GERMAN DEVELOPMENT OF GAS TURBINES FOR ARMOURED FIGHTING VEHICLES

(1) INTRODUCTION

During the investigation of the activities of Dr. Ing. Porsche, it was learned that he was associated with a project for the development of a gas turbine installation for the Tiger tank. The investigation was stated to be in the hands of Dipl. Ing. Otto Zadnik, who was visited at his small office at Rheinau, on the Austrian-Swiss frontier by Flight Lieut. Ellerton, R.A.F., and H.W. Goldthorpe, U.S. Ordnance on 26.5.45. Following their assessment of the target, an investigating team visited Rheinau on 22.6.45., and after considerable difficulty with frontier guards, etc. succeeded in locating Otto Zadnik.

During the course of his interrogation, it was learned that Zadnik, although closely associated with the whole gas turbine project, was concerned mainly with the installation and transmission. He was fully informed on all aspects of the project but had not actually worked on the turbine, compressor, or other components. Zadnik had been assisted in his work by four young engineers - Weitzel, Koepell, Jung, and Hermann, but these being German had been ordered to leave Austria some days previously. Zadnik was therefore questioned alone.

During his interrogation, reference was made to the various specialists who had been responsible for the components of the assembly, i.e., compressor, turbine, combustion chamber, control, etc. and where possible these were interrogated.

The report which follows summarises these interrogations which were supplemented by a large number of documents, reports, and drawings, etc.

The main body of the report broadly covers the information obtained during the interrogations in Germany. More detailed descriptions, compiled as a result of subsequent interrogation of the various specialists in England, and examination of the captured documents, are included in the form of Appendices.

(2) Information obtained during interrogation of - Dipl. Ing. Otto Zadnik.

Zadnik, although primarily a specialist in electrical transmission, was in charge of the gas turbine project. His duties were to co-ordinate the work of the independent specialists, i.e., combustion, turbine, compressor, control, etc. and also to ensure that the complete installation would meet the specified requirements. He was personally responsible for the design of the transmission and for the installation of the whole power plant.

Questioned as to the reasons for the study of gas turbines, he gave the following :-

I. A gas turbine can work with a safe fuel - it was proposed to use Diesel oil.

II. Smaller and simpler than the conventional lay-out.

III. Smooth and free from vibration.

IV. Requires no cooling system.

V. The problem of air filtration simplified.

Two schemes were under consideration :-

(1) A conventional turbine arrangement of blower, combustion chamber, and turbine on a common shaft - with the net power taken from this shaft.

(2) A primary turbine just large enough to drive the blower, about 30% of the total air being diverted via an auxiliary combustion chamber to a high speed work turbine, which is coupled to the tank transmission.

The design work in connection with stage (1) had been practically completed but it was realised that the complication of the transmission consequent upon the torque characteristics of the turbine made it unsuitable for application to a tank. The fundamental details of stage 1 are however applicable to stage 2 and much of the design can be transferred directly to stage 2.

Stage 1.

The general installation in a vehicle is as shown on Drawing No: 3060-G-T-101 Einbau, the principal characteristics being as follows :-

The unit (known as Unit 101) develops 1000 B.H.P. @ 14000 r.p.m. and weighs 450 Kg., has a calculated fuel consumption of 450 gms./P.S./hr. Its poor torque speed characteristics necessitate the use of an extremely complicated transmission system and the whole installation was found to be too large for the Tiger tank, for which it was intended. The transmission system, which was designed by Zahnradfabrik of Friedrichshafen, involved the use of a cooling unit with a capacity of $4\frac{1}{2}$-litres and weighing 40 Kg.

An attempt has been made to provide centrifugal air filtration by means of two vent pipes partitioned on the diameter to duplicate the centrifugal effect. Receptacles are provided to trap the centrifuged dust which is evacuated from the traps by an independent blower. The velocity of the air through the pipes is 70-80 met/sec, the total air flow being 10 Kg/sec.

Various types of compressors have been considered as follows :-

I. A nine-stage axial blower by Brown Boveri and Company of Mannheim, the engineers involved being Reuter, Waldmann, and Hrynischak; Profs. Weinig and Kamm were also associated with the design.

II. A seven-stage axial blower by Dr. Freidrich of Gottingen and Messrs. Brückner - Kannis of Dresden, using a tip velocity approaching that of sound and giving a much smaller machine.

III. A blower of the Heinkel-Hirth type by Dr. Vanicek, comprising a diagonal stage, and a number (uncertain) of axial stages preceding it.

The blowers are designed to compress the air adiabatically to a pressure of 4.5 atm., the inlet temperature being 40°C. and the delivery temperature 180°C.

Some of the characteristics of Stage 1 (Unit 101) were then described : -

The fuel consumption is high, at full load this is 450/500 gms./P.S./hr., falling to 430 at 70% output, which gives the optimum consumption. The turbine runs at 14000 r.p.m. at full output, rising to 14500 r.p.m. at no load. Under the latter condition the fuel consumption will be from 50/60% of the gross full load consumption.

The torque, speed and temperature characteristics are as shown on Figs: 25 & 28 (curves 101).

The anticipated consumption for this unit was so high - at least 90-100% more than a good I.C. engine - that alternative schemes were studied. It was stated that twice the fuel tank capacity could be accommodated, thus restoring the radius of action. The supply question, however, would still remain unsolved.

Stage II

Because of the difficulties associated with Stage 1, it was decided to proceed with alternative schemes, and the one adopted was outlined by Zadnik as follows :-

The arrangement (known as Unit 102) consisted of (a) a primary stage consisting of a compressor and turbine, and (b) a work turbine. The compressor unit runs at 14000 r.p.m. and supplies 70% of its air to the combustion chamber of the primary turbine. Thirty per cent of the air is directed via regulator valves to the combustion chamber of the work turbine, this latter running at 20,000 r.p.m. The torque, speed and specific fuel consumption characteristics of this arrangement are shown on Figs:25 & 28 (curves 102), from which it will be seen that the stalled torque is about $2\frac{1}{2}$ times the torque at maximum speed. The estimated fuel consumption of 450 gms./P.S./hr. at maximum speed is believed to be capable of improvement to about 300 gms./P.S./hr. by the use of a heat exchanger which will be described later. In either case the specific consumption will rise to infinity in the stalled condition.

One of the major problems of this design is the development of a control system which will maintain the proper balance between the fuel requirements of the primary unit and the work turbine and so avoid excessive temperatures and speeds in either and an extravagant consumption of fuel.

The proposed control is by centrifugal governor and a suitable linkage, manual control being effected through the governor spring over a range of from 5000 to 14000 r.p.m.

Reference has previously been made to the use of a heat exchanger, which if carefully designed to avoid excessive pressure loss, should materially improve the fuel economy. Some such device is considered essential if a tolerable fuel consumption is to be achieved.

Development work upon a special type of heat exchanger was begun at Brown Boveri at Heidelberg by Hrynischak. This works on the regeneration principle and consists of a rotating drum made of ceramic material assembled in such a way that gases will pass radially through the walls with a minimum of resistance. The exhaust gases pass from outside to inside, while the air from the blower passes from inside to outside. The drum is rotated and a suitable partition inside the drum separates the fresh air from the exhaust gases. See Sketches (Fig. 35) This arrangement avoids the necessity for passing the heat through a partition but enables it to be removed from the same surface through which it has been absorbed. In effect the ceramic drum is a reservoir which absorbs heat from the exhaust during one half of a revolution and gives it up to the air during the other. An indication of the performance is given by the temperature figures on (Fig. 35).

When questioning Zadnik for more detailed information of the turbine, he stated that this information could be obtained from Dr. Alfred Muller, whose whereabouts however were unknown to him. An assistant to Dr. Muller, Herr Kolb, was thought to be living on a farm between Wangen and Isny, about 30 Km. away.

Zadnik agreed to accompany us in our search and permission from the French was obtained for him to accompany us out of the district. After an almost fantastic cross country journey, Kolb was located at Willatz. He had no documents in his possession but knew the whereabouts of Dr. Muller, who was some 30 Km. away, and agreed to guide us to him. Permission was then obtained for both Kolb and Muller to be taken to Rheinau the following day for a discussion in Zadnik's office.

3) Joint Interrogation of Zadnik, Alfred Muller and Kolb.

Muller began by outlining his association with gas turbines. In 1936, at the suggestion of Prof. Kamm he made a study of supercharger turbines for his thesis for his Doctor's degree and became convinced of the future of gas turbines for land, sea, and air.

In 1943, he decided that gas turbine motors were the most suitable type for tank propulsion, but could not interest the military authorities.

The reasons for his preference for this type of motor were :-

(1) Lightness.

(2) Cheapness.

(3) Ability to use low grade fuels with consequent reduced fire risk.

(4) Simplicity of transmission due to high stalling torque when separate work turbine is used.

(5) Absence of need of cooling system.

(6) His belief that sufficiently high temperatures could be employed to permit the size of the unit to be considerably smaller than the best piston engine practice.

Whilst he thought it easy to produce efficient units of large size, it became much more difficult as sizes were reduced. Efficient units of 700-800 H.P. were possible, but the main difficulty lay in the compressor.

As an example he quoted the efficiency of compressors for engines of 5000 H.P. down to 3000 H.P. as 86-88% dropping to 82-87% for an engine of 1000 H.P.

In January 1944 he designed and produced turbo supercharger No: 801.E, which he claimed to be the present best in Germany. (An arrangement drawing was subsequently found amongst his documents and is included at Figure 36).

Continuing his resume, he stated that in 1936, he realised that the blade of the turbine was a fundamental consideration.

Blades of the steam turbine type were unsuitable, and special steels were required, of which Germany was very short. He therefore made a study of hollow blades and found that a steel capable of operating at 800°C. as a solid blade could handle 1000°C. as a hollow blade.

Experiments were conducted on hollow blades with varying quantities of air flowing through them. The gas temperatures used were 900-920°C. for stator blades and 800-820°C. for running blades, th air flow through the blades varying from 7 to 15% of the total air supplied.

The experimental results agreed very well with those calculated fc the inner end of the blade but deviated somewhat at the free end, the following being typical results. -

Air %	Root Temp. °C.	Tip Temp °C. Calc.	Tip Temp °C. Actual
7	400	670	725
10	375	645	725
15	350	610	710

The critical point on the blade is not of course the temperature at the free end where the stress is a minimum, nor is it necessarily at the root where the stress is a maximum, but will probably be at a point some distance above the root where the strength of the blade is reduced by temperature to a figure equal to-or less than - the dynamic loading on the blade as indicated in Fig. 37.

This work was done in 1938 and later improved results were obtained by the use of an inner deflecting vane placed inside the blad The insert has raised pimples to maintain a uniform distance from the inner surface of the blade and also to give a high air velocity. This reduces the quantity of air required for a given degree of cooling to about half the previous figure.

An exhaust turbine tested with gases at 950°C. and a tip speed of 410 met/sec. with only 3% of the total air supply gave excellent results.

The cost of these hollow blades has been steadily reduced from 12 marks to 0.6 marks each by improved manufacturing technique. The latest method is to start with a rolled prismatic bar of special shap turn the blade section circular and drill through the entire length, press the blade to the desired section and then finish the root. In this connection Muller made reference to Dr. Hans of Junkers.

In one type the blades are held between two discs, between which the air is fed. Alternatively, the blades are welded to a single dis the air being fed through holes drilled at a suitable point beneath t blade.

In the D.B. exhaust driven superchargers, such as were seen at t Heinkel-Hirth Laboratory, at least twenty machines have been enduranc tested for upwards of 200 hours at a gas temperature of 900/950°C. wi between 5 and 10% of air through blades without inserts. With the insert a machine has been run for 150 hours at 950° gas temperature, using only 3% of the air, using blades having no nickel, only chromiu and manganese. With nickel only 1% air would be necessary, or if nic and 3% air were used, a higher gas temperature could be used. With] nickel and 2% air, temperatures of 950/1000°C. should be possible. The cost of 1% cooling air is equivalent to 20/30 gms. on the specific consumption.

Asked to quote a practical example, he suggested the following for a 5000 H.P. turbine for land use. -

Steel for blades - Boehler S.A.S. 8.

Iron 59%; Chr 17%; Ni 15.1%; Mol 2.2%; Cu 1.8%; Tantalum 1.05%;

Nb 1.05%; Si 1%; Mn 0.9%; Carbon 0.9%.

This is a good steel and was obtainable in Germany until 1942.

With cooled blades, gas temperatures of 900-950°C. could be used. 10-stage compressor compressing to 4-5 atmos. abs. 5-6 stage turbine. Cooling air 4-5%.

Fuel consumption of such a turbine without heat exchanger would be about 320 gms/PS/hr. for 900°C. and 300 gms. for 950°C. within limits of ± 20 gms.

These figures are based on experience of about eighteen months ago and should be capable of improvement to the extent of about 20 gms.

With the present type of heat exchanger, it is easy to lose by pressure drop all that has been gained from the heat exchange, and it is therefore necessary to employ the regenerative type.

Limit of permissible pressure drop in heat exchanger = 300-400 mm. H_2O. With a wire type of heat exchanger it is theoretically possible to achieve a pressure drop of only 200 mm. H_2O.

Experiments with this type of heat exchanger have been carried out by Brown Boveri at Heidelberg and efficiencies as high as 90% of the theoretical maximum have been recorded by Ritz - AVA Gottingen.

Muller considered that with 2-3 years development, and using such a heat exchanger, consumption figures of 150-200 grams/PS/hr. should be possible.

<u>Tank Turbine</u>

The foregoing relates to Muller's development work on gas turbines generally and is the background upon which he based his development of the tank turbines. In 1943 the military authorities were not interested in turbines for tanks and work on this project was not commenced until the middle of 1944.

The first scheme considered consisted of a 5-stage blower coupled
directly to a 2-stage turbine. The power take-off was from a third stage
1 in the turbine - arranged coaxially with the other two stages but with no
mechanical connection between them. This arrangement is shown in Fig. 1.

This arrangement suffered from the serious drawback that when the load was removed for any purpose, such as changing gear, the power turbine needed to be heavily braked to avoid dangerous over-speeding.

The blower and first turbine might be regarded as a boiler for supplying the second turbine. As an alternative to braking, the air supply to the second turbine must be cut off by spilling, to allow of gear changing, etc.

The power turbine must be under control at all times, which is extremely difficult to achieve, and the scheme was therefore abandoned.

A second scheme was then produced having all three stages of the turbine coupled together.

It was intended to transmit the drive through some form of hydraulic torque converter, Thoma (Hydrostatic) or Fottinger, (Hydrodynamic), the shortage of copper ruling out the use of an electric drive.

In this scheme, rotating fuel burners were considered as a means of avoiding hot spots in the turbine and an ingenious device was incorporated to avoid heavy centrifugal pressures (about 350 ats) on the fuel at the burners. The device consisted of an interruption of the hydraulic column upstream of the burner so as to reduce its effective length.

It appears to have been overlooked that although burners rotating at rotor speed will avoid hot spots in the static blades, they are conducive to hot spots in the rotating blades which would not occur with fixed burners.

The general arrangement of this second scheme is shown in Fig.2, both fixed and rotating burners being included.

It was then decided to change to a standard B.M.W. design of combustion chamber with stationary burners. The arrangement is generally as shown on Fig. 3.

This represents the final design of the coaxial lay-out eferred to as Scheme 1 in the Assessment Report on this target and earlier in this report, and is the type used for the tank installation scheme shown on Drawing No: 3060 G-T-101 Einbau. (Fig. 26).

The unit, described in more detail later, was estimated to weigh 450 Kilograms and to develop 1000 H.P.

The designed speed was 14000 r.p.m. and it was connected to a reduction gear of which an arrangement drawing was provided by Zadnik. To compensate for the poor torque-speed characteristics of the unit, the output of the reduction gear was taken through a transmission system embodying two six-step overlapping ranges and designed by Zahnrad-fabrik. A large oil cooler weighing about 90 lbs. was required to cool the transmission and the turbine bearings.

The main features of the compressor-turbine unit are as follows :-

The compressor is of the 9-stage axial type, the rotor being of special construction to provide a smooth exterior surface of approximately parabolic form. The method of fixing the blower blades is shown in Figure 7 the blades being solid.

At the delivery end of the compressor are two rows of straightener vanes to remove the rotational component of the air before the combustion chambers.

The combustion chambers are of standard B.M.W. design but of slightly reduced size. There are fourteen chambers. The turbine motor has three stages with both rotating and static blades of the hollow air cooled type with internal deflectors. The blades are welded to the turbine discs, the construction being as shown in Figure 12.

The blower is connected to the turbine by a large diameter hollow shaft which serves also to convey the cooling air for the rotating blades of the turbine.

A solid central shaft ties the turbine to the blower to balance axial thrust.

The construction of the stator blades of the turbine is shown in Figure 13 the passage of the cooling air for these blades being radially inwards. It is claimed that the exit of the cooling air at the tips of both stator and rotor blades provides a sealing device for avoiding tip leakage.

A diffuser is provided at the turbine exit to give a discharge pressure of 1.05 atmos (abs). The pressure at the last stage of the turbine is .9 atmos. (abs).

The characteristics of this unit are shown on Figs. 25, 27 and 28.

The air flow through the unit is approximately 10 Kg/sec.

The latest scheme - described in the Assessment Report as Scheme 2 - consists of two separate units - (See Fig. 15).

(a) A unit substantially as that described above and handling 10 Kg air/sec. and running at 14000 r.p.m. of which only 7 Kg./sec. is fed to the turbine, which has been correspondingly reduced in size, but is of similar design.

   This unit, which might be regarded as "the boiler" for the work turbine is illustrated in Figure 4. The turbine has three stages, the blade length being reduced.

(b) A separate combustion chamber and work turbine to which is led the remaining 3 Kg/sec of air from the blower. This air is bled from the blower by a special collecting device also to be seen in Fig. 4.

The combustion chamber, which has not yet been designed, is intended to comform to the B.M.W. design and will have only one or two burners.

The turbine has two stages and is based upon the well tried B.M.W. exhaust turbines. The power developed is 1000 H.P. at a speed of 20,000 r.p.m., the overall dimensions being only 320 mm. diameter x 450 mm. long. Only the rotating blades are cooled internally and a special air connection from the blower is provided for this purpose. In this turbine the exit gases are reduced to a minimum velocity by means of a diffuser.

The construction of the blading is similar to that employed for the other turbine. The thrust from the turbine is taken on a normal radial bearing, the thrust amounting to 5/600 Kg. (See Fig. 5).

Dr. Muller considered that noise at the intake to the blower could be reduced to a satisfactory level by a combined filter and silencer.

The characteristics of this turbine are shown on Figs. 25 and 28.

The transmission system for this consists of a two speed epicyclic gear operated by two stationary electro-magnetic multi-plate clutches. arrangement drawing of this was obtained from Mr. Zadnik and is shown in Figure 38. An additional two speed gearbox is required to give suitable operating ranges for road and cross country work. Gear changin on this box can only be effected when the vehicle is stationary.

For starting purposes a special fuel pump for handling light fuel (understood to be petrol) is fitted, and for running, a second fuel pump is provided to handle heavy oil (diesel or boiler oil). The pump intended is a gear pump similar to that used by B.M.W., but smaller. Th full load burner pressure is 60 Atm. It is proposed to fit a Junkers governor from their jet plane unit.

The power take-off pinion appeared to be large but Dr. Muller state that the design was based upon that of the D.B. blower pinion which has speed of 24000 r.p.m.

Dr. Muller stated that the static blading might prove difficult at high temperatures and he anticipated that a good deal of development would be required. Junkers have had some trouble from distortion.

He mentioned that experiments have been conducted with ceramic blades in exhaust turbines. In 1939 a test was run with a gas temperatu of 900°C. at a blade speed of 150 met/sec., but the blade failed. The material used was synthetic corundum. The experiment was dropped in favour of the cooled metallic blade but Dr. Muller thinks that an uncool blade will finally be developed. Ceramics are brittle and do not take kindly to sudden changes of temperature. The uncooled blade avoids complication and loss. He suggested that a combination of metallic and ceramic material may be a possible solution using sintered material, containing - possibly - tungsten.

Dr. Muller stated that he was not a "party" man and in February this year he was superseded by Dr. Max. A. Muller, who was a "party" man, but his five assistants did not work happily with his successor and he was subsequently ordered to continue the work but declined. He took copies of all the drawings he could and hid them in the country, where he now is. These drawings he has now handed over to the investigating team.

He particularly stated that he was anxious to come to England to continue turbine development which appears to be his only interest in life.

(4) SUMMARY:

The investigation of this target may be summed up briefly as follows :-

(a) Otto Zadnik was actually engaged upon the design of only one portion of the tank project, viz, the transmission. Although he had an over-riding responsibility for, and a good general knowledge of the whole project, he was unable to provide details of the power unit.

(b) Dr. Alfred Muller, who for some eighteen months, had been primarily responsible for turbine and turbo-blower development for aircraft (See his charter at Appendix 2) was made responsible for the design and development of the tank power unit. Dr. Muller has behind him a wide experience of gas turbines and blower development, but little or no development work appears to have been carried out on the tank motor itself.

Schemes for a tank installation, based on his experience, have been prepared, and, if the necessary time is devoted to their development, it does not seem unreasonable to suppose that it may be possible to achieve the anticipated results from the scheme, which does not incorporate a heat exchanger. The greatly improved efficiency anticipated when using a heat interchanger is, of course, entirely dependent on overcoming the formidable problems involved. Only by the development of a satisfactory heat exchanger would it be possible to approach the fuel consumption of a conventional power unit.

Of the other problems to be solved, not the least is that of control.

(c) Even at the present stage it would seem that the reduced size of the tank turbine will permit the use of larger fuel tanks and so partially restore the circuit of action.

(d) The torque characteristics (Scheme II), freedom from vibration, and the absence of any cooling system, make the gas turbine very attractive for tank use.

(e) This investigating team is not in a position to state whether or not the knowledge of gas turbines possessed by Muller is in advance of that available in Great Britain. It is considered, however, that the information which Muller can provide would make possible the design of a tank installation which would work sufficiently satisfactorily to form the basis of future development.

(f) Muller in the course of his career has designed a multi-cylinder two-stroke engine, drawings of which were brought away for examination.

DOCUMENTS

In addition to the documents and drawings which have been translated or reproduced and made use of in this report, a considerable quantity of other documents and drawings were obtained, which, for various reasons, such as, insufficient technical interest, amount of translation involved, unsuitability for reproduction, etc. are not included in this report.

These are listed in Appendix I and will be held available for examination.