Endnotes

Authors' Introductory Remarks

1. See the German edition of the Wikipedia, https://de.wikipedia.org/wiki/Karl_Kollmann_(Ingenieur); last accessed on December 22, 2020.
2. The title of the bound document was *Konstruktion und Berechnung von Schleuderladern zur Leistungssteigerung von Verbrennungsmotoren, insbesondere Flugmotoren* (Construction and Calculation of Centrifugal Compressors for Performance Improvement of Internal Combustion Engines, Especially Aircraft Engines).
3. Perhaps the best-known equivalent in the UK are the books written by former Rolls-Royce engineers, published by Rolls-Royce Heritage Trust.
4. Douglas, C.E., *War Against Friction*, Race Engine Technology, Issue 54, May 2011.

Chapter 1 – Prelude

1. Diplom-Ingenieur, a now phased-out degree in Germany equivalent to the Master of Science (MS) degree in the Anglo-World. Dr. Kollmann's degree was in mechanical and electrical engineering (*Maschinenbau und Elektrotechnik*).
2. Many of the *German Document Centre* (GDC) documents are still available to consult at the Imperial War Museum archives in England, UK – the references for these documents begin with the prefix "GDC" (https://www.iwm.org.uk/collections/item/object/1030013279). They include extensive series of technical documents, reports and other papers (mainly in German, with some translations) concerning German aeronautical research and development primarily during the WWII, originally collected in the German Document Centre of the Ministry of Aircraft Production / Ministry of Supply, covering a wide range of scientific and technical subjects in the field of aeronautics and relating also to technical developments within specific aircraft and aeroengine manufacturing companies such as Junkers, Focke-Wulf, Messerschmitt, BMW, Daimler-Benz and Hirth. These documents are frequently referred to throughout the text.
3. *1951 folgte Kollmann einem Ruf auf den Lehrstuhl für Maschinenkonstruktionslehre und Kraftfahrzeugbau an der Technischen Hochschule Karlsruhe*. In Germany, university staff often chose their future leaders by committee and invited them from industry to take senior university positions. Thus "calling them", to leave their positions in industry – a very high level of achievement was required to elicit such an invitation, and such an offer was rarely declined.

Chapter 2 – Introduction

1. Martinuzzi, P.F., *German supercharger tests*, The Aircraft Engineer, Volume XIX, No. 2, pp. 505-598, February 29, 1940.
2. The JANAF (*Joint Army-Navy-NASA-Air Force (JANNAF) Interagency Propulsion Committee*) thermochemical tables are compilations of the thermodynamic properties of substances over a wide temperature range, with single phase tables for the crystal, liquid, and ideal gas state.
3. The pyramid inch was supposed to be 1/25 of the 'sacred cubit', an ancient unit based on the forearm length from the tip of the middle finger to the bottom of the elbow. It was about 1/1000 greater than a modern British inch. Pyramidologists claimed that the total length of the four sides of the pyramid was 36,524

(i.e., 100 times the number of days in a year) if measured in pyramid inches. Exact measurements made by the famous Egyptologist Flinders Petrie put an end to that myth.

Chapter 3 – Basic Theory of Centrifugal Compressors

1. *Heinkel HeS-011* is one of the first designs with a compressor stage design, which can be considered a precursor to the modern "mixed-flow" impeller.
2. Needless to say, in this treatise the term "future" should be understood to be from the perspective of Dr. Kollmann in late 1940s.
3. In his manuscript, Kollmann has plots of Equation 3.9 for different values of the compressor pressure ratio. They are not reproduced in this narrative. Equations such as 3.9 are today very simple to evaluate in an Excel spreadsheet, even on a smartphone. This was a big chore in 1930s and 1940s when engineers had only pen, paper and slide rules to work with. Thus, charts or nomograms were used widely to facilitate quick calculations and rough estimates.
4. Even if C_8 were 0, the error would be quite small because C_0 is about 100 m/s so that the error in H_{ad} is about 500 m, which is 500 / 10,000 = 5% for typical adiabatic head at 6 km altitude.
5. The originator was listed as Eck from *The Design of High Efficiency Turbomachinery and Gas Turbines* by D.G. Wilson (MIT Press: Cambridge, MA, 1984).
6. Kollmann and other German authors use the symbol F for the area (from the German *Fläche*) and b for width (from the German *Breite*). We decided to use the more familiar and intuitive A for area.
7. Engineers on both sides were loaded with this onerous task. While using seven-figure logarithmic tables, they still did the requisite math to modern day standards. For example, a 360° volute was simply 360 defined 10 taper wedges cut out and assembled by a pattern maker to a tolerance of better than 0.1 mm ready to cast volutes from (Rolls-Royce). The hours taken to do the calculation were not as demanding as one would think because people were so fast and accurate using these methods at that time.
8. From von der Nüll, *Lader* (Superchargers), 1945, translated and issued by TPA 3, technical Information Bureau for Chief Scientist, Ministry of Supply, GDC 10/13127 T.
9. The very first question to be answered, even before starting thermodynamic calculations, is this: What kind of compressor, axial or centrifugal? This, of course, is outside the scope of the present work. A quick discussion of axial compressors can be found in Chapter 8.
10. *Duralumin*, invented in Germany in 1903, is a now-obsolete trade name for an aluminum alloy containing copper, manganese and magnesium. It was first used in airplane frames in WWI (by Junkers).
11. *Elektron* is the trade name for a magnesium alloy.
12. HZ (*Höhen Zentrale*) Anlage is a double-sided two-stage pre-compressor (driven by a DB 605 engine) that delivers compressed air to two DB 603 engines. It was conceived for application to high-altitude (about 14 km) reconnaissance planes *Dornier Do 217 P* and *Henschel Hs 130 E*. The concept goes back to WWI, when it was applied to giant airplanes manufactured by *Zeppelinwerke Staaken*. These airplanes were equipped with four 260 HP engines that were supplied by charge air from a central compressor driven by a 120 HP engine. A similar concept was proposed by Ackeret of BBC in 1941 (BBC patent CH 221503, see Figure 4-94 on pp. 209 in Eckardt's book cited in Chapter 11, [7] in that chapter).
13. Barometric pressure and ambient temperature at 9,000 m altitude are simply stated as givens in the report. In Ref. [3] in Chapter 3, von der Nüll provides the following altitude corrections with h in kilometer and subscript 0 denoting ground conditions (valid up to h = 11 km):

$$T = T_0 - 6.5h$$

$$P = P_0\left(1 - \frac{6.5h}{288}\right)^{5.26}$$

$$\rho = \rho_0\left(1 - \frac{6.5h}{288}\right)^{4.26}$$

Using these formulae, with P_0 = 1.0 atm and T_0 = 15°C, P and T become 0.3029 atm and 229.65 K.

14. Von der Nüll was a staunch proponent of the piston engines and was not exactly warm to the emerging turbojet technology. This technology was strongly promoted by Helmut Schelp in the RLM, who was instrumental in making the *Messerschmitt Me 262* jet fighter a reality. After the war, Schelp was von der Nüll's boss at Garrett AiResearch, LA (private correspondence with Dietrich Eckardt).

Chapter 4 – Mechanical Construction

1. The first supercharged engine was a two-stroke radial engine built by the US company *Murray-Willat* in 1911-12. Even reciprocating compressors were tried early on with predictably no success. In 1917, an aircraft powered by a 175-HP engine with a *Rateau* supercharger maintained ground pressure at an altitude of 18,000 ft. Although progress was made, supercharged engines did not reach a stage of mass production for use in combat aircraft. In 1917, the US government asked *General Electric* (GE) to take up the development of supercharged engines. *Dr. Sanford Moss* of GE takes the credit for the first successful demonstration of a supercharged engine in the USA. This was achieved in 1918 at about 14,000 ft altitude on a mountain (Pike's Peak) with 350-hp rated Liberty engine, which, without supercharging could only develop 230 hp at that height.
2. See *Complete Casting Handbook: Metal Casting Processes, Metallurgy, Techniques and Design: Metal Casting Processes, Techniques and Design*, Butterworth-Heinemann, Professor John Campbell, 2011 – Section 2.1.1. Bi-films are the pet subject of Campbell, who participated in the creation of the famous *Coscast process* for manufacturing motorsport engine components. The bi-film is essentially the entrained oxide film from a casting mold with high turbulence poured in a standard atmosphere, which then results in effectively un-bonded zones in the final component which promote fatigue failure.
3. Also see the archive document IWM, GDC 11/489 for a study on the cross-sectional areas through the compressor as a whole, including the diffuser and volutes.
4. Pfleiderer and Thuss, *Einige Regeln für die Ausbildung von Ladern grosser Förderhöhe*, Forschungsbericht der Deutschen Luftfahrtforschung Nr. 1981, 1944.
5. Dr. Kollmann made this statement in 1940s. Even in today's standards, 90% axial compressor (isentropic) efficiency is pretty good.
6. Mechanical stresses in curved blades are considerably higher than with straight radial blades, because the curved blades try to "straighten" themselves through the centrifugal forces.
7. See E. Strauss*, Festigkeitsberechnungen hochbeanspruchter umlaufender Scheiben. Die Spannungen in einem Laufrad einer Axialgelaufer*, Deutsche-Luftfahrtforschung FB 1041, 1939.
8. Dr. Kollmann uses the term 'Elektron', also known as *Elektronmetall*, a magnesium-based alloy first developed in Germany in 1908.
9. The tangential stress here appears to have been slightly misrepresented on this particular graph, which should follow the same broad trends as Kollmann's Figure 4.32; in that the tangential stress should not converge on the same end-point at the impeller tip.
10. See the archive document IWM, GDC-11/105T, *Strength and vibration analysis for a steel rotor of DB 603 U Engine*, Bruckner, April 3, 1944.
11. For further details see VDI Forschungsheft 311, Band 12, 1941. Dr.-Ing Max Schilhansl.
12. Alloy 1310.6 is a manganese-vanadium steel comprising of: C: 0.38-0.45, Si: <0.5, Mn: 1.6-1.9, P and S: <0.035, V: 0.1-0.18. This alloy had a minimum 0.2% yield strength of about 885 MPa when in forged condition, with ultimate tensile strength at 1,225 MPa.
13. A free rotating impeller is one not sunk into the back face of the impeller casing, but one where the edge of the impeller front face disc is blended down and has cut-outs between the blades.
14. Daimler-Benz tested this by sprinkling crocus powder on the blades, then connecting the impeller to a signal generator and by making a frequency sweep, identified the resonant frequencies by observing when the powder collected itself into identifiable patterns, each signifying a mode-shape. The blades failed on the same lines showed by the edges of the powder mounds.

15. It is worth remembering the previous statements about the blade vibration being in a severity level approximately to the third power of the height of the blade (reflecting the beam stiffness equations), and hence a tiny change produces a colossal increase in blade stiffness.
16. Here Kollmann makes a cryptic remark that “the Heinkel-Hirth unit cannot be discussed in proper depth here since a separate report is available which deals with it specifically.” This Hirth report was unpublished and has not been located at the time of going to press.
17. The *Ljungström* turbine is a steam turbine invented by two Swedish brothers in 1908. It is a radial flow turbine with two rotor wheels rotating in opposing directions, e.g., one clockwise and the other counterclockwise. There is no diaphragm with stators in between. One rotor wheel acts in that role for the other wheel. Its advantage is higher shaft work output via the same principle as the velocity compounded *Curtis* stage. Its disadvantages are limited size and complex gearbox to combine contra-rotating shaft outputs to a single output. Animation of the operation of the Ljungström turbine can be found on the internet.
18. Active clearance control is used in modern heavy-duty industrial gas turbines to control the turbine blade tip clearance during startup, normal operation and shutdown. This is accomplished by cooling air flow through the casing wall with adjustable flow rate and temperature to keep the expansion and contraction of the casing wall in step with the radial expansion and contraction of the rotor blades.
19. Swirl throttle or *Dralldrossel* in German is what is known today as the ‘inlet guide vanes’ (IGVs)
20. For example, in the Russian AM-35 and AM-38 V12 aeroengines by Mikulin, as fitted to the Il-2 *Shturmovik* ground attack aircraft.
21. This was done on the main inlet to the early *Rolls-Royce Kestrel* superchargers. It lowers the efficiency as it is in effect acting as a swirl throttle by applying pre-swirl to the inlet air. It allows a simple impeller design, but at the cost of performance and was quickly dropped by Rolls-Royce. The early BMW 801 superchargers also used the same system.
22. Pfleiderer, *Sound ground rules for construction of superchargers with high pressure head*, DVL Research Report Nr. FB1981, May 18, 1944.
23. Per von der Nüll (see the reference cited in Ref. [7] in Chapter 3), the casing can also be made from aluminum or magnesium alloys. In most cases, a satisfactory result is obtained with wall thicknesses of 3 to 5 mm. Good rigidity can be ensured by appropriate ribbing. The inner surface of the casing wall must be machined to a smoothness to minimize friction with the airflow.
24. Pfleiderer and Weinrich, *The influence of the pipe conduit before and after the supercharger on the compressor characteristic curves*, FB1935, May 1944.
25. *Die Aufladung von Flugmotoren*, 1947, Daimler AG Corporate Archives Stuttgart DBAG-F318

Chapter 5 – Casing Design and Lubrication

1. The axial play in a deep groove ball bearing is typically too large for some designs, in which case a pair of angular-contact bearings ‘match-ground’ can be used to permit very small axial play without a preload being applied to take up play.
2. Upgrading roller bearings for use in the most arduous conditions is still done in this way today in high performance piston engine design. Often a solid cage is the only upgrade path available to improve the high-speed performance of a bearing, especially when it cannot be increased in axial or radial dimensions. The materials suggested by Kollmann for such purposes have not changed appreciably since he wrote this book in 1947.
3. AISI 52100 alloy steel is a high carbon, chromium containing low alloy steel with 1.3-1.6% Cr content.
4. This will increase thrust loadings as pressure will build up more easily behind the impeller, and also generally reduce the efficiency of the compressor as the tips will not be well aligned with the diffuser inlet and a large gap may develop between the impeller edges and the casing.
5. It is perfectly possible for bearings to overheat in this scenario to the point where the steel turns blue and loses its hardening, with some steels this can occur at surprisingly low temperatures.
6. See page 7 in *Comparison Between Oil-Mist and Oil-Jet Lubrication of High-Speed, Small-Bore Angular-Contact Ball Bearings*, Pinel, Signer and Zaretsky, NASA TM-2001-210462. August 2001 (available from NASA Technical Reports Server NTRS).

7. See *Present Technology of Rolling-Element Bearings*, Richard J. Parker, NASA Lewis Research Centre, January 1, 1983. (available for download from the NASA Technical Reports Server, NTRS).
8. See the chart on p. 25 in *Investigation of 75-millimeter-bore Cylindrical Roller Bearings at High Speeds*, Macks and Nemeth, Lewis Flight Propulsion Laboratory, NACA, November 1950.
9. These figures for the DN factor are not too different from those today. Generally, the very highest performance bearings today might be expected to reach an absolute peak value of 3,000,000 but at very short lifespan and continuous running at a DN factor of 2,000,000 would still be considered high today.
10. Shortage of key materials crippled German piston engine designers during the war. This is discussed in great detail in **TSHR**. The greatest problems were shortages of nickel, chromium, cobalt, silver, vanadium, platinum and copper, which were needed for high temperature alloys for engine valves & exhaust manifolds, and in the case of platinum also spark plugs. Silver was used by the Allies in journal bearings for their high-power aeroengines such as the V1710 with great success.
11. In the USA, Packard manufactured bearings for Merlin V-1650 engine to be used in P-51 Mustang. These bearings had a steel base covered with an extremely thick layer of solid silver. On top of it, there was a final layer of lead-indium. It was far superior to anything that was made in Germany at the time (p. 280 in **TSHR**).
12. *ADMOS Gleitlager GmbH* is a company specializing in plain bearing manufacturing and laser coating.
13. *Antimony* is a chemical element with the symbol Sb and atomic number 51. Antimony forms a highly useful alloy with lead, increasing its hardness and mechanical strength.
14. See the archive document GDC-17/152 (materials laboratory reports from *Junkers Motorenwerke*, 1941-1943).
15. This is countered today by molding *polytetrafluoroethylene* (PTFE) nano-particles into the seal material itself during manufacture, such that a low friction surface always presents itself even when the surface layer is removed over time. Companies like *GregSeal* in the UK manufacture such seals.
16. With the exception of low-speed shafts where modern carbon-faced contact seals have taken over in water-pumps, the concerns Kollmann has here still hold true. Modern seals in this application are also still non-contact in type.

Chapter 6 – Multistage Superchargers

1. High performance centrifugal compressors for modern piston engines might attain 650 m/s tip speed, for example a 110 mm diameter impeller at 113,000 rpm shaft speed – giving a pressure ratio of about 4:1.
2. The effect of methanol water injection above the rated altitude of the engine will only occur if the mixture is introduced before the compressor; otherwise, neither will the impeller be cooled to increase the tip speed, nor will the temperature drop increase the pressure ratio of the compressor.
3. Hans Pfau, *Einfluß* der *Leistungsverhältnisse der Einzelstufen auf das Verhalten mehrerer hintereinander geschalteter Lader bzw. mehrstufiger Lader,* Jahrbuch der Deutschen Luftfahrtforschung, 1938 II- S196ff.
4. Therefore, the compressor stage speeds leapfrog each other with the hydraulic coupling acting to smooth out the transitions, see the DB 627 engine power/altitude graph shown in Figure 7-25 for a graphic illustration of the above process at work in the real engine.
5. MILCH Microfilm, Vol 42, Frame #6395, April 3, 1943.
6. Because the flow is not yet compressed at this point, since the mass flow rate is constant through the compressor, at the first stage inlet its volume will be at its highest level. The velocity is often nearly constant through the compressor as the cross sectional areas will be reduced in line with the local compression ratio.
7. This overhanging bearing was eliminated from the design of the Rolls-Royce Merlin engine in the release of the 100 series. It resulted in improved inlet aerodynamics at the compressor inlet.
8. It is worth noting that this direction of propeller rotation is opposite to that found in Bf 109 during WWII. Later models had shielding slats that were installed above the exhaust stacks, which were extended on that side of the engine where the supercharger inlet protruded out. The fact that Bf 109 was not originally designed for the DB 600 series engine may explain this anomaly.

9. See the engine mounts used in the very late Bf 109 versions with the DB 605 D engine with the larger supercharger for an example of this change in the engine mounting geometry.
10. Later K “Kurfürst” models had a top speed of 725 km/h (200 m/s) at 6 km altitude, which corresponds to a dynamic head of 2,070 m.

Chapter 7 – Drive System

1. This is at odds with automotive engine practice where designers are used to the torsional vibration being *lowest* at the rear. The difference is that the “rear” of the aeroengine is effectively the “front” of the automotive engine, because it is at the opposite end of the propeller, which from the perspective of torsional vibrations takes the form of the gearbox flywheel in the automotive engine i.e. the largest local inertial disc in the equivalent torsional system.
2. NASM, MALL, B2-300340-01 — *Germany, Piston Engines. Questions asked of Visiting German Scientists on Internal Combustion Engines: Wright-Field*, June 19, 1946 (page 4, paragraph 1)
3. Dan Whitney P.E., *A German Assessment of the Allison V-1710 Aircraft Engine*, https://www.enginehistory.org/Piston/Allison/GermanAssessmentAllisonV-1710-R1_1.pdf
4. The coupling part connected to the input shaft is known as ‘impeller’, which acts as a pump. The coupling part connected to the output shaft is known as ‘runner’, which acts as a turbine. The reader can refer to many YouTube videos, which illustrate how the hydraulic coupling works. Unfortunately, it is very difficult to discern the basic principle of operation from the videos of the actual component. It is best understood from Föttinger’s patent drawing (see Figure 7.13).
5. Actually, it is the speed ratio but also equal to coupling efficiency when $M_1 = M_2$.
6. Daimler-Benz developed a variable valve timing mechanism for this engine at the end of the war, which was designed to set the valve overlap to reduce as aircraft altitude rose, to take account for the lower external air pressure.
7. The idea of a central compressor delivering pre-compressed charge air to the main propulsion units goes back to WWI, e.g., see the endnote 10 in Chapter 3. Interestingly, Russians had the same idea, the ATsN (*Agregat Tsentralnovo Nadduva* - centralized supercharger) for deployment on the high-altitude *Petlyakov Pe-8* bomber (TB-7 – TB for *Tyazhyoliy Bombardirovshchik* or ‘heavy bomber’). It was designed in Kharkiv Aviation Institute by a team led by Arkhip Mikhailovich Lyul’ka (1908-1984), who was the father of Russian gas turbine jet engines. The central supercharger was driven by a 750 hp *Klimov M-100* engine and supplied pre-compressed charge air to four 950 HP propulsion engines (*Mikulin AM-34FRN*).
8. See TNA, KEW, AVIA-15/1648, *New High Altitude Fighter Air Staff Requirement and Policy” and AVIA-15/1618, “Liquid Oxygen & Nitrous Oxide Equipment in Spitfire*.
9. Note that, whilst this gives good results, it does present the friction/mesh coefficient incorrectly as peaking at the pitch circle diameter, when in fact at that location sliding reaches zero and therefore friction reaches its minima. More recent papers have corrected this, although it does not seriously impact the accuracy of the results of their model.
10. Certain oil manufacturers and testing outfits spend a lot of time and money with elaborate laboratory apparatus to obtain such data. Persuading them to part with it may require some perseverance!

Chapter 8 – Alternative Systems

1. In research labs at TU Stuttgart (*Forschungsinstitut für Kraftfahrwesen und Fahrzeugmotoren Stuttgart*) during the war, a 48-cylinder air cooled engine was developed at the, each of which was boosted by two axial superchargers. The overall design was never implemented in production, but the compressors appeared to work successfully.
2. Meher-Homji, C.B., Prisell, E., *Dr. Max Bentele – Pioneer of the Jet Age*, GT2003-38760, ASME Turbo Expo 2003, June 16-19, 2003, Atlanta, GA.
3. From the May 1945 Report, *Turbine Engine Activity at Ernst Heinkel AG*, IWM CIOS File No. XXIII-14.

4. Adopted from Tiwari, M, *Axial Compressor Design with Counter-Rotation and Variable RPM for Stall Mitigation*, Embry-Riddle Aeronautical University (2014).

Chapter 9 – Interlude

1. Tip or blade lean is the movement of airfoil sections normal to the chord line (the straight line joining the leading edge of the blade with its trailing edge). It is measured as an angle (e.g., 0° for zero lean).
2. Lead is being progressively phased out from many commercial vehicle components (batteries being an obvious exception) due to its harmful impact on human health and environment.
3. It should be noted that Zeppelins and German Gotha bombers (later in the war, including daylight and night raids) made strategic bombing raids to London during the war.
4. Heinkel He 100 briefly held the world speed record at 746.606 km/h (463 mph) on March 30, 1939. Heinkel test pilot Hans Dieterle flew the eighth prototype to set the record. Messerschmitt ultimately broke that record with the first prototype of the Me 209 (not the Bf 109!). For details see Ref. [2] in Chapter 9.

Chapter 10 – Exhaust Gas Turbine

1. As discussed earlier in the book, multistage superchargers were needed at such high altitudes to achieve the requisite pressure boost. This went hand in hand with increasing parasitic power imposed on the main engine shaft to drive the supercharger. Consequently, driving at least the first stage of the supercharger with an exhaust gas turbine was the ideal solution.
2. Note that PR* is defined herein as the ratio of inlet-to-discharge pressures. In many gas dynamics texts, PR* is defined the other way, i.e., the ratio of discharge-to-inlet pressures. In that case PR* = 1/1.9 = 0.526.
3. In case of incomplete scavenging, left-over exhaust gases in the cylinder hurt combustion efficiency (or cause knocking) in the next cycle and reduce power output.
4. Blowdown happens between exhaust valve opening and BDC. During blowdown, residual exhaust gases are expelled from the engine before the exhaust stroke begins (see Figure 10.8).
5. From the archive document GDC-11/312, *Comparison of DB 623 V4 with three-way and six-way exhaust gas collector manifolds*, December 23, 1942.
6. DB 627 was DB 603 with a two-stage mechanical drive supercharger and after-cooler. Development was abandoned in March 1944.
7. On page 5 of Evaluation Report No. 539 (16 Apr 46); the translator has the name of the developing engineer as ‘Leitz’. This is almost certainly a typo. The person in question must be Dr. Karl Leist, who was in charge of the development of Daimler-Benz turbofan engine 109-007.
8. *Zweikreis Turbine Luftstrahl* (ZTL) is German for Double-Circuit Turbojet. The two circuits refer to the airflow through the engine core (i.e., compressor, combustor and turbine) and the secondary (bypass) airflow through the ducted fan. See Section 11.4.1 for more on this.
9. The BMW 801 is an air-cooled, supercharged 14-cylinder (arranged in two rows) radial engine. The basis for BMW 801 is the American Pratt & Whitney Hornet, for which BMW a took out a construction license in the 1930s. Over 28,000 units were made and used in bombers such as Ju 88 and fighter planes, e.g., the Focke Wulf Fw 190. This was the first engine outfitted with the *Kommandogerät*, a mechanical-hydraulic device that could control the fuel flow, the angle of inclination of the propeller, the supercharger setting, the fuel-air ratio, and the ignition timing automatically and all at the same time, depending on the position of the throttle
10. Another planned turbocharged BMW engine was 801 Q, also based on 801 E engine, with the Hirth turbocharger 9-2426. Its delivery was expected in mid-1945. Its projected performance was 1,715 HP at 12..2 km altitude, easily making it the most power engine of the war.
11. The name of this aircraft, *Störtebeker*, said to be given by Hitler, comes from a 14th century German privateer in the Baltic, who was the leader of a group known as *Vitalienbrüder*. The name is both a nickname and a surname, meaning “empty the mug with one gulp” in Low Saxon (Wikipedia).

12. Plans called for production of 300 to 400 Ju 388s a month at seven different manufacturers. Only 176 were completed by the war's end (including some Ju 188 conversions). The Ju 388 J (heavy/night fighter) was produced in the greatest numbers, with 102 being built. In addition, 48 Ju 388 L-1s (reconnaissance) as well as ten Ju 388 K-0s and six Ju 388 K-1s (bombers) were built by Henschel before production was cancelled in February 1945. The Luftwaffe received only 23 Ju 388s in service. A very few Ju 388 L-1 may have flown some photo reconnaissance sorties during 1944 and 1945, but the type was never fully operational.
13. The Ju 388 L-1 at the *National Air and Space Museum*, with construction number (*Werke Nummer*) 560049, was the eighth of the series manufactured at *Weser Flugzeugbau*'s Nordenham plant. Parts of the airframe were built at ATG in Altenburg and at *Niedersachsische Metallwerke Brinkmann & Mergel* in Hamburg-Harburg. Completed early in 1945, the aircraft was captured by U.S. troops at Merseburg in 1945 and is the only Ju 388 known to exist.

Chapter 11 – Turbojet Engines

1. Technical Bulletin No 2, published in January 1941. Cited from p. 24 of [17] in Chapter 2. In all fairness, von Kármán stated in his memoirs (p. 225 in "The Wind and Beyond," Little, Brown and Company, Boston, MA, 1967) that the report was written and issued while he was in Japan.
2. *Napier Nomad, An Engine of Outstanding Efficiency*, Flight, 30 April 1954, pp. 543-552. The article also contains a summary of the lecture given by *E. E. Chatterton*, the chief engineer of Napier's piston engine division, to the Royal Aeronautical Society (April 1954), *Compound Diesel Engines for Aircraft*.
3. Part of the reason for the impressive performance obtained by the Nomad was down to Napier engineer 'Tiny' Dilbert. During WWII, he helped lay the foundations of what would become known as Time-Marching Integration, for computing compressor work through the system. Their goal was to distribute the compression work evenly throughout the axial compressor stages. (Per private communication with one reviewer - undocumented.)
4. Modern industrial gas turbines are pushing the 500 MW rating limit (in 50 Hz) with airflows more than 1,000 kg/s, which would be difficult to achieve in a piston-cylinder configuration with comparable power density.
5. Hoffmann, N., *Reaction Propulsion by Intermittent Detonative Combustion*, German Ministry of Supply, Völkenrode Translation, 1940. Cited by Kailasanath, K., 2000, *Review of Propulsion Applications of Detonation Waves*, AIAA Journal, Vol. 38, No. 9, pp. 1698-1708
6. Section 11.2.2.1 is based on information from Interrogation Report No. 4 in AIR-40/78, *German Turbo-Jet engines - BMW Types*, Kew National Archives, London.
7. Curtis wheel is a velocity-compounded impulse stage with a row of fixed nozzles followed by two or more rows of moving blades alternating with rows of fixed blades. It was invented by *Charles G. Curtis* (1860-1953), who, in his early designs, used velocity compounding and pressure compounding in the same machine. His 1901 5,000-kW vertical steam turbine in Schenectady plant of General Electric is an ASME landmark.
8. Two engineers in RLM, Helmut Schelp and Hans Mauch, were instrumental in RLM's reaching out to aircraft and engine manufacturers to develop jet engine powered aircraft.
9. German engineers and aerodynamicists, especially those with academic R&D background, realized the advantage of the axial compressor in aircraft propulsion early on. One of them was Dr. Anselm Franz, the chief designer of the Jumo 004 in Junkers, who was instrumental in convincing Helmut Schelp in the RLM to focus on the axial designs. Consequently, the RLM supported Junkers and BMW but not Heinkel, who continued with centrifugal compressor designs.
10. The Japanese produced a derivative, the *Ishikawajima Ne-20* that was intended to power the *Nakajima Kikka*, Japan's first jet fighter, of which only one prototype flew before the end of the war. After the war, BMW engineers who had emigrated to France used their expertise to produce the *Snecma Atar (Atelier technique aéronautique de Rickenbach)*. The Atar was derived from BMW 018 design and it powered many of the French post-war jet aircraft, including the Vautour, Étendard and Super Étendard, Super Mystère and several models of the Mirage. In USSR, the BMW 003 formed the basis for the RD-20 which powered the Mig 9. Similarly, Jumo 004 B was adopted by the Soviets as RD-10 and powered their fighter Yak-15. (RD stands for *Reaktivny dvigatel'* or reaction engine.)

11. For example, *Pratt & Whitney F119*, the afterburning turbofan engine developed for the *Lockheed Martin F-22 Raptor* advanced tactical fighter. This engine has contra-rotating high and low-pressure turbines.
12. *Brandenburgische Motorenwerke*, *Bramo*, was the company resulting from the reorganization of Siemens-*Halske* aircraft company in 1936. Bramo was later purchased in 1939 by BMW to become *BMW Flugmotorenbau*.
13. Refer to the published memoirs of German fighter aces *Johannes Steinhoff* and *Adolf Galland* for the rocky history of the introduction of *Messerschmitt Me 262* into combat service. The saga even includes a “pilot’s mutiny” to force Göring’s resignation.
14. Adolf Galland admits that, in the history of aircraft design and construction, this was a singular feat indeed. Nevertheless, he was vehemently opposed to this project because it had “insufficient performance, range, armament, bad conditions of sight, and dubious airworthiness.” On top of everything, it would take away resources from badly needed Me 262 (pp. 268-69 in [16] in Chapter 11).
15. A more elegant solution would be to generate electric power to drive motors for traction. This was prevented by the shortage (and poor quality) of copper needed for motor windings.
16. According to a blog post on the web (https://blog.tiger-tank.com/tanks/gas-turbine-jagdtiger/ - last accessed on 02/12/2021), the only working prototype ever built appeared on a Henschel *Jagdtiger* self-propelled gun provided by Porsche. The unit (Porsche referred to it as Type 305) was installed longitudinally in the tank’s engine compartment. The exhaust pipe rose upwards from the rear of the vehicle. In order to remain unseen from the air, testing of new vehicles took place in forested areas. The exhaust from the gas turbine emerged at 350°C, which, according to witnesses, set fire to the trees around it. We have not been able to verify the source and veracity of this information.
17. Section 11.3.2 is based on information from Interrogation Report No. 42, AIR-40/78, *German Turbo-Jet engines - BMW Types*, Kew National Archives, London.
18. Before joining Daimler-Benz, Prof. Karl Leist worked in DVL where he first concentrated on exhaust gas turbines and later on turbofan powerplants (known as ZTL*, Zweikreis-Turbine-Luftstrahltriebwerk*). He first started with DB 670 (ZTL 5000), a ducted fan with compressor feeding an afterburner, driven by a DB 604 X-24 engine (with four inline rows of six cylinders in X arrangement) delivering 1,864 kW (2,500 hp). As expected, at 1,700 kg weight and 600 kg thrust, it had a dismal thrust-to-weight ratio (900 km/h at 6 km altitude) and stood no chance.
19. Adolf Galland is adamant on this one (pp. 30-31 in Ref. [16] in Chapter 11): “In effect, the actual battle sector over England represented not even one tenth of the total area of the island.” The implication was that the British could manufacture Spitfires, Merlin engines, and train pilots to put into the Battle of the Britain unimpeded.
20. Before and during WWII, Germany had two *Graf Zeppelin* class aircraft carriers in planning, designated A and B, with the official design covering the five year period 1934-1939. The first one, A, named *Graf Zeppelin* was launched in 1938. Construction was stopped in 1940 until being ordered to resume in 1942. In 1943, once again, construction was stopped. The unfinished ship was scuttled in 1945. It was salvaged by the Soviets and towed to Leningrad. The ship was broken up there in 1948-49. The second one, B, was also launched in 1938 but its building was stopped in 1939 and the vessel was broken up four months thereafter. Each carrier had a displacement of 23,000 mt and designed to carry 42 aircraft; 30 Ju 87D dive bombers and twelve Messerschmitt Bf 109 G fighters. (Gröner, E., *German Warships 1815-1945, Volume One: Major Surface Vessels*, Conway Maritime Press Limited, London, 1990, pp. 71-72.)
21. *Schnellst* (German for fastest) in *Schnellst Bomben Träger* is a word play on *Schnellbomber* (fast bomber), which originally referred to *Dornier Do 17* and *Junkers Ju 88* twin-engine medium bombers favored by the *Luftwaffe* in the 1930s. Originally, strategic heavy bombers were championed by the Luftwaffe General *Walther Wever*, who supported Junkers and Dornier to develop the heavy four-engine bombers Ju 89 and Do 19. Unfortunately, when Wever died in a plane crash in 1936, the Luftwaffe lost the only high level strategic bomber proponent in its leadership. Initial successes in Poland and France masked the deficiency, which became painfully obvious during the Battle of Britain when not-so-fast-after-all Do 17 and Ju 89 (and especially the infamous Junkers Ju 87 *Stuka* dive bomber) were decimated by Spitfires and achieved little.

Chapter 12 – Piston Aeroengines

1. Models 109 and 110 were developed by the Bayerische Flugzeugwerke before it became Messerschmitt so that they are usually referred to as Bf 109 and Bf 110, respectively.
2. See p. 400 in **TSHR**. Apparently, Speer and Saur resorted to 'creative' accounting and reporting methods, mixing repaired, modified and upgraded aircraft with brand new ones – presumably to fool Hitler. The discrepancy in numbers may add up to as many as 8,000 fighter aircraft.
3. The original source of the data is *The German Economy at War* by A. S. Milward (London: Athlone Press, 1965). See endnote 2 for a cautionary note on the accuracy of the numbers reported by Speer's Ministry.
4. Heinkel P-1076 is a high altitude piston engine fighter inspired by the He 100 design. It was designed to have a very smooth surface and used a surface evaporation cooling system on the engine cowling and the entire fuselage rear section. The wing was slightly swept forward by 8° and was constructed as a two-piece, two-spar all metal structure. There were flaps on the entire wing trailing edge, with the outermost serving as ailerons and the inside ones serving as landing flaps. The cockpit was pressurized and was supplied with a clear-vision canopy. It did not leave the drawing-board.
5. The DB 602 was a liquid-cooled V-16 (not inverted) diesel aeroengine (88.5 liter displacement volume) designed and built in the early 1930s. The engine powered the two Hindenburg class airships. It was rated at 1,100 HP (BMEP of 6.5 bar) at 1,650 RPM (sea level). Its compression ratio was 16:1. Under the model name of MB 502, the engine powered *Schnellboots* (speedboats) as well.
6. Eisenlohr also explains that they tried to build an engine of a simpler construction, i.e., a 12-cylinder engine (DB 603) from a 16-cylinder one. The performance would be the same, but it would take one and a half to two years to be ready (i.e., by the end of 1943 or early 1944). The 16-cylinder engine that he talks about is DB 609, an inverted V16. It did not work because it was far too ambitious with the time left; especially, the torsional vibrations in the long and heavy crankshaft presented too difficult a problem to solve.
7. "They can be made from wood." Substitution of wood for aluminum was not just an expression of exasperation or contempt. Due to the scarcity of aluminum, the tail assembly of Bf 109 G was made from wood. One should also mention the *de Havilland DH 98 Mosquito*, the British twin-engine, multi-purpose aircraft, whose frame was constructed mostly of wood. For the longest time, the Mosquito was the bane of Göring and the Luftwaffe. Its German counterpart was Kurt Tank's Ta 154 *Moskito* (it was conceived as an answer to *the* Mosquito), which also made extensive use of wood construction. Ta 154 was powered by two *Junkers Jumo 213 E* two-stage supercharged engines. Only a handful had been completed before cancellation (the wood construction was not robust enough). A few of them served with *Nachtjagdgeschwader* 3. Some were used as training aircraft for the jet pilots.
8. See the archive document GDC-11/702, *Entwicklungsstand der Motoren mit kombinierter Aufladung DB 621 (DB 605 basis) und DB 622 (DB 603 basis)*, 5 Oktober 1942.
9. See the archive document GDC-11/282 – *Report on development and sea-level power of DB 605 engine with DBT 506 turbochargers*.
10. See the archive document GDC-11/845 for discussions on the Bf 109, dated January 29, 1943.
11. See the archive document GDC-11/1141 for further details.
12. See the archive document GDC-11-521, *Höhenmotor DB 628 für Jäger under Verwendung des Abgasturboladers DBT 306*, January 17, 1942 (Report has Kollmann`s signature on the final page.)
13. See the archive document GDC-11-612, *Entwurf für RLM – Vortrag Turbinen*.
14. See the archive document GDC-11-257, *Erprobung des Laders Stufe 1 am Motor DB 628 V2. Lauf am 11 Dec 1942*.
15. From von der Nüll's notes translated by the Technical Information Bureau (the archive document GDC 10/13127 T, 1945)
16. Negative G happens when the aircraft accelerates downward at a rate larger than the gravitational acceleration, i.e., $g = 9.81\ m/s^2$.
17. Dual-choke updraft carburetors manufactured by The S.U. (Skinner and Union) Carburetter Company Limited in the UK.

18. *Royal Air Force* (RAF) pilots tried to neutralize the carburetor failure in negative G maneuvers by rolling their aircraft over and diving upside down.
19. H. R. Ricardo, *Note on Fuel Injection*, December 11, 1936, Aeronautical Research Committee, Engine Subcommittee, Report 2761 (ICE 1128).
20. CFR (*Cooperative Fuel Research*) octane number is the whole number nearest to the volume percentage of iso-octane (2,2,4-trimethylpentane) in the blend of iso-octane and normal heptane, which the fuel matches in knock characteristics when compared by a procedure developed by the CFR Committee in the 1930s.
21. Marseille is today one of the most highly regarded German pilots, as unlike many of his fellow fighter aces, the vast majority of his 157 victories were obtained in the West, not on the Russian front – where in the early years, poor Russian tactics and inferior aircraft enabled easy pickings. He died at the age of 22, the cause of death ruled to be colliding with the tail of his stricken fighter during bailing out. Recent biographers of Marseille hold that he held the Nazi leadership in fairly poor regard and was prone to poking fun at them. A luxury probably afforded him only by his extremely high propaganda value to Germany as the Luftwaffe's most famous ace of the entire African campaign.
22. In the authors' view, the official report may have been doctored to put the blame on a rogue failure, so as not to destroy pilot morale by admitting that there was an endemic design problem, which could therefore, at any moment, happen to any German pilot.
23. General Schmid was the intelligence chief of the *Luftwaffe* from January 1938 to November 1942. Although he was not an aviator, he was given the command of *I. Jagdkorps* from September 1943 until November 1944. After that, until the end of the war, General Schmid was the commander of *Luftwaffe West*.

Chapter 13 – The Pilots

1. Strictly speaking, the Luftwaffe did not accept a 'kill' without a witness (i.e., a wingman). Otherwise, it was considered only a probable and did not add to the score of the claiming pilot.
2. Group Capt. Johnson was credited with 34 individual victories over enemy aircraft, as well as seven shared victories, three shared probable, 10 damaged, three shared damaged and one destroyed on the ground. He flew 700 operational sorties and engaged enemy aircraft on 57 occasions (from the *Wikipedia*).
3. There is a widely circulated myth that the P-38 was known as *Der Gabelschwanz Teufel* to Germans. In fact, the Germans referred to that aircraft simply as P-38 or *Lightning*. The moniker is most likely a propaganda or moral boost ploy invented by the pilots themselves or some reporter.
4. Major Bong, a *Congressional Medal of Honor* winner, died in California while testing a *Lockheed P-80* jet fighter shortly before the war ended.
5. In fact, the highest scoring aces on the Allied side were *Ivan Kozhedub* with 62 victories and *Alexander Pokryshkin* with 59. Pokryshkin, a master of aerobatics and dogfight, was the more famous of the two and it is likely (although not known for sure) that he met Erich Hartmann in aerial combat.
6. *Signal*, published by the *Wehrmacht* from 1940 through 1945, was an illustrated magazine, specifically targeting audiences in neutral, allied, and occupied countries (as a propaganda tool). Signal was published fortnightly (plus some special issues) in as many as 25 editions and 30 languages, and at its height had a circulation of 2,500,000 copies.
7. Until 1973, when *Giora Epstein* of *the Israeli Air Force*, with 17 confirmed kills in 1967 *Six Days War*, 1969-70 War of Attrition and 1973 *Yom Kippur* war, surpassed Bär's feat. Eight of Epstein's victories were with the French-built Mirage III, a delta wing fighter designed primarily as a high altitude interceptor. His other nine victories came in an *IAI Nesher*, an Israeli-built version of the *Mirage 5*. Five of his kills were downed using air-to-air missiles, the rest with cannon (from the *Wikipedia*)
8. Knoke does not mention the specific aircraft. Nevertheless, it is highly likely that it was Bf 109 G-6 with DB 605 ASM – combination of AS (supercharger with improved high-altitude performance) and M (MW 50 injection for improved low/medium altitude performance). It probably used lower octane B4 fuel.
9. Much of the early practical development work on GM-1 (after Dr Otto Lutz at TU Braunschweig did the chemistry) was done at the *Luftfahrtforschungsanstalt Herman Göring* (LFA Institute - Braunschweig-Völkenrode).

The very first code name for nitrous oxide in the Luftwaffe (1940s) was *Mona*; thereafter it was renamed 'Göring Mischung 1'. One can only surmise that the LFA-HG engineers thought it was a good career development strategy to name their work after the boss. It is also possible that they made a sly connection between Göring's clownish ways and the laughing gas as a well-hidden joke.

10. Willy Messerschmitt cites an event, which was 'on record' according to him, when a *Mosquito* pilot bailed out on the approach of an Me 262 before the latter opened fire Ref. [4] in Chapter 12. Needless to say, this story should be taken with a grain of salt.
11. P-51 D was powered by a *Packard (Rolls Royce) V-1650-7 Merlin* 12-cylinder, liquid cooled engine with a power output of 1,490 HP at 3,000 RPM. Its two-stage supercharger had two speeds. The boost pressure was automatically linked to the throttle. An air-to-water aftercooler was installed between the supercharger and the engine.

Chapter 14 – The Original Reference Material

1. This academic research group was the rough equivalent of the Royal Aeronautical Society of Great Britain and held very prestigious annual conventions in Munich with international attendance. Many of these reports are available at the Imperial War Museum, Duxford, England.
2. *Luftfahrttechnik* is an official repository for "State of the art best-practice" in design. Only a very select few experts at the top of their field were invited to contribute, Prof. Dr-Ing. Kollmann was of course one of them. Copies exist for consultation at the library of the Royal Aeronautical Society in Farnborough, England.
3. The *Zentrale für wissenschaftliches Berichtswesen* (ZWB) was set up in the early 1930s in Germany as an official academic body whose job it was to collate and distribute academic scientific study articles inside Germany. Many of these reports can be found at the Imperial War Museum, Duxford, England.