings and damage by incendiary ammunition containing phosphorous caused a great many fatalities and grievous injuries to aircrew. To alleviate this, heavy fuels were developed, somewhere between diesel and petrol in behavior, which were much less prone to catch fire. These were known as `safety-fuels` and had been of keen interest to chemists since the 1920`s, when a paper was written by French chemists outlining the basic principles of such fuels[12]. These fuels had been put out of reach of most nations as they proved almost impossible to atomize using a carburetor, and even if they could be encouraged to do so by preheating, did not ignite reliably with spark ignition either.

For these four reasons, it was deemed highly important to conceive and manufacture aircraft engines which could operate without any sparking plug system at all and exhibited some aspects of compression ignition. Since aero-diesel engines of the required output were too heavy for high performance military aircraft relative to the performance from a petrol spark ignition engine, the only solution was to adapt the petrol engine to operate by a method closer to the diesel process.

This was successfully carried out by Dipl-Ing. Penzig, for which he gave the new process the name *Ringverfahren*[13]. He initially described it in a lecture given to the German Air Ministry entitled "The Otto-Diesel Engine" on the 1st of February 1940[14].

The lecture began:

> "A new working process is described for combustion engines which has the following characteristics: -
>
> Mixture formation according to the Gasoline engine method by injecting the fuel in the mixture in the induction or compression stroke.
>
> Ignition according to the Diesel engine by injecting an easily ignitable oil into the gasoline mixture.
>
> This is called the Otto-Diesel process. It is used with low compression ratios of the gasoline engine and therefore requires ignition-fuels which are much more ignitable than the usual Diesel Fuels. The new process has the following advantages: -

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[9] Germany had no native supply of natural rubber, and relied on synthetic "Buna" rubber from 1939-1945. At the time this synthetic rubber had properties considerably inferior to that of natural rubber, both mechanically and in terms of sealing performance.

[10] See GDC-FD-2872-46-20, original page numbers 1 and 3.

[11] See BIOS ER-540, 16th April 1946. Interrogation of Daimler-Benz personnel Kollmann and Rothe.

[12] "Fire Prevention on Airplanes" J. Sabatier, Bulletin No.56, *Service Technique et Industriel de L`Aeronautique*, Jan 1929.

[13] "Ring Process" – the origin of the name is unknown.

[14] "Der Otto-Diesel-Motor" I.G Farben Aktiengesellschaft, Ludwigshafen am Rhein, Bericht Nr. 414, F. Penzig. (FD-2872-46-20)

Power is controlled not by throttling but by alteration of the excess air ratio. This gives low fuel consumption under part load.

The ignition system is not affected by the deposits from antiknock substances and there is not interference with radio communications.

The requirements for the antiknock performance of the fuels are less than those of the gasoline engine with the same compression ratio of 8:1

The knock limit of fuels does not depend so much upon the mixture strength. This fact is particularly striking with aromatic fuels.

This new process is not very sensitive to the quality of the mixture. Therefore high boiling point safety fuels such as TZ900 can be used."

Penzig conducted his work at Ludwigshalven, and published his work enabling the German aero-engine design and manufacturing firms Hirth, Jumo, BMW and Daimler-Benz AG to test the system on their own military service engines of the time. The surviving records suggest that this was carried out only on single-cylinder laboratory engines.

The development of these systems progressed in two main stages, firstly by injecting a special secondary fuel into the combustion chamber by direct injection to cause the mixture to ignite, and secondly a development of this using instead an injector spraying into a pre-chamber, which was obviously in turn connected to the main combustion chamber of the engine.

The final development utilised chamber pressure to act as the pumping mechanism for this special fuel, enabling the elimination of the complexity of a second mechanical fuel pump, this is shown in Figure 8. All the German engines in use at this time were already of direct mechanical petrol injection type, the control of which was actuated by a complex mechanical computer unit. The computer unit adjusted ignition timing, throttle position and fuel flow via temperature and pressure sensors relaying signals mechanically into a system of cams and gears, forming a rudimentary mechanical computer. This was known as the *Kommandogerat*[15], and was pioneered by Dipl-Ing. Helmuth Sachse at BMW Munich in the late 1930`s. It was one of the major technological advances unique to the German military engine development programme of the time, and enabled consideration of complex engine control systems which may have been unfeasible to British and American engineers early in the war[16].

3 Technical Development of German Flame-Spray Gasoline Ignition

3.1 R-300 – Ignition by flame-jet spray

Rather than attempting to use a very high compression ratio to ignite the petrol mixture in pure diesel engine fashion, the ringverfahren method a dual-fuel system, with two independent mechanical direct injection fuel pumps, of cam driven plunger type, see Figure 4. After testing a huge variety of possible fuels, I.G. Farben discovered that one suited all the requirements. This fuel was Diglycol-Diethyl-Ether; dubbed "R-300", which was also subsequently used in Diesel engines as a starting aid[17].

$$C_2H_5 - O - C_2H_4 - O - C_2H_5$$

The fuel was required to not exhibit high levels of corrosive action to common metals, to be stable in storage but to auto-ignite at exceptionally low pressures, the first tests were done in diesel engines adapted for petrol injection. During testing, the compression ratio was lowered in successive stages to give the point at which R300 would fail to auto-ignite. This limit was found to be highly dependent on the engine configuration but a compression ratio of 8:1 was found to work well in all conditions. Whilst the process could be operated at much higher compression ratios,

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[15] "Command Module"

[16] Naturally such developments were studied in depth by technical intelligence in England and America, in departments named A.I.2.g and T-2 respectively (*Air Intelligence Department 2*, Section G, and *Technical Intelligence Group 2*).

[17] British Intelligence Objectives Sub-Committee report 1609, page 4.

the military engines of the time running at the knock limit could not be altered to the higher compression ratios of the diesel engines without detonation occurring.

	Unit	**R300-Fuel**
Specific Gravity	kg/Litre	0.91
Boiling Point	Deg. C	180
Crystallisation Start	Deg. C	-45
Viscosity -30 Deg.	cSt.	5.94
Viscosity 20 Deg.	cSt.	1.5
Viscosity 50 Deg.	cSt.	0.93
Viscosity 99 Deg.	cSt.	0.56
Calorific Value	Kcal/kg	6880
Air Consumption	Kg/kg	9.3
Steam Pressure 80 Deg.	Atm.	0.02
Steam Pressure 100 Deg.	Atm.	0.05
Steam Pressure 150 Deg.	Atm.	0.35
Refraction	-	1412
Flash Point	-	780
Cetane No.	-	190
Oxygen Content	%	22

Table 1: R300 Fuel Specification.

Initial tests showed that not only were considerable improvements in the knock behaviour of the fuels possible, but that the engine could be run successfully at ultra-lean conditions without difficulty (see Figure 3).

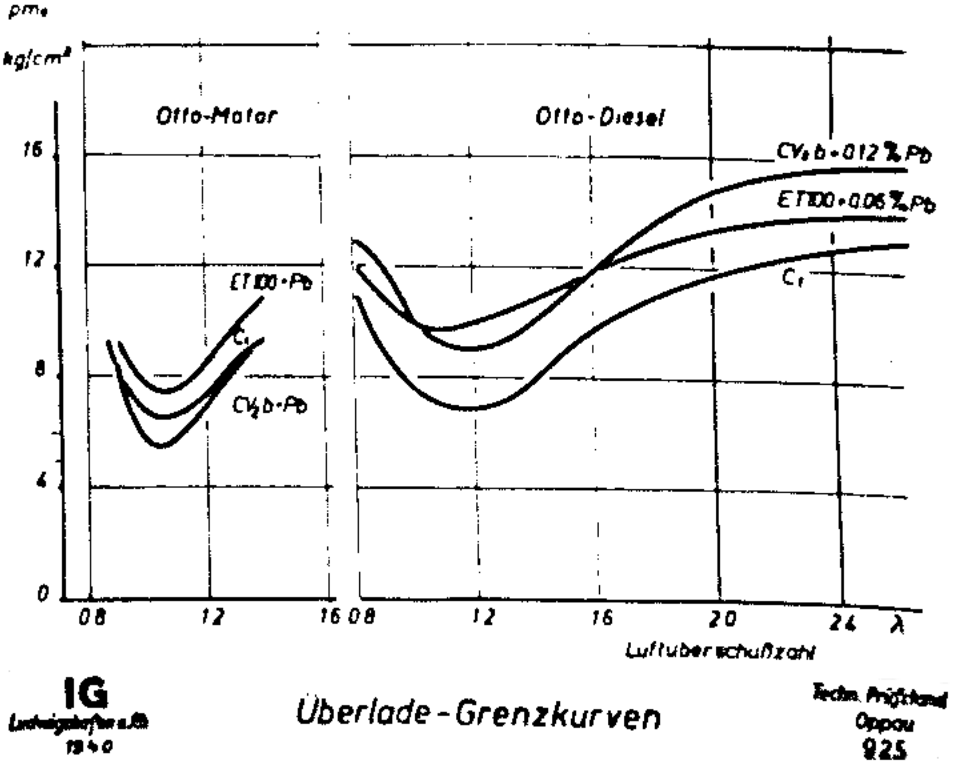

Figure 3: 1940 test on knock limited BMEP of three fuels by spark (Otto-Motor) and jet ignition (Otto-Diesel).

The data shown from this first test compared three aromatic fuels, in terms of the BMEP limit by knock, vs lambda[18]. The first observation is that the engine was able to run at an extended lambda range. The lean limit was extended from 1.3 to 2.4 whilst the BMEP minima's were raised by around 1 bar and the upper limits by around 3 bar over that obtainable from spark ignition. Most of the gain was from running at leaner conditions which could not be obtained by pure spark ignition

The rise in BMEP obtainable from the high compression jet-ignition engine, was so high in the lean region that the test had to be stopped at Lambda 3 because to reach the knock limit absolute manifold pressure in the test reached 3 bar, and could not be increased further without exceeding test limitations. The service military engines of the time were limited to around 1.4 bar MAP, running on an inferior fuel of around 87 MON, rather than the test fuels here which were all around the 100 MON[19].

3.2 BMW Testing – 1st December 1940

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[18] "*Luftüberschußzahl*"

[19] For example "ET100+0.06Pb" is pure Iso-Octane with 0.06% T.E.L. added.

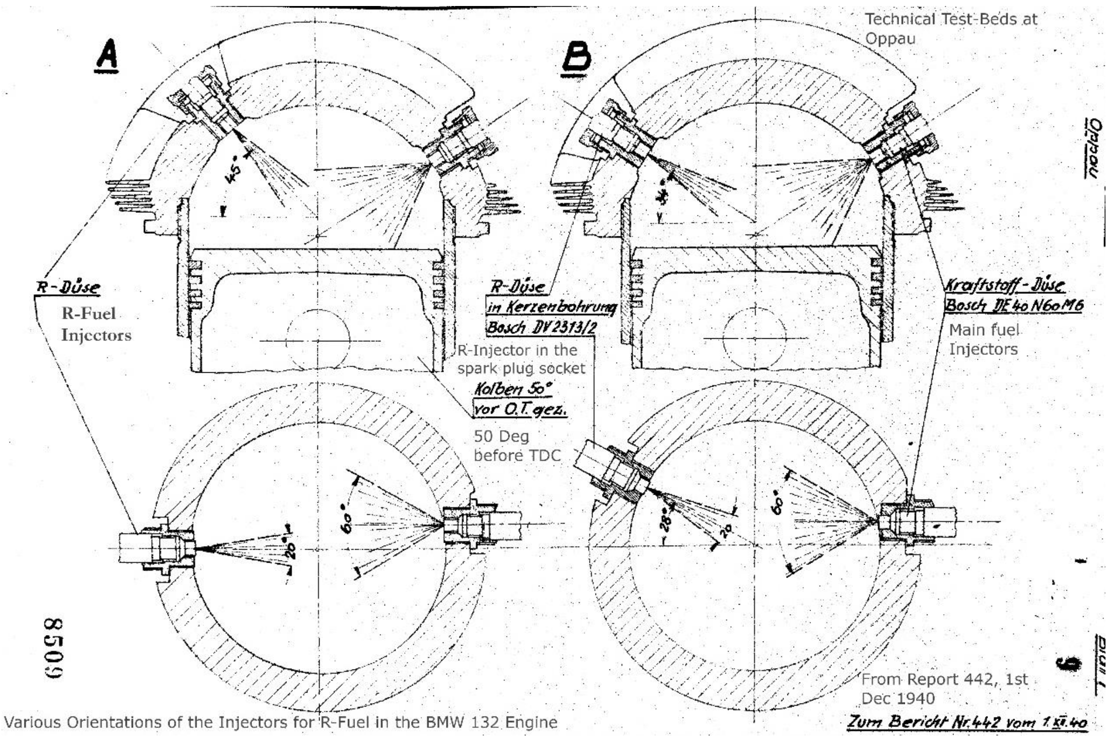

Figure 4: BMW air cooled testing - late 1940, chamber layout[20].

Testing on aging air-cooled BMW132 engines commenced, which were conducted at the same I.G.Farben lab but with the BMW132 cylinder head fitted (for ref. 155 mm bore). The behavior was of a similar trend to tests with the "ring-method" tested in other cylinder designs. The notes on the graph showing that thermal efficiency was in certain areas 12% higher with the "ringverfahren" process as compared to traditional spark ignition see Figure 5. The two systems appeared to have the same thermal efficiency of 33% at full load, with the advantage of the ring-process over spark ignition maximising at low and medium loads. The peak difference being about 4% thermal efficiency in favour of flame jet ignition.

The engineers found that the BMW air cooled engine could also be started at room temperature, without the spark plug at all, provided that at least 50 mm^3 of R300 was injected per cycle.

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[20] GDC-FD-2866-46-1_015

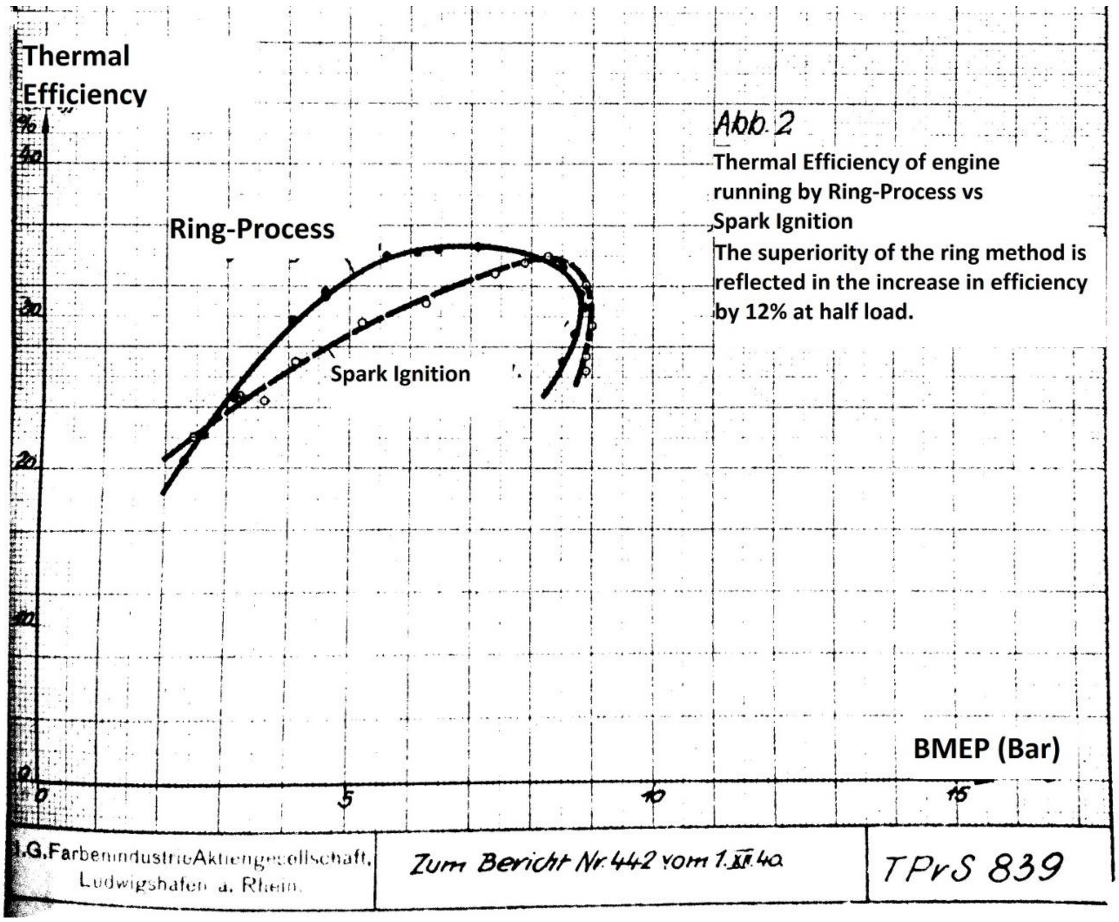

Figure 5: BMW thermal efficiency comparison, x-axis is BMEP in BAR[21].

The paper concludes:

> "Application of the ring process to the BMW132N.
>
> The ring process shows the same advantages with the BMW cylinder especially in the ranges of part loads, as in other aero-engine cylinders which had been tested. It is possible purely by adjustment of the mixture to idle at constant speed. Specific consumption between 90 and 50% remains approximately constant on the minimum value of 1850kCal/bhp-hr (normal spark ignition engine was around 1900kCal/bhp-hr).
>
> It is possible to start the engine with R-fuel at room temperatures without a sparking plug. The influence of the cylinder temperature on power and consumption shows that cooling-air control is necessary. Below 1000rpm it is better for consumption to inject only R-Fuel. When the R-Fuel nozzle is fitted into a sparking plug socket the starting behaviour is a little better but gives no advantage in respect of power and consumption. The injection advance angle can be kept

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[21] GDC-FD-2866-46-1_017

> constant (at constant speed) for the whole range of loads, which is not possible with water-cooled cylinders.
>
> Furthermore we can operate with the same R-Fuel quantity for the whole range by injecting R-Fuel generously
>
> (which gives a particuarly low consumption at full load)."[22]

3.3 Junkers-Jumo211 Engine Testing – April 1941

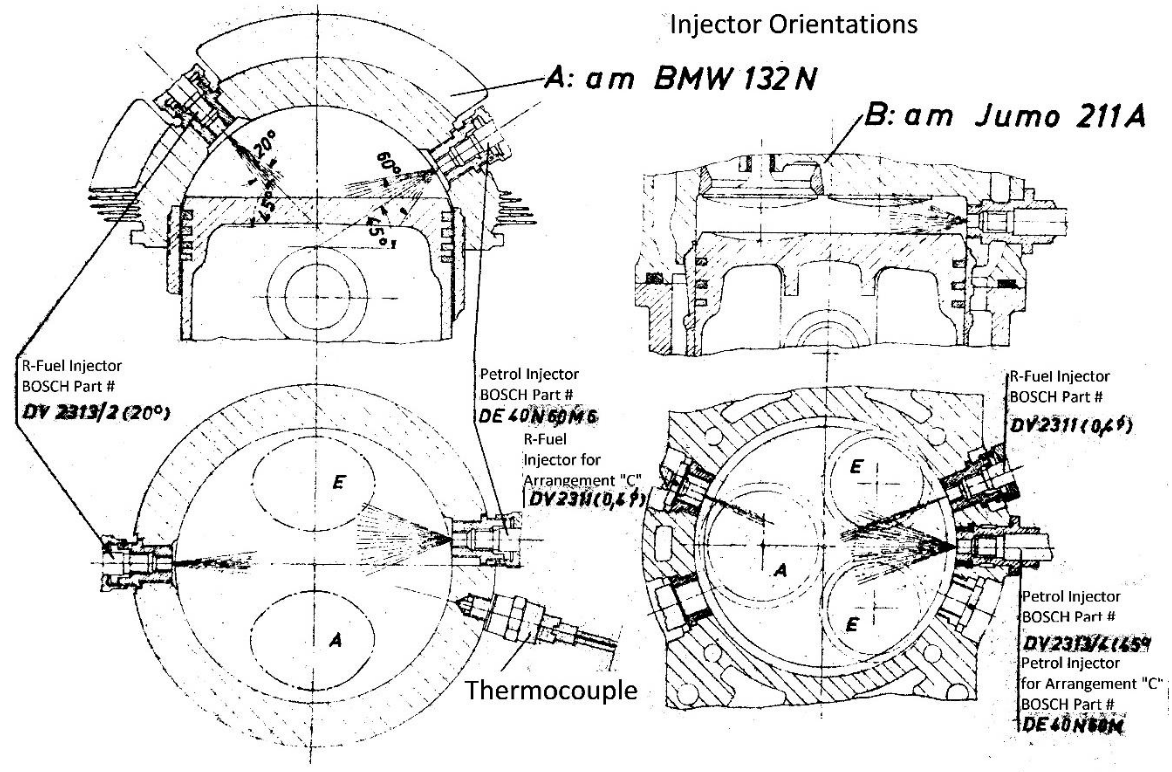

Figure 6: BMW132 vs Jumo211 cylinder test[23]

IG Farben began a series of tests to establish the influence of both metal temperature of the cylinder wall, and of air intake temperature on an engine running with the "ring-process". Although the air-cooled BMW132 was just a testbench engine, the water-cooled Jumo211 was a frontline military engine at the time. The Jumo chamber has five inlets as standard, these being four spark plug threads (only two being utilised at any one time, the other two being used on other cylinders in the full V12 engine installation for reasons of access inside the aircraft). The other being for the normal direct fuel injection system. In this test one of the un-used sparking plug threads is re-purposed to inject R300 fluid[24] by direct injection, positioned next to the main fuel injector[25] (see the lower right-hand side image in Figure 6).

> "The following holds good for both models: favourable performance in the rich mixture region at low intake air temperatures. Low consumption and slowly decreasing performance in the weak mixture field (from half load) at high air temperature".

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[22] GDC-FD-2866-46-1_021

[23] GDC-FD-2866-46-7_013

[24] "R-Stoff"

[25] "Benzin: Bosch-Düse"

One set of data, from the Jumo211 is shown below in Figure 7. Arbeitsdruck being MEP, Verbrauch, fuel consumption, Ladelufttemperature being boost air temperature when admitted to the cylinder, auspuff temperature being exhaust gas temperature and voreinspritzung being injection timing in “KW”, crankshaft degrees before TDC.

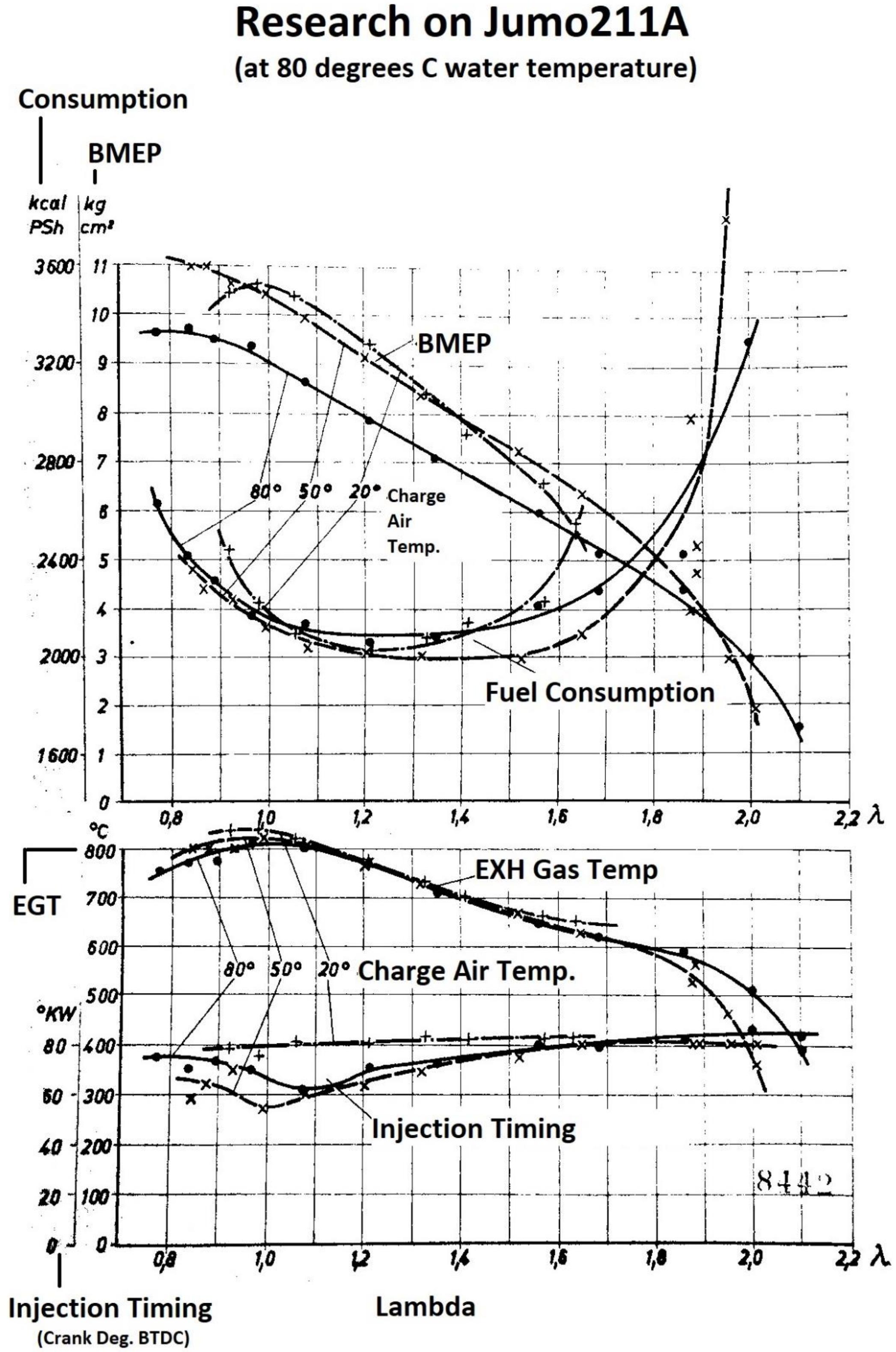

Figure 7: Tests on varying air & water temperatures together with injection timing[26].

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[26] GDC-FD-2866-46-7, Page 14.

3.4 Prechamber Ignition Experiments

Early experiments had used test engines with a supplemental spark ignition system purely for starting the engine, which was then switched off and run only by the injection of the R300 fuel. Studies were conducted to determine if the engine could be modified to also start without any spark ignition or glowplug type equipment either, to reduce the complexity and weight of the whole installation. The testing showed that reliable self-ignition without any spark or glowplug in cold conditions required the R300 fuel to be injected at the same mass flow rate as the normal main engine fuel supply (which is about ten times the normal flow of R300 required), and in addition that the air entering the engine be pre-heated[27].

The Hirth firm pioneered the early work on pre-chamber design for the `Otto-Diesel` by using the design of diesel engine pre-chambers initially designed by the German engineer Prosper L`Orange[28]. A major advantage of which was that the self igniting characteristic of the fuel then depended on the temperature of the pre-chamber itself – and not the bulk temperature of the engine. Hence by heating the pre-chamber, the engine could be started much more easily and economically than by preheating the engine, or the entire engine intake airflow.

Initial tests with the same pre-chamber as the diesel engine, but with gasoline as the fuel proved very disappointing and reached only 9 bar BMEP. Instead the chamber volume was doubled to 6 cm^3 , and the fuel injected at much higher pressure with a secondary mechanical pump instead of the “self-pumped” system implemented by the L`Orange company. These changes produced remarkably better results.

> “Tests were made to determine in principle under what conditions the gasoline mixture in the main combustion chamber could be ignited via a chamber. In these, we injected the ignition fuel into the chamber by means of a pump and nozzle, i.e. we regulated it. Prior investigation had shown that the most suitable chamber dimensions for a 1-Litre cylinder were 5 to 6 cm^3, with a channel diameter of 5-6 mm. The results were remarkable.
>
> R-Fuel consumption was very low with 4 to 5 mm^3/cycle injected: the angle of injection, and the chamber and cylinder temperatures affected the power and consumption of the engine less than with solid injection.”

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[27] GDC-FD-2872-46-9T_007

[28] Then advanced by his son Rudolf, and now trading today as *Woodward - L`Orange*

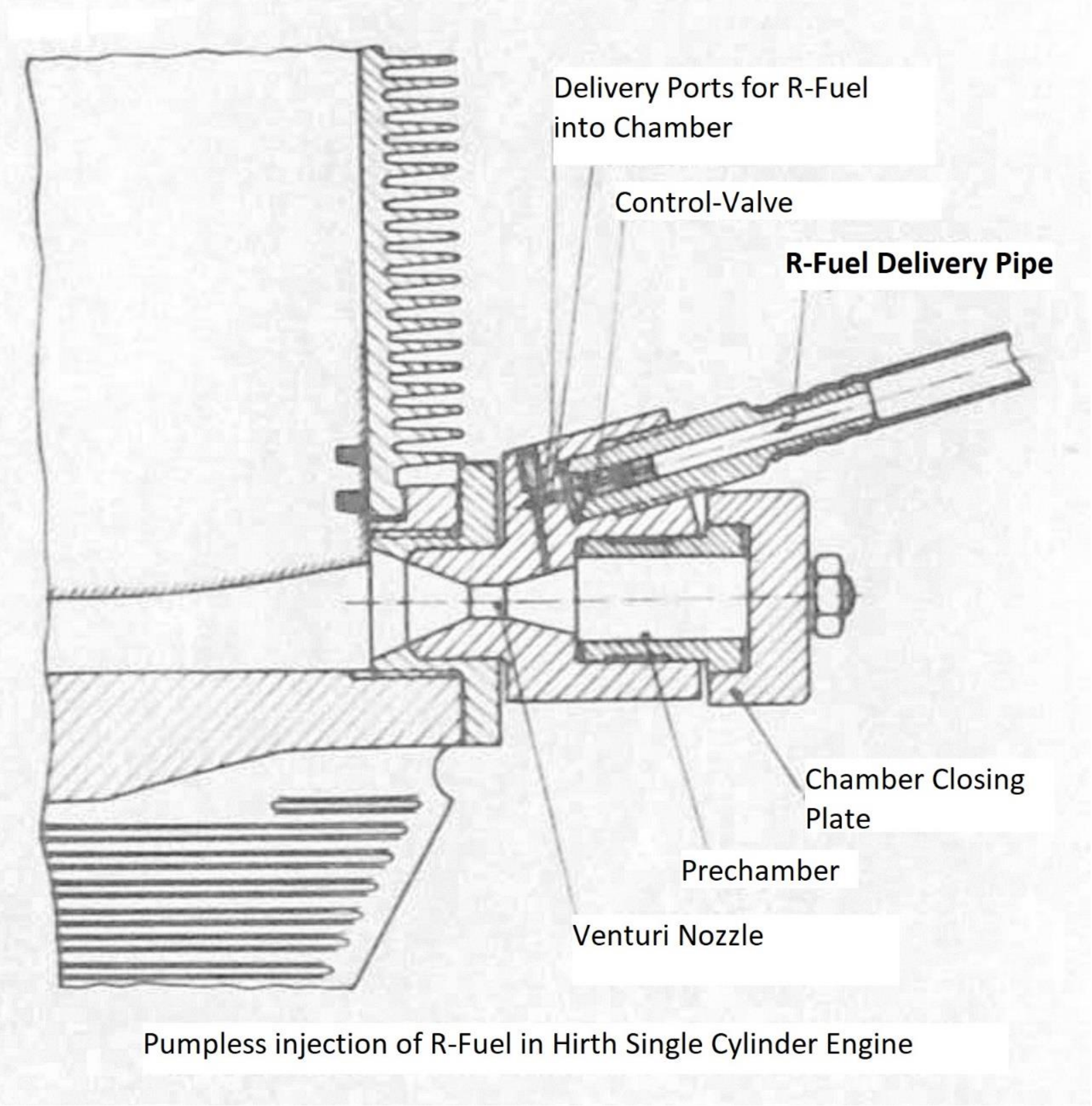

Figure 8: Pump-less injection into the pre-chamber[29].

3.5 15th May 1943 – DB601 Pre-chamber Testing

Further testing was carried out by the IG Farben labs, on applying this system to the DB601 single cylinder engine[30]. The V12 version of which formed the powerplant for the early Messerschmitt Me109 aircraft, which represented the bulk of the German Airforce fighter strength for the duration of the Second World War.

> "Using the DB6001 cylinder with a Hirth pre-combustion chamber, different pre-combustion chambers of our own manufacture and the pre-combustion chamber of a MWM diesel engine, experiments were carried out to improve the knock behavior of the ring process. With one pre-combustion chamber of our own manufacture a general raising of the knock limit by 1 to 1.5 bar MEP was attained...in general it was evident that the pre-combustion chamber was only really efficient in the very lean mixture region, whilst during enrichment the pre-combustion in the chamber was bad owing to lack of oxygen. Thus to obtain the best performance it is necessary to advance the R injection angle...in spite of this the experiments on knock behavior indicated that this kind of ignition is better than the direct jet."[31]

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[29] FD-2872-46-9T, Page 13.

[30] GDC-FD-2866-46-66, Page 10.

[31] GDC-FD-2866-46-66, Page 2.

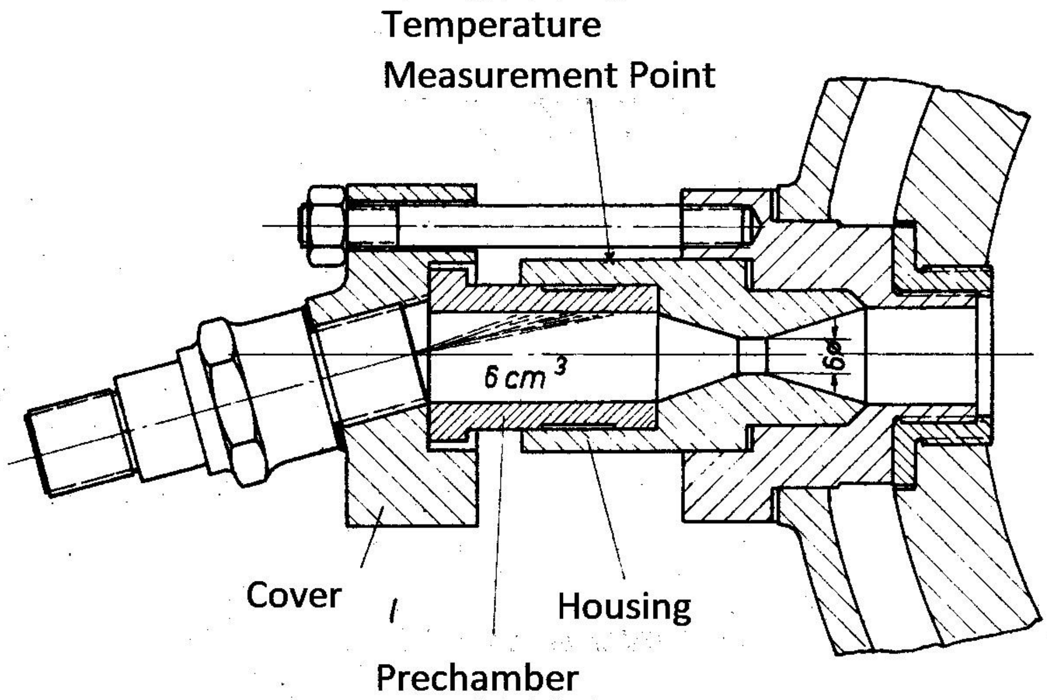

Figure 9: Pre-Chamber designed and manufactured by the Hirth company, on Daimler-Benz DB6001 engine[32].

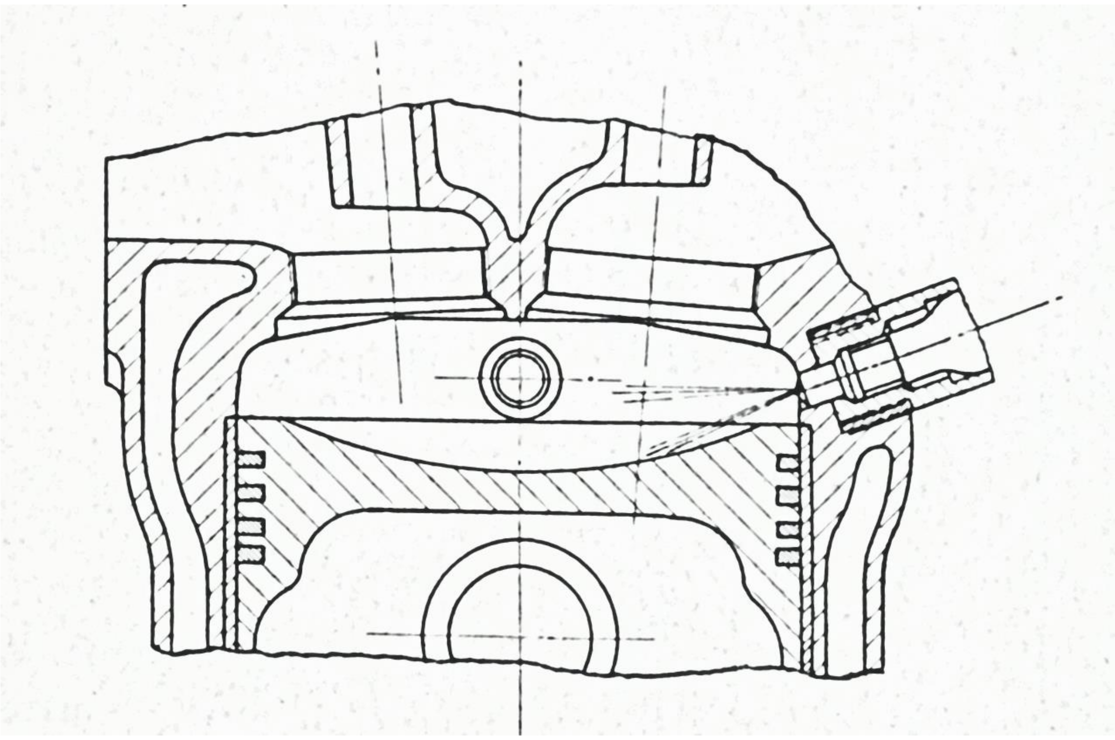

Figure 10: DB601 engine, showing position of standard main fuel injection nozzle in the chamber.[33]

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[32] GDC-FD-2866-46-66, Page 10
[33] GDC-FD-2866-46-66, Page 12

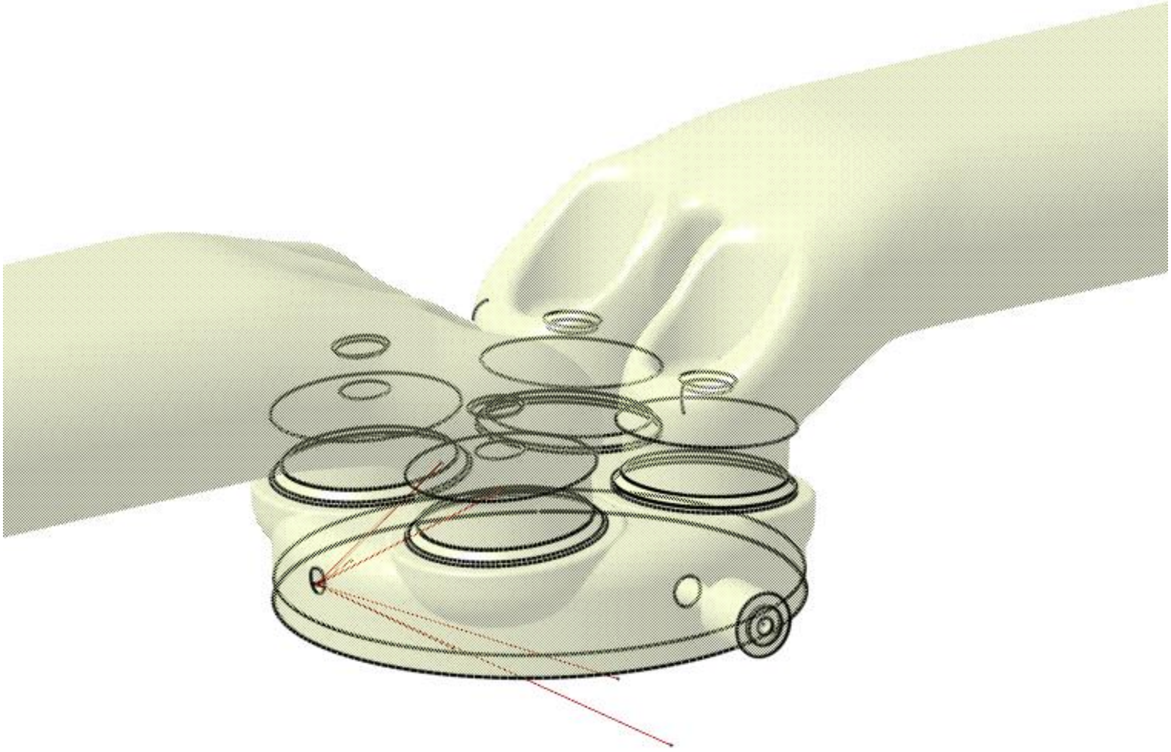

Figure 11: The CFD Fluid Domain for the DB601 with Prechamber and Flame-Spray Ignition

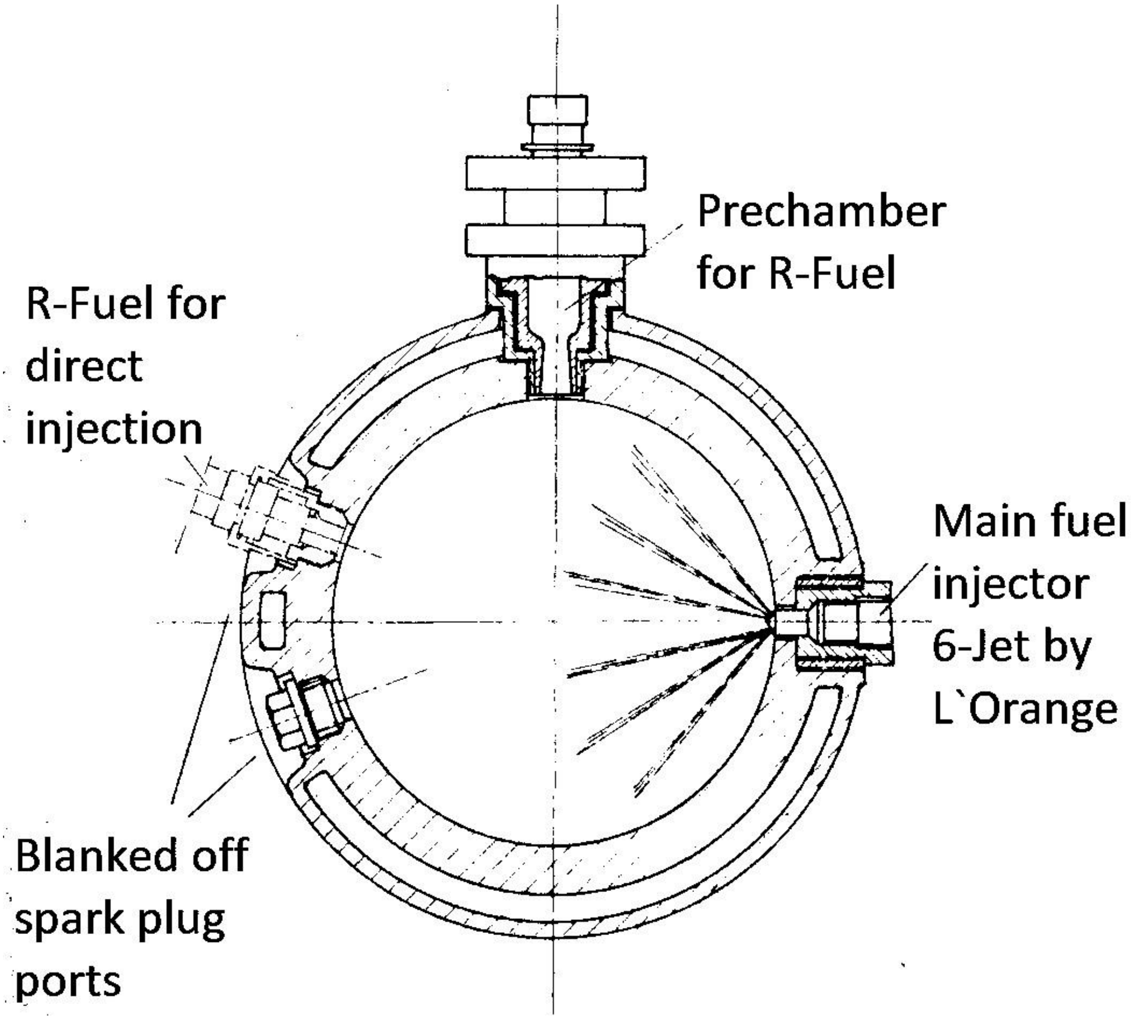

Figure 12: DB601 engine showing top-down view of the chamber layout, `Vorkammer` is the prechamber. Top left is the previous position for direct injection of the R300 fuel, now replaced with the prechamber at the very top centre[34].

The pre-chamber idea had started with that of a Diesel engine.

> "In the pre-combustion chamber of the diesel engine part of the combustion space (about 20 to 25%) is constructed though a narrowing of the main combustion space. The smaller part of the injected fuel burns here, and the ensuing excess pressure blows the prepared mixture with strong atomization and turbulence through the constricted passage into the main combustion space. The purpose of these tests was to show whether there was an improvement in the `Ring-Process` through a similar premixing of the ignited R-Fuel separately from the gasoline fuel, especially in the knock properties as compared to the gasoline process and the direct R fuel injection"[35]

Efforts were taken to thermally insulate the pre-chamber, and as can be seen in Figure 13, the pre-chamber was thermocoupled. According to the tests by Hirth, spraying the fuel at angle against the sides of the pre-chamber internal wall provided the best results (see top centre view on Figure 13).

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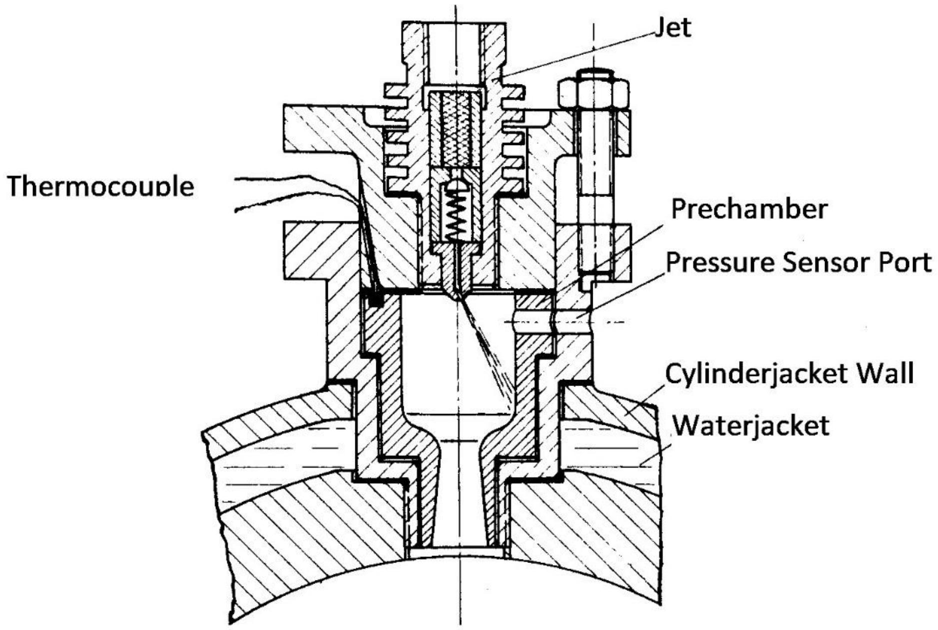
[34] GDC-FD-2866-46-66, Page 12

[35] GDC-FD-2866-46-66, Page 1


Installation of the Prechamber and Mountings into the DB6001 Single Cylinder Engine

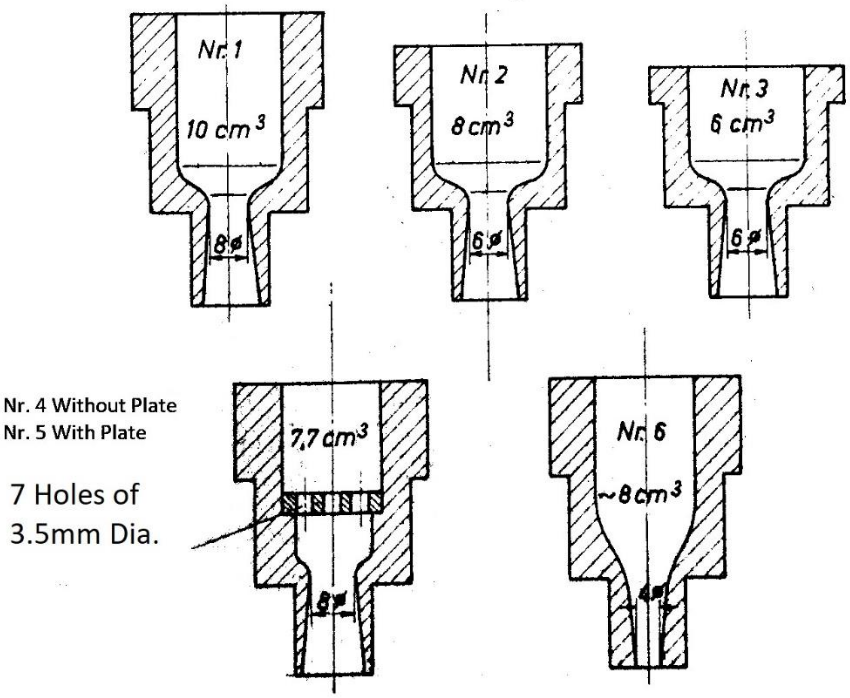

Various Prechamber Designs

Figure 13: Various prechamber designs tested in May 1943[36]. A small bore `Indizier-Bohrung` was used to connect to a quartz cylinder pressure sensor.

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[36] GDC-FD-2866-46-66, Page 21.

3.6 Heat Rejection to Water with the Ring-Process

The significantly lower energy rejected to the engine coolant systems with this R300 ignition system also seems highly significant, although it is speculative as to the exact mechanisms for it to occur as it appears that this may not be restricted to just lean (and hence cooler) burn conditions[37]. The engineers at the time commented that:

> "Tests run with air-cooled cylinders as well as liquid cooled engines have demonstrated that the cylinder head temperatures were considerably lower with the Ring-Process. It a liquid cooled engine the heat carried away by the coolant was 15 to 25% lower with the Ring-Process than with spark-plug ignition at full-load. Further tests were planned but not completed to determine how this difference in heat-loss may be accounted for, particuarly since the exhaust gasses did not show an increased heat loss of equal amount"

Further comment was made in a later report by Chief Engineer, Dipl-Ing Penzig at I.G. Farben on the 1st September 1942[38]:

> "...the heat quantituies rejected to the cooling water are different. This was already pointed out by BMW Spandau (IIIM-Report No 464 of September 9th 1941). Tests with air-cooled engines showed tghat the cooling was obviously too strong. It was found for instance that...we could observe cylinder head temperatures of 220 degrees C with the spark ignition process and 180 degrees with the ring-process. By removing cylinder coolin-fins with a weight of 1.7kg per cylinbder we suceeded in increasing the head temperatures to the usual value of the gasloine spark ignition process.
>
> By exhaust analuses we tried at first to find differences if any in the course of combustion. Ths results are shows on page7[39] and show that the experimental points of the two processes lie with sufficient accuracy on common curves.
>
> Test of coolant heats are shown on page 8, We used a DB6001 cylinder under conditions sililar to those of the previous chapter.

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[37] See CIOS-XXX-I-78 Page 8

[38] GDC-FD-2866-46-35T Pages 5 and 6

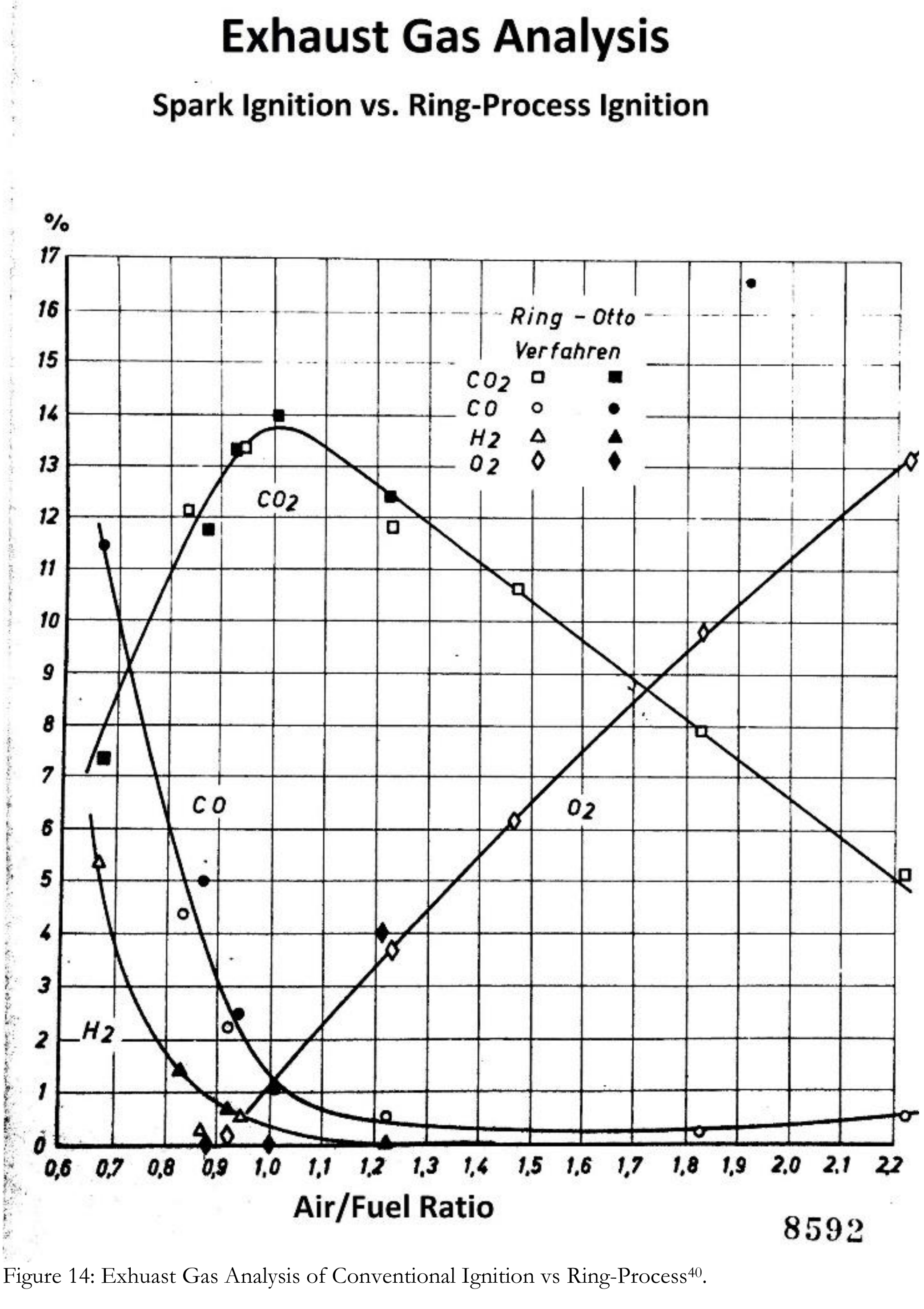

Figure 14: Exhuast Gas Analysis of Conventional Ignition vs Ring-Process[40].

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[40] GDC-FD/2866-46-36, Page 18.

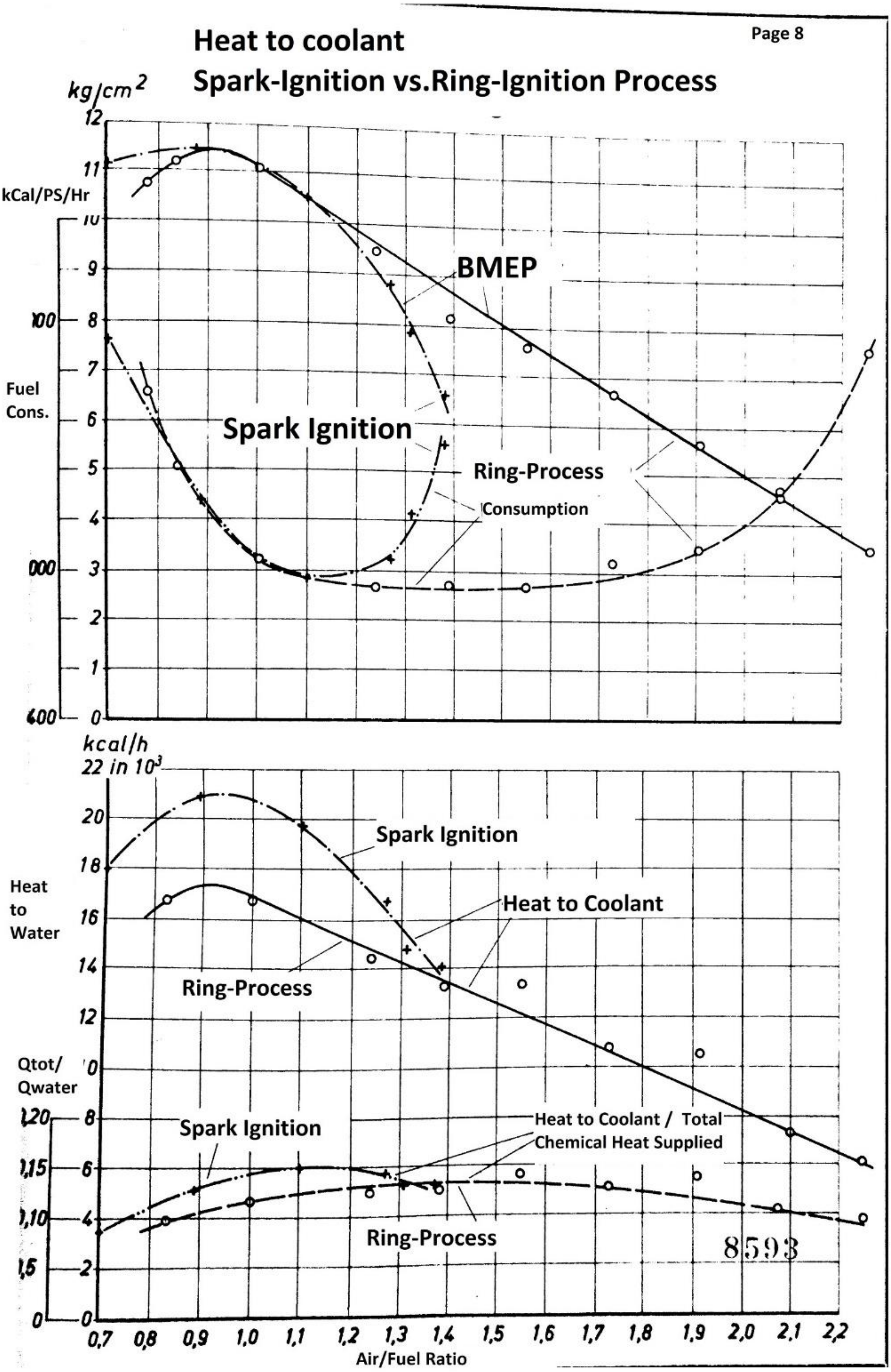

Figure 15: Heat to Coolant of Conventional Spark vs Ring-Process Engines[41].

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[41] GDC-FD/2866-46-36, Page 19.

We had, however another test-stand so that higher-outputs were achieved. The circulation of the coolant was throttled down as far as possible within saftey limits, and thus caused a jump in temperature of about 10 degrees. “Power to Drive Engine Waterpump” shows the power of the I.G. Farben pump used for cooling comparing it with that of the standard DB601 coolant pump.

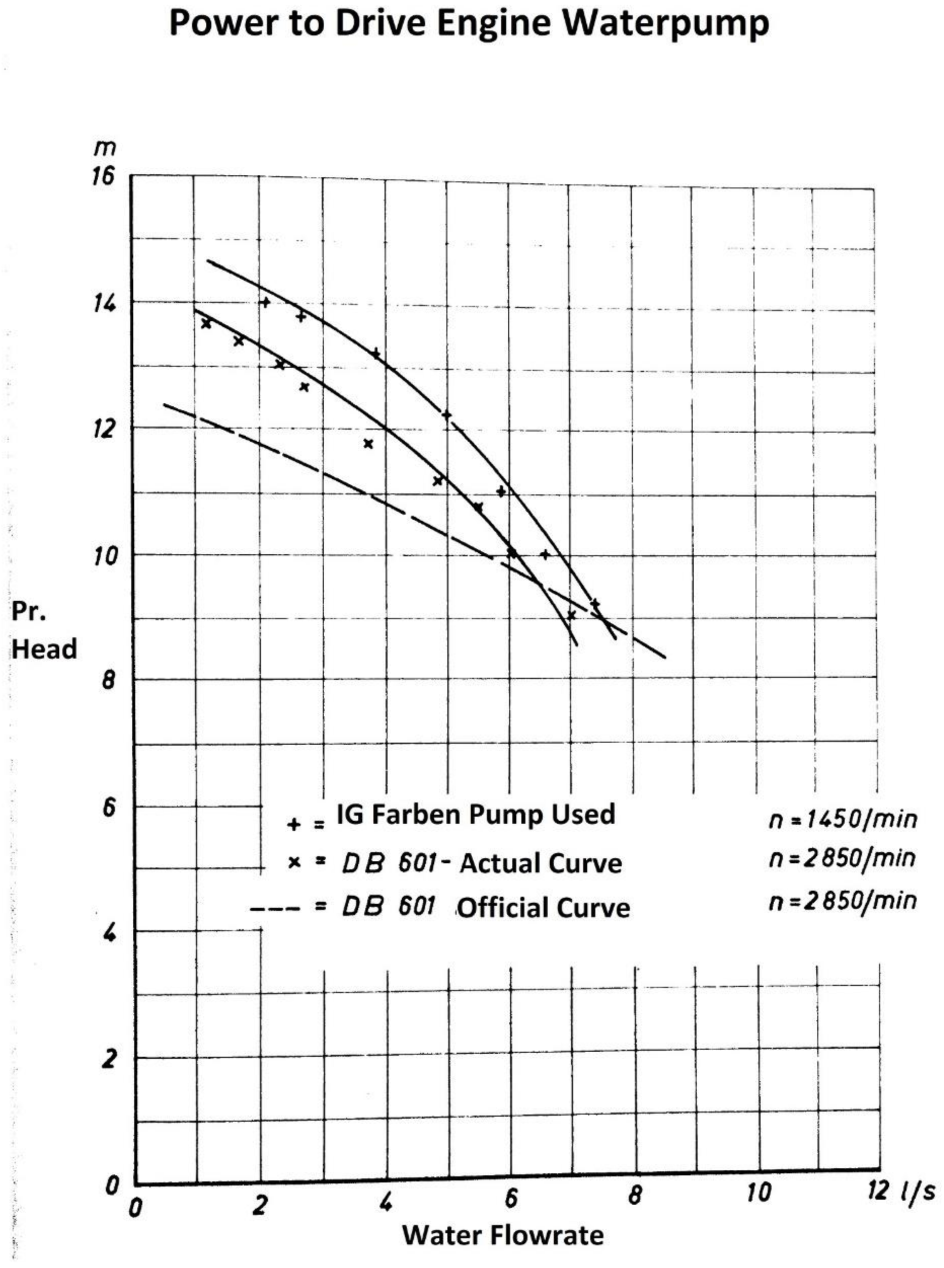

Figure 16: Water Pump Characteristics used in Ring-Process Tests[42].

The heat rejected to the coolant is considerably greater at the power peak in the spark ignition engine than in the ring-process. If we call the coolant heat of the ring-process at this piont ‘100%’ the heat discharge of the ring-process, with a spark ignition engine it rises to 125%. Reconed on the whole heat supplied, the coolant heat in the spark ignition engine is about 3% greater than in an engine operated by ring-process.

The heat given to the coolant when using the ring-process rises at high excess-air ratios, which is obviously caused by slow combustion.

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[42] GDC-FD/2866-46-36, Page 20.

> The exhaust gas and oil temperatures were also measured, do not show that an increased exhaust gas temperature gives the compensation for where the lower coolant heat has gone.
>
> We do not know what causes the reduced coolant heat. This is all the more remarkable in that the form of the diagram described in the previous section suggests a certain after-burning during the expansion stroke. It is intended to carry out thorough tests about the course of the combustion and solve the question of the coolant heat differences."

In contemporary publications the lower heat released to coolant may be explained by the fact that in a combustion event where ignition is initiated at multiple locations (i.e. not one point-source like a spark-plug) the rate of combustion is increased, thus slightly lowering the time for conduction into the engine cylinder and chamber faces[43]. Interestingly it has also been reportsed in the same paper that HCCI engines with spray ignition had also in certain cases demonstrated lower thermal efficiency due to the extra surface area of the prechamber nose protruding into the combustion chamber. It is possible that in much smaller bore automotive engines (half the diameter of the WW2 engines) that the relative area increase caused by the prechamber nose is much larger than that exhibited in the wartime engines.

4 An End to the Wartime Research

With the worsening war situation in Germany later in the war, this research was curtailed as it was decided that it would not have immediate military value. The only reason this research survives is that when Allied engineers and Scientists took all note-worthy research back to the UK in 1945 – key papers were preserved in what is now the building occupied by British Intelligence Mi5. In the 1970`s the portions of this research declared to not have viable current military application were declassified and the remaining papers donated to a public archive, where they may now be consulted in Cambridge. Some of the papers cited here were translated to English in 1947 by the British Intelligence Objectives Sub-Committee, and Combined Intelligence Operations Sub-Committee (BIOS & CIOS).

5 Conclusions Today

The testing carried out was clearly successful in its aim of developing an engine running on the Otto-Diesel process, which is to say with a mixture ignited by compression only, and with output governed by fuel flow not air-flow, but using gasoline as the main engine fuel.

In terms of the performance of the system by injection the ultra-low octane R300 fuel directly into the cylinder without a pre-chamber, appears to be the most favorable option at very rich fuel mixtures, as the low amount of potential oxygen in the pre-chamber appears to limit the amount of fuel which can be successfully burned without a misfire. However, this behavior seems to have been significantly driven by the limitations of the fuel systems available in that without electronic controls, it seems unlikely that the process could be optimized to operate well under a wide variation of running conditions. An overall gain in fuel economy over the typical operating range of these engines was estimated at 5% when using flame-spray ignition instead of spark[44].

The most important aspect of the testing seems to be the excellent performance of flame-jet ignition at very lean mixtures. Which enable it to perform at lambda ranges where the mixture cannot be ignited at all by conventional spark ignition.

It is unlikely that in contemporary applications that the choice would be followed of using a secondary fuel source to inject a flame-spray which ignites under compression only, but would instead be to utilize a sparking plug to ignite the mixture within the pre-chamber to initiate the flame-spray[45]. An example of which would be the Mahle jet ignition system , which incorporates an injector and spark plug in a centrally mounted position to supply the flame-ignition.

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[43] A CONTROL-ORIENTED JET IGNITION COMBUSTION MODEL FOR AN SI ENGINE, Ruitao Song et al. Proceedings of the ASME 2015 Dynamic Systems and Control Conference DSCC2015 October 28-30, 2015.

[44] See BIOS-FR-1609 page 2

[45] Not possible at the time due to the spark flashover at high altitudes as the low atmospheric prssure ceases to be an effective electrical insulator in the magneto and the high tension lines. This was alleviated to a degree in WW2 by feeding boosted air from the compressor exit into the magneto casing and ignition cable outer sheath, but still did not allow the very highest altitutdes to be reached even with such measures.

The systems supply around 3% of the total calorific value with a secondary injector mounted in the side-facing direction to supply the remaining main-engine fuel volume as per Figure 16.

It is interesting to note that the best tests carried out by I.G. Farben on WW2 aero engines in 1943 showed a data point at 10 bar BMEP at lambda 1.9, not significantly outside the ideal range 2.3-2.5 currently being aimed for in mainstream automotive use for low NO_x.

With the possibilities apparent for fully electronic control of nearly all engine operating parameters, the development of the pre-chamber systems seems ripe for exploration. A better understanding of the mechanisms behind the potentially lowered heat-rejection to coolant being particularly promising to reduce vehicle mass and package size in the reduction of cooing system capacity, reviewing of further original reports is underway to prove that this was occurring at fixed Lambda conditions. A further apparent mechanism currently open to investigation would be studies on the possibility to control the temperature within the pre-chamber to determine if any active heating could be beneficial under certain circumstances such as cold running conditions.

Disadvantages:

This system of flame spray ignition seems to have resulted in poor performance at very cold environmental conditions, and some method of controlling the inlet air temperature, and reducing the coolant flow of the engine under cold running conditions was recommended in the original reports. Also, some cylinder types, seem to have responded very poorly to the pre-chamber addition, and others not. At the time it was unclear as to why these differences occurred[46]. This was temporarily solved at the time by retaining a spark ignition system for use under very cold conditions until the engine warmed up. Alternatively, a small external IC engine running on the ground at the airfield was used to feed in artificially heated air into the main engine intakes to resolve this.

The running at low air temperatures was the principle reason for the development of the pre-chamber for administering the “R300” ignition fuel into the chamber[47].

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[46] See BIOS-FR-1609 Page 9 and also CIOS-XXX-I-78

[47] See GDC-FD-2866-46-35T Page 11

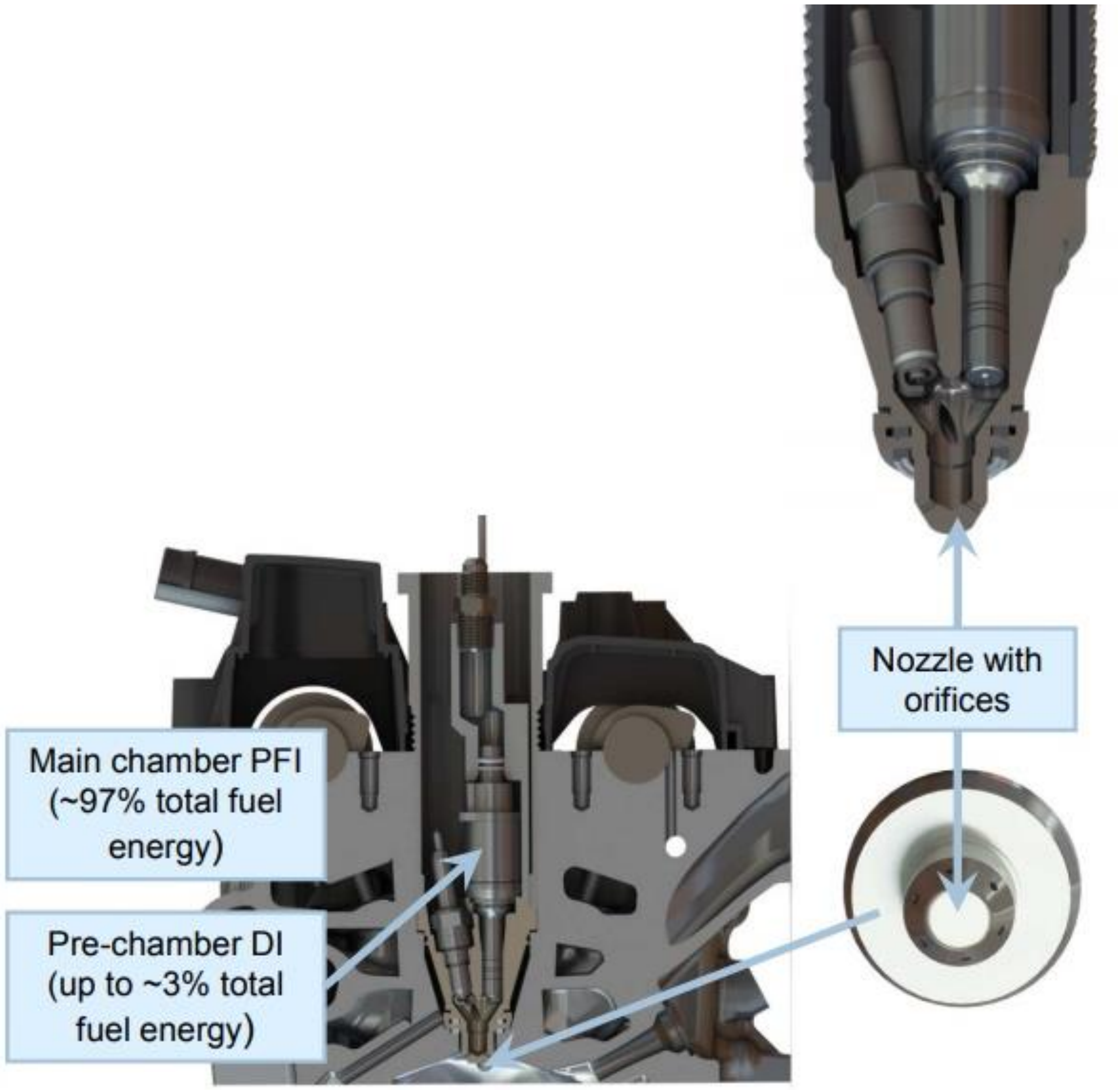

Figure 17: Mahle prechamber system[48].

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[48] Next-Generation Ultra Lean Burn Powertrain, Michael Bunce, Mahle Powertrain, 6th December 2015.

6 References

The data used to construct this report is not in the public domain, but may by prior appointment be consulted at the following address:

Dr Stephen Walton
IWM Duxford
Duxford
Cambridgeshire
CB22 4QR
United Kingdom

It forms the remains of a once larger collection of technical information removed from German firms by British forces in 1945, which resided in the offices now run by British Intelligence Mi5 in London, until the collection was de-classified and archived at the Imperial War Museum, where it now rests.

Arrangements to view the original paper documents at Duxford can be made by contacting IWM directly.
https://www.iwm.org.uk/research/research-facilities

The documents are part of the sub-collection referred to as the "GDC Collection", reference numbers covering the papers in this report are below, which must be provided to the Curator at least one week in advance.

1940/02/01 - GDC-FD-2872-46-20 - IG Farben Bericht 414 – The Otto-Diesel Engine
1940/12/01 - GDC-FD-2866-46-1 - IG Farben Bericht 442 – BMW132
1941/04/03 - GDC-FD-2866-46-7 - IG Farben Bericht 451- BMW132 & Jumo211
1941/05/01 - GDC-FD-2866-46-12 - IG Farben Bericht 460 – Jumo211
1941/07/07 - GDC-FD-2866-46-15 - IG Farben Bericht 467 – Diesel vs R200 vs R300 Fuels
1942/02/13 - GDC-FD-2866-46-31T - IG Farben Bericht 493 – Ring process at various compression ratios
1942/05/25 - GDC-FD-2866-46-36 - IG Farben Bericht 501 – Peak Cylinder. Pressures
1942/09/01 - GDC-FD-2866-46-35T- IG Farben Bericht 500 – The Ring Process – Development Review
1943/01/29 - GDC-FD-2872-46-8 - Lilienthal-Gesellschaft für Luftfahrtforschung – BMW323
1943/05/15 - GDC-FD-2866-46-66 - IG Farben Bericht 541 – Pre-chamber for the Ring Process with DB6001
1943/01/29 - GDC-FD-2872-46-9T - Lilienthal-Gesellschaft für Luftfahrtforschung – Prechamber
1945/07/xx - GDC-CIOS-XXX-I-78 - Combined Intelligence Objectives SubCommittee - Ringverfahren Process
1946/04/16 – GDC-BIOS-ER-540 – Interrogation of Daimler-Benz Staff Kollmann and Rothe.
1947/xx/xx - GDC-BIOS-FR-1609 – British Intelligence Objectives SubCommittee - Ringverfahren Process

Note that the designation "T" means this report is translated from German to English, the BIOS and CIOS reports are always in English and hence have no "T" in the designation. The total in the above amounts to 358 pages, around 80% of which is in German.

Notes:

The BMW132 was a radial air-cooled engine developed by BMW in the mid 1930`s, a single cylinder version was used as a standard test-bed.

The Jumo211 was a water-cooled inverted V12 engine developed in what is now East Germany in Dessau by the Junkers-Jumo company. It was developed into the Jumo213 which was fitted to the most advanced German interceptor fighters in the final stage of the Second World War, such as the Focke-Wulf Ta152 and Fw190-D.

The DB6001 was a single cylinder version of the Daimler-Benz DB601 inverted V12 water-cooled engine, which was used in all early Messerschmitt Me109 aircraft, for example the Me109E in the Battle of Britain. This engine was made into a big bore version of the same cylinder spacing called the DB605 which powered all the late model Me109`s such as the Me109G and Me109K which flew until the end of the war.

BIOS = British Intelligence Objectives Sub-Committee (UK only report)
CIOS = Combined Intelligence Objectives Sub-Committee (UK / US collaboration)