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Report on a Special Gas Turbine Principle (Project No. LP-256) 31133

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Analysis Division, AMC F-TR-2186-ND

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The principle and the design of a gas turbine with constant-pressure combustion and thermal compression, in which the pressure is built up by the increase of temperature of the working substance, are described. The engine, except for its stationary combustion-chamber design, is very similar to the well-known constant-volume intermittently burning gas turbine with rotating combustion chambers. By means of a supercharging fan, fresh air enters the engine, is precompressed, and flows into the channels formed by the rotor blades to displace there the low-pressure hot gas. As soon as the rotor channels are completely filled with fresh air, ducts in the front and rear walls of the engine housing, leading to the combustion chamber, open. Gas from the combustinn chamber flows into the rotor channels increasing the pressure there to the pressure prevailing in the combustion chamber.

Copies of this report obtainable from Air Documents Division; Attn: MCIDXD

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TECHNICAL REPORT

No. F-TR-2186-ND
GS-USAF WRIGHT-PATTERSON
AIR FORCE BASE No. 61

ATI No. 31133

REPORT ON A SPECIAL GAS TURBINE PRINCIPLE

(Project No. LP-256)

Dr. H. J. Pabst von Ohain

Release Date:
March 1948

HEADQUARTERS AIR MATERIEL COMMAND
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WRIGHT-PATTERSON AIR FORCE BASE
DAYTON, OHIO

REPORT ON A SPECIAL GAS TURBINE PRINCIPLE

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Report on a Special Gas Turbine Principle

(Project No. LP-256)

Dr. H. J. Pabst von Ohain

ABSTRACT

A special principle of gas turbines is described and investigated for aircraft application. A general description of this engine is provided, and an instructive picture of each individual process is disclosed. Tests results already obtained are discussed. Suggestions are given for a testing program, and for a new test engine to be used in completing the previous test results.

BIOGRAPHICAL NOTE

Dr. H. J. Pabst von Ohain was born in 1911, in Germany. He studied practical physics and flow technique in Berlin and in Goettingen. After 1936 he was employed for a period by Heinkel, Warnemuende, in the field of flow machines for aircraft drive, specializing in turbojets. In 1943 he became head of development with Heinkel-Hirth, Stuttgart. He had become a member of the German Academy of Aeronautical Sciences in 1941.

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REPORT ON A SPECIAL GAS TURBINE PRINCIPLE

1. Introduction

In this study a constant-pressure combustion turbine in which the pressure is built up by the increase of temperature of the working substance will be described. An engine operating according to this method is simple and not sensitive. High gas temperatures can be reached, due to a strong internal cooling. The pressure obtained is determined by the temperature rise of the working substance and is independent of the revolutions per minute; hereby favorable conditions for the control of the engine are given. The total efficiency without heat exchanger can actually be maintained between 18 and 22% by using a pressure ratio ranging between 4 and 5.

In general the weight per horsepower cannot be given, because the construction differs according to the intended use of the engine. It seems that, in comparison to the normal gas turbines, very favorable values can be attained.

2. Engine Description

A gas turbine operating according to the principle given in the introduction is shown in Fig. 1. A cell rotor 1 is placed in the housing 2; the housing partially covers the cell rotor by means of its walls 7 and 8. (See Fig. 1, Sections E-F and G-H.) Opening 3 connects the combustion chamber with the cell rotor by channels 14 which are located in wall 7, and by channels 15 which are located in wall 8. The supercharging fan 9 is directly driven by the cell rotor 1. The turbine 10 runs independently of the cell motor. The cell rotor is shown in Fig. 2. Detail of its construction will be discussed in par. 6. The engine, according to Fig. 1, is very similar to the well-known constant-volume turbines with rotating combustion chambers. As contrasted with the engine of Fig. 1, the constant-volume turbine which employs intermittent burning does not have the stationary combustion chamber 4, the openings 3, or channels 14 and 15.

These constant-volume turbines of known construction do not work satisfactorily, because the actual process of intermittent combustion is difficult, and the observed performance and thermal efficiency are insufficient.

3. Method of Operation

The engine, according to Fig. 1, operates as follows: By means of the supercharging fan 9, fresh air enters at 11 and is precompressed. The precompressed fresh air flows through the sector-shaped inlet opening 5 (Sector I, Fig. 1, Section E-F) into the cells, and displaces the low-pressure hot gas which flows out to the atmosphere through the bypass 6. As soon as the cells are completely filled with fresh air they enter the space between the two walls 7 and 8, thus being connected with the combustion chamber 4 at the inlet side by channels 14. (See Fig. 1 Longitudinal Section and Section A-B.) Assume hot gas with the pressure P and the temperature T in the combustion chamber. The gas flows through channels 14 from the combustion chamber 4 into the cells. By this connection between the combustion chamber and the cells, the pressure in the cells rises to the pressure in the combustion chamber. The hot gas flowing into the cells exerts an impulse moment upon the walls of the cell rotor.

This process is described in detail as follows: Hot gas flows into a cell, thereby inducing a pressure rise as soon as it passes the first channel 14. The kinetic energy of the hot gas produced by the pressure difference between the combustion chamber and the cells is changed into mechanical energy. That is accomplished by the hot gas flowing through the channels, almost rectangularly to the cell walls, with a velocity higher than the tip speed of the cell walls. The values of the driving power and the efficiency produced by this process will be discussed later. (See par. 4 c.)

The pressure built up in the cells depends on the quantity of the hot gas poured into the cell. This quantity is determined by the throat area of the channels 14, by the peripheral velocity of the cell walls, and by the thermodynamical condition of the combustion gas. The throat area of the first channel of the four stationary hot-gas

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channels 14 must be such that, under the given circumstances, the pressure produced in the cell amounts to only a small percentage (about 30%) of the pressure difference between the scavenging fan and the combustion chamber. By this method of dimensioning, the pressure oscillation against the average pressure is small (about 15%); therefore, the flow in channel 14 is approximately steady. The same consideration is applicable for the remaining three stationary hot-gas channels 14 in Sector II (Fig. 1 Section A-B). When a cell has passed the four channels in Sector II, the pressure in the cells has nearly reached the pressure in the combustion chamber. Therefore, the velocity of the gas in the four channels in Sector II has individual values according to the decrease of the pressure difference between the combustion chamber and the cells.

When the pressure in the cell has nearly reached the pressure in the combustion chamber, the cell moves into Sector III of the rotor. (See Fig. 1 Section C-D.) In this sector, the opposite end of the cell also is connected with the combustion chamber by channels 15. (Fig. 1 Longitudinal Section, and Section C-D.) The direction of channels 15 is the reverse of the direction of channels 14. Hereby a flow of the gas is produced according to the arrow signs (Fig. 1, Longitudinal Section). The compressed fresh air flows into the combustion chamber through channels 15. The cell is filled entirely with compressed hot gas. The effect of the mixture in the cells of hot gas and fresh air will be discussed later. (See par. 4 a.)

It was assumed at the beginning of this chapter that in the combustion chamber there is a certain pressure P and a certain temperature T. The value of the pressure P can be derived as follows.

Within Sectors II and III the cells, together with the combustion chamber, form an hermetically sealed room; therefore, the weight of gas inclosed in this room will be constant while the engine is running under stable conditions. Consequently, the cells leaving this room must carry out exactly the same weight of gas as is carried in by the entering cells. Since the cell volume is constant, the absolute pressure of the hot gas, P, increases in proportion to the absolute temperature T_h.

$$P = P_o \cdot T_h/T_f$$

T_h = absolute temperature of the hot gas in the cells leaving Sector III.

T_f = absolute temperature of the fresh air in the cells entering Sector II.

P_o = absolute pressure of the fresh air in the cells entering Sector II.

P = the absolute pressure of the hot gas in the combustion chamber. The combustion-chamber pressure is the same as in the cell in Sector III.

Therefore, the pressure ratio obtained in the cells depends only on the temperature ratio, and is independent of the individual processes by which the temperature increase from T_f to T_h was achieved.

The cells containing high-pressure hot gas enter the Sector IV, Fig. 1, Section G-H. The cells in this sector are sealed on one side by the wall 7, and opened on the opposite side (Fig. 1 Section E-F and G-H). The hot gas flows through the adjustable vane 13 (Fig. 1, Section K-L) into the turbine 10. The hot gas remaining in the cells will be displaced by fresh air. (See Fig. 1, Section E-F.) This process was described in the preceding paragraphs.

Summarizing: The whole process consists of four partial processes, which operate in Sectors I to IV.

Partial process 1 in Sector I: Scavenging of cells with fresh air

Partial process 2 in Sector II: Leveling of pressure between the combustion chamber and the cells

Partial process 3 in Sector III: Exchange of the compressed fresh air for hot gas

Partial process 4 in Sector IV: Expansion of hot gas

In the following paragraph, thermodynamical characteristics of the whole process and quantitative details of the four partial processes will be given.

4. Thermodynamic Characteristics

a. General Relations Between Temperature, Pressure, Output Power, and Efficiency

The process described in par. 3 can be carried out in a hypothetical engine consisting of a combustion chamber and a cell connected by channels (Fig. 3.) To explain the thermodynamic process such a simplified arrangement is especially appropriate.

The simplified arrangement shown in Fig. 3 (numbers do not necessarily correspond to those of Fig. 1) consists of valves 1, 2, 3, and 4, fuel nozzle 5, cell 6, combustion chamber 7, connecting channel between the combustion chamber and cells 8 and 9, hot-gas outlet 10 and fresh-air inlet 11. The operating method is the same as described in par. 3.

The hypothetical engine may operate on either of these two limiting cycles:

(1) Absolute separation of hot gas and fresh air within the cell

(2) Complete mixture of hot gas and fresh air within the cell

The operation with absolute separation is now to be described. The attainable energy can be produced by means of a turbine placed within the channel 8 (Fig. 7) or by a piston 12 installed within cell 6. (See Fig. 3.) For descriptive simplicity the piston instead of a turbine is assumed. This assumption is justified, because the thermodynamic action of a piston is fully equivalent to that of a turbine. The four partial processes are as follows:

Partial Process 1 (Fig. 3) Valves 1 and 2 are open; valves 3 and 4 are closed. The piston moves from position c to a; fresh air entering at 11 flows into cell 6; low-pressure hot gas is driven out of the cell through nozzle 10.

Partial Process 2 (Fig. 4) Valves 1 and 2 close; valve 3 opens; and valve 4 remains closed. The hypothetical piston 12 moves from position a to position b. The volume of fresh air decreases from V_0 to V' (Fig. 4, PV Diagram); hot gas flows into the cell 6 through channel 8 and through the open valve 3. The pressure of fresh air increases adiabatically from P_0 to P. The hot-gas pressure, on the side of the piston open to the combustion chamber, has the constant pressure P. The useful work of this partial process is equal to the area of the shaded triangle. (See Fig. 4 PV Diagram.)

Partial Process 3 (Fig. 5) Valve 4 opens; valves 1 and 2 remain closed; valve 3 remains opened. The piston moves from position b to position c, whereby the compressed fresh air is driven into the combustion chamber through channel 9 and opened valve 4. Cell 6 is entirely filled with high-pressure hot gas. The only work required in this exchange process is that necessary to overcome gas-flow friction. In an ideal process no friction exists, so theoretically, no work is done in transferring the compressed air from 6 to 7. In a real engine, the work necessary to overcome gas friction is supplied by inertia forces in the machine, which are built up from preceding cycles.

It may be mentioned that in combustion chamber 7 the pressure suffered a decrease when some hot gas flowed out of the combustion chamber into cell 6, within partial process 2. This decrease is small if the volume in the combustion chamber is large in comparison to the volume of the cell. The pressure decrease is compensated again by the compressed fresh air being conducted into the combustion chamber within partial process 3, because the volume of the air conducted into the combustion chamber after being heated, is equal to the volume of hot gas which flowed from combustion chamber 7 into cell 6 in partial processes 2 and 3.

Partial Process 4 When the cell 6 is entirely filled with high-pressure hot gas (Fig. 6), valves 3 and 4 close, valve 2 opens, and valve 1 remains closed. Piston 12 remains motionless at position c. The hot gas flows out through the nozzle 10 and is able to do work by means of a piston, a turbine, or by jet reaction. This is an adiabatical process. The value of this work is equal to the area of the shaded triangle in the PV Diagram (Fig. 6). V'' means the volume of the expanded hot gas.

In the following paragraph, thermodynamical characteristics of the whole process and quantitative details of the four partial processes will be given.

4. Thermodynamic Characteristics

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In the following, the process with complete mixture of hot gas and fresh air within cell 6 will be discussed. Partial processes 1 and 4 do not change, as a consequence of the mixture accomplished within the cell; therefore, it is only necessary to substitute partial processes 2a and 3a for partial processes 2 and 3 respectively.

Partial Process 2a. In the description of partial process 2, a mixture of hot gas and fresh air was avoided by means of the hypothetical piston 12.

If the partial process 2a is accomplished by means of a turbine 13 placed within the channel 8 (Fig. 7), the same amount of energy can be attained as by means of a piston. The hot gas flowing through the turbine into the cell is expanded to the pressure within the cell. The pressure within the cell rises to the pressure within the combustion chamber. If fresh air and hot gas are together, unmixed, under the same pressure in a chamber, the pressure does not change as a result of a mixture of the gases. This is in agreement with the perfect gas law. Hence, the mixture of hot gas and fresh air does not change the working conditions (mass flow and mean-pressure ratio) of the gas turbine 13 placed within channel 8.

Partial Process 3a. In the previously described partial process 3, the compressed fresh air was conducted into the combustion chamber while cell 6 was completely filled with high-pressure hot gas. In this process 3, with absolute separation of hot gas and fresh air, the volume of the compressed fresh air was only a small part of the cell volume. (See Fig. 5.)

The mixture of hot gas and fresh air has a disadvantageous consequence upon the partial process 3a, because higher volume must be exchanged between the combustion chamber and the cell. It is necessary that the entire fresh air as well as the hot gas cooled by the mixing of the fresh air, be induced into the combustion chamber, because otherwise the temperature of the hot gas in the cells is essentially lower than the temperature of that in the combustion chamber.

The comparison of both processes-with absolute separation and with complete mixture within the cell - has the following results:

(1) The pressure ratio P/P_0 is the same, because the cell temperature is the same. The relation between cell temperature T_h and pressure P was explained in par. 3.

(2) The energy produced in partial processes 2 and 4 is the same.

(3) The volume which must be exchanged in partial process 3 is essentially enlarged.

Therefore, the ideal process shown in the PV Diagram (Fig. 8) is the same for absolute separation and for complete mixture in the cell, because no friction losses exist in the ideal process. The PV Diagram of Fig. 8 is, therefore, a larger-scale drawing of the combination of the PV Diagrams of Figs. 4 and 6.

In the actual process, the complete mixture of hot gas and fresh air within the cell is a disadvantage; either the friction losses are increased, because the gas volume is increased, or mixed gas remains in the cell, lowering the gas temperature. This reduced temperature lowers the pressure ratio. Herein lies the most important difficulties of the first tests. (This is described in the short report RR-2of Mr. Schaefer, October 1946.)

The following equation discloses the energy developed in partial processes 2 and 4. The energy of one unit of weight of working substance is:

$$E_{part.\,proc.\,2} = R\,T_f\left[\frac{T_h}{T_f} - 1 - \frac{K}{K-1}\left(\left(\frac{T_h}{T_f}\right)^{\frac{K-1}{K}} - 1\right)\right] \cdots 1$$

$$E_{part.\,proc.\,4} = R\,T_h\,\frac{K}{K-1}\left(1 - \left(\frac{T_f}{T_h}\right)^{\frac{K-1}{K}}\right) - R\,T_f\left(\frac{T_h}{T_f} - 1\right) \cdots 2$$

$$E_{total} = R\,\frac{K}{K-1}\left[T_h\left(1 - \left(\frac{T_f}{T_h}\right)^{\frac{K-1}{K}}\right) - T_f\left(\left(\frac{T_h}{T_f}\right)^{\frac{K-1}{K}} - 1\right) \cdots 3\right.$$

R = gas constant

k = c_p/c_v, ratio of the specific heat of the air heated at constant pressure to constant volume.

The introduced heat amount W for one weight unit of the working substance amounts to

$$W = c_p\left(T_h - T_f\left(\frac{P}{P_o}\right)^{\frac{K-1}{K}}\right)$$

c_p = specific heat of the air at constant pressure.

The thermal efficiency of the ideal process, η_{id}, according to Fig. 6 has the value:

$$\eta_{id} = 1 - \left(\frac{P_o}{P}\right)^{\frac{K-1}{K}}$$

This expression is valid for every constant-pressure procedure with adiabatic compression and expansion. For the process described the following applies:

$$\eta_{id} = 1 - \left(\frac{T_f}{T_h}\right)^{\frac{K-1}{K}}$$

because

$$\frac{P_o}{P} = \frac{T_f}{T_h}$$

With the actual process, two kinds of losses occur:

(1) Frictional losses, which are not dependent upon the pressure in the combustion chamber. These losses are composed of the ventilation losses in partial processes 1 and 3, of the total friction (air and bearing) of the rotor. The ratio of these energy losses to the attainable energy E_{total} is designated by ε; $\varepsilon = E_{friction\ losses} / E_{total}$

(2) Energy losses which occur with the transformation of the hot gases into mechanical force, in partial processes 2 and 4. The actual efficiency at the conversion of the energy of the hot gases into mechanical energy is designated by η_τ.

When these losses are considered, the result of attainable energy E_a:

$$E_a = E_{total} (\eta_\tau - \varepsilon)$$

Correspondingly, the following equation is valid for the thermal efficiency:

$$\eta_{therm} = \eta_{id} (\eta_\tau - \varepsilon)$$

$$\eta_{therm} = \left(1 - \left(\frac{T_t}{T_h}\right)^{\frac{K-1}{K}}\right) \cdot (\eta_\tau - \varepsilon)$$

The thermal efficiency is presented in Fig. 9 for the three various pressure ratios in dependence upon η_τ. The thin straight lines going through the zero point represent the efficiency for $\varepsilon = 0$.

The value of ε cannot be given generally. From test results it can be assumed, on Fig. 9, that (ε) can amount to 0.15 if the pressure ratio has the value 3. The energy E is nearly doubled if the pressure ratio increases from 3/1 to 4/1, and is tripled if the pressure ratio goes from 3/1 to 5/1.

For that reason, the value of (ε) amounts to 7.5% at a pressure ratio of 4/1, and to 5% at a pressure ratio of 5/1. The strong, solid curves in Fig. 7 present the thermal efficiency, with consideration of the friction and ventilation losses. These curves are calculated with variable specific heat.

b. Special Characteristics of the Thermal-Compression Engine with Cell Rotor

The general relations between temperature, pressure, efficiency and performance are explained in the preceding paragraphs. The special characteristics of the device with cell rotor will now be described. The total process consists of a mechanical compression and of the described "Thermal Compression" process. The detailed processes are given in Fig. 11 in the PV Diagram for a unit weight of the mass flow. The four partial processes in this diagram are as follows:

Partial Process - Scavenging

The fresh air at point 1 of the PV Diagram, Fig. 11, is compressed and simultaneously changed from zero velocity to the velocity of the cell rotor. The total energy imparted to the fresh air is represented by the diagonally and horizontally shaded areas between the points 1 - 4, Fig. 11.

This total energy is divided into:

(1) The kinetic energy of the circumferential velocity of the fresh air in the rotor (horizontally shaded area between the points 3 and 4)

(2) The kinetic energy of the axial velocity in the rotor (diagonally shaded area between points 2 and 3)

(3) The energy for increasing the static pressure of the fresh air from the initial condition 1 to condition 2 in the rotor during the scavenging period (diagonally shaded surfaces between points 1 and 2)

At the end of the scavenging period, the fresh air is suddenly rammed by the rear wall of the housing 8 (Fig. 1). A compression shock wave travels against the direction of the scavenging velocity and calms the entire fresh air in the cell. The produced pressure ΔP is, for low pressures, approximately:

$$\Delta P = \rho \cdot C_{ax} \cdot W$$

W = sound velocity

C_{ax} = axial velocity

ρ = mass density

The condition of the air is represented in Fig. 11 by point 5. The area of the triangle 2, 5, 13 represents the energy which is necessary to bring the inflowing fresh air to condition 5. This area equals the diagonally shaded area, between the points 2 and 3, which represents the kinetic energy of the axial velocity of the fresh air with condition 2

The displacement of the walls 7 and 8 (Fig. 1, Sections E-F and G-H) is so dimensioned that in normal operation of the engine, the shock wave reaches exactly the front end of the cell when the cell is closed by the front wall 7.

For the energy calculation, the following are to be considered:

(1) A part of the fresh air flows, together with the rest of the hot air, out of the rear end of the rotor and does not participate in the other processes; this part can amount to about 20% of the total fresh air.

(2) The entropy of the fresh air is increased by the losses in the supercharging fan, by friction losses in the cell, and by losses caused by shock compression.

The mass flow is proportional to the revolutions per minute, because the fresh air is delivered by means of a blower or by the rotor. Therefore, the conditions for the scavenging of the cells can be fulfilled at any speed. The compression by shock wave will be complete at a certain speed only. Complete compression at all speeds requires a variable-position control of the walls 7 and 8 (Fig. 1).

Partial Process - Pressure Equalization in the Cells

The energy attainable in partial process 2 is represented by the diagonally shaded area between the points 5, 6 and 9. This energy is directly transmitted to the rotor in the thermal compression engine with a certain efficiency. (See par. 3.) This efficiency is calculated as follows:

C_u = average circumferential velocity of the gas

u = circumferential velocity of the cells

E_L = shock losses of the gas jet hitting the cell walls of the rotor, based on one unit weight of gas

g = acceleration of earth

$$E_L = \frac{(c_u - u)^2}{2g}$$

The total energy of the gas based on one unit of weight is the kinetic energy $c^2/2g$. The value $C^2/2g$ equals approximately $c_u^2/2g$, because the direction of c is nearly tangential. Herewith results, for the energy E_R transmitted to the cell rotor:

$$E_R = \frac{c_u^2}{2g} - E_L$$

The turbine efficiency of the cell rotor η_τ amounts to the energy E_R divided by the total energy $c_u^2/2g$.

$$\eta_\tau = \frac{E_R}{c_u^2/2g} = \frac{c_u^2/2g - E_L}{c_u^2/2g}$$

$$\eta_\tau = \frac{c_u^2/2g - (c_u-u)^2/2g}{c_u^2/2g}$$

$$\eta_\tau = u/c_u\,(2 - u/c_u)$$

The efficiency of the partial process 2 dependent upon u/c_u is presented in Fig. 13. If, for example, one takes: $u = 820$ ft/sec; $c_u = 1960$ ft/sec; the result is $u/c_u = 0.415$; $\eta_T = 0.65$.

The diagonally shaded area (Fig. 11) between the points 5, 6, and 9, multiplied by the turbine efficiency η_T, must be equal to the shaded area between the points 1 to 4, increased by the losses in the scavenging process and by the friction losses of the rotor. This is the condition for the autorotation of the cell rotor.

The flow conditions in the channels 14 (Fig. 1) depend upon the revolutions per minute. The reason for this is that the total weight per second of the hot gas flowing through the channels 14 should be nearly proportional to the revolutions per minute, while the pressure ratio between the combustion chamber and the cells is independent of the revolutions per minute. By using special precautions in building channels 14, satisfactory engine performance throughout the operating range may be obtained with stationary channels, without the necessity of changing the channel areas depending upon the speed.

The described process of the pressure equalization was considered as a nearly static process. That means that the intensity of the compression waves which go out from channels 14, and which run through the cells, is very slight. For that reason, the pressure differences in a cell are negligible. In consequence, there is no overlapping between partial processes 2 and 3.

In special cases, such an overlapping is desired in order to support partial process 3. The increase of intensity of the compression waves is obtained by special construction of the channels 14. The power concentration of an engine can be increased by such construction; however, it is difficult to obtain favorable operational conditions for every speed.

Partial Process - Exchange of Hot Gas and Fresh Air

In partial process 3, the compressed fresh air flows through the diffuser 15 (Fig. 1) into the combustion chamber, while the same volume of hot gas enters the cells in Sector III (Fig. 1) through the channels 14. The condition of the fresh air is changed from condition 6 to condition 7 by flowing through the diffuser. (See Fig. 11.) This results in a higher pressure in the combustion chamber than in the cells. The attainable energy of this constant-pressure process is, in the ideal case, equal to the area between the points 6, 7, 8 and 9. In the actual process, this energy is very small and can in most cases be neglected. The reasons for this are the mixing of the fresh air and the hot gas in the cells, and the losses in the diffuser.

The conditions for the exchange of the fresh air and the hot gas are equally attainable for any speed, because in sector III the gas flow in channels 14, Fig. 1, and the fresh air flow in channels 15(Fig. 1) are caused by the blower-like effect of the rotor, so that the mass flow is proportional to the speed.

Partial Process - Expansion

The attainable energy in the expansion process is presented by the area of the triangle between points 9, 10 and 11.

Two limiting cases of the expansion can be distinguished:

(1) The expansion of the gas is produced in a certain part of the cells, e.g., in a throat at the end of the cells; in this case, the discharge velocity of the gas slowly decreases. At the beginnning of the expansion, the gas has a velocity corresponding to the pressure gradient between points 9 and 11 in Fig. 11. The velocity of the discharge drops to 0 and a remnant of the expanded hot gas remains in the cells. With this kind of expansion a special control of the wall 7, Fig. 1, dependent upon the revolutions per minute, is not necessary. The circumferential size of the wall 7 is calculated for the maximum revolutions per minute and for the maximum pressure. A disadvantage of this expansion is that the velocity of the expanded gas is not constant, and that the initial values of the velocity are very high. A schematic configuration representing this case is shown in Fig. 12a.

(2) The second limiting case is the expansion of the hot gas caused by expansion waves. These waves move through the gas in the cells with the velocity of sound; this causes a more uniform velocity of the largest part of the gas in the cells (this velocity is essentially smaller than the top velocity which the gas reaches with the first type of expansion); and, finally, almost no motionless hot gas remains in the cell. A schematic configuration representing this case is shown in Fig. 12b.

The main difficulties of expansion by expansion waves are the following:

(1) The velocity of the expansion waves depends upon the gas temperature in the cells, and is independent of the speed. Therefore, a control of the timing for the wall 7 is required for varying speeds, in order to adhere to the best operational conditions (par. 4, Fig. 1).

(2) The velocity of the fresh air during the scavenging procedure is essentially less than that of the hot gas in the cells. As a result, a second expansion wave reflects on the cool air at the beginning of the scavenging period. This delays the hot air and accelerates the fresh air. This combination between the expansion process and the scavenging process can be utilized for eliminating the scavenging fan. This causes several difficulties similar to those described in the process of combination of partial processes 2 and 3. Special measures are necessary, in order to obtain more favorable operational conditions within a larger range of speeds.

Both limiting cases of the expansion cannot be carried out in practice. The actual expansion is always a combination of the two limiting cases. The type chosen depends upon the application of the engine. 1/

The attainable expansion energy can be used as the supplementary thrust by jet reaction, or it can be converted into mechanical energy by means of a turbine. Gas is admitted to the power turbine for only a part of the cycle, (Fig. 1, Sections G-H and K-L). As a result, the turbine efficiency does not exceed 70%. For most purposes it is useful if the turbine runs independently from the rotor. In this case, the torque of the turbine can increase to twice the value of the maximum in the normal operation, if the turbine is slowed down by external influences.

Blade-Clearance Losses

In partial processes 2, 3, and 4, the pressure in the cells is higher than the pressure of the atmosphere. This causes gas to flow out between the gap of the walls and the housing, causing a decrease of the actual pressure in contrast to the calculated pressure $P = P_0\ T/T_0$.

This decrease is designated as Δ P.

$$\Delta P = P \cdot \Delta G/G\ ;$$

G represents the required weight of air per second, and ΔG the loss of weight per second through the gap.

1/ The exact evaluation of all unsteady flow processes for the first model RR-2 has been carried out by R. Kassner, mainly using the method of Sauer, German Report 1675.

A rough estimation of the gap losses is possible by the equation:

$$\Delta G/G = F_S/F_C \cdot v/u$$

F_S = area of the gap between housing and rotor

F_C = area of the cell wall

v = velocity of the gas in the gap

u = circumferential velocity of the center of the cell walls

In making this estimation, neither variations of the density of the gas nor contraction of the flow in the gap is taken into consideration.

The gap area may amount to about 1% of the area of the cell wall. When the velocity in the gap is from three to four times as great as the circumferential velocity of the cell walls, the value of Δ G/G lies under 4%. The radial gap losses are about the same.

In this calculation, no gap losses were assumed against the direction of rotation of the rotor, because the gas flowing out in this direction through the cells is conveyed back again into the pressure range without decreasing the fresh air filling of the cells. This return transport requires a definite energy, the calculation of which is not being made here.

Heat Transfer Losses

A heat exchange occurs between the cell rotor and the hot gas or fresh air within the cells. Therefore, the temperature of the hot gas in the partial processes 2 and 3 decreases; the temperature of the fresh air in partial process 1 increases. This results in a decrease of the attainable pressure ratio. The time interval of each partial process is so slight that the heat transfer is small. The increase or decrease of the temperature amounts to about 20°F.

c. Comparison with Known Processes

Constant-Pressure Combustion Process

In Fig. 9, the efficiency curves of a normal constant-pressure combustion-gas turbine, with pressure ratios 3, 4 and 5, and gas temperatures in the combustion chamber ranging between 1450° and 1650°F are drawn in dotted lines. The compressor and the turbine efficiency are assumed to be equal. This efficiency is termed η_T

From the shape of the curves, one can recognize the difference between the described process and the normal constant-pressure gas turbine. With the normal constant-pressure turbine, the required power for the compressor must be delivered from the turbine. The useful output is, therefore, the difference between the turbine power and the compressor power. The total efficiency and the useful output are greatly influenced by the efficiency of the turbine and the compressor. As a result, the decrease of the total efficiency is very great if the compressor and the turbine efficiency decrease slightly. (See Fig. 9.)

In contrast to this, the useful output and the total efficiency of the thermal compression process is a product of the ideal values, with the factor ($\eta_T - \varepsilon$). The course of the over-all thermal efficiency curve of the thermal compression process, dependent on the turbine efficiency, η_T , is considerably flatter than in a normal constant-pressure turbine. If, for example, a pressure ratio of 5:1 and a turbine efficiency η_T = 0.7 is assumed, then the total efficiency, including all friction losses, amounts to 23%.

The normal constant-pressure turbine would reach this thermal efficiency, at the same pressure ratio with a compressor and turbine efficiency of 84% and without any loss in the combustion chamber.

In comparing the two processes, two points must be considered:

(1) The unsteady admission in the thermal compression process leads to the result that the average values of η_T amount to 70% or less. The turbine in the thermal compression cycle, due to inherent pressure fluctuations caused by the rotation of the cell rotor, always operates with a varying inlet pressure. The thermal efficiency of a turbine with varying inlet pressure is generally lower than the efficiency of a turbine with constant-pressure inlet. The average efficiency of a turbine with variable inlet pressure varies between 65 and 75%.

(2) The peak temperature in the cells amounts to 1950°F with a pressure ratio of 5:1, whereas a combustion-chamber temperature of from 1450° to 1650°F is assumed for the normal turbine.

A comparison of the two processes based on these different temperatures is justified, because the temperature of the rotating parts of the described engine is about one half of the gas temperature, as a result of the partial admission and owing to the internal cooling.

Constant-Volume Combustion Process

The constant-volume process consists of three partial processes:

1. Scavenging

2. Constant-volume heating

3. Expansion

The two processes - scavenging and expansion - are the same as those described in the thermal compression process. Partial Process 2, constant-volume heating, corresponds to the two processes 2 and 3 of the thermal compression process, par. 4a.

The ideal Constant-Volume Process has the special feature that the working substance is not changed, as to volume and weight, before and after the heating. The same holds true for the thermal compression described in par. 3. For that reason the same connection exists between pressure and temperature for both processes. Further, both processes have the characteristic that the effective power and the total efficiency are obtained directly by multiplication of the ideal values with ($\eta_T - \varepsilon$). The differences in the two processes concern the following two points:

(1) With the constant-volume process, the air is heated in the cells, the particles of hot gas in a cell being formed from the particles of fresh air in the same cell, so that the air-weight is constant before and after the heating.

With the thermal compression cycle, an exchange process consisting of the partial processes 2 and 3 (see par. 4a) takes place, instead of the immediate-heating process. After the exchange process, the weight of the hot gas in the cell is the same as that of the fresh air, as with the constant-volume process. But in contrast to the constant-volume process, the particles of hot gas in a definite cell are not formed from the particles of fresh air of the same cell.

(2) With partial process 2 (see par. 4a), mechanical energy is produced, corresponding to the diagram in Fig 4. This has the result that the power output per mass flow, and the efficiency of the thermal-compression process, is essentially higher than the corresponding values of the constant-volume process when both are based upon the same temperatures.

A great similarity exists, in both procedures, in the construction details for the types with stationary as well as with rotating cells.

Pressure Exchanger

The pressure exchanger is a device in which two gases of different initial pressure are brought into immediate contact. The gas with high initial pressure expands in the pressure exchanger and compresses the gas with low initial pressure. Two types of the pressure exchanger can be distinguished. One type works with static pressure exchange, the other with dynamic exchange by means of compression shock waves and expansion waves.

The pressure exchanger achieves the expansion and the compression process of two gases in one engine. It yields the same effect as a machine group consisting of compressor and turbine (Fig. 10). The thermodynamic process in the pressure exchanger is a normal constant-pressure process.

The difference between the pressure-exchanger process and the described procedure is as follows: The hot gas that has entered the pressure exchanger is fully expanded to the same pressure as the entering fresh air. The weight flow of the hot gas entering the pressure exchanger is less than the weight flow of the fresh air, since the pressures of hot gas and fresh air are equal on the high-pressure and the low-pressure sides. The excess compressed gas is led into a special turbine which produces the useful power output. The pressure ratio is, therefore, determined not only by the temperature, in contrast to the thermal compression process, but also depends upon the losses in the pressure exchanger and upon the ratio of the weight of hot gas, flowing through the pressure exchanger, to the total mass flow. (See report by Dr. Hussman.)

The pressure exchanger and the thermal-compression engine are similar in construction details, especially in the cell rotor. In both engines the hot gases and fresh air alternately pass the rotor, so that an extremely high temperature can be permitted for the hot gas.

The entire thermodynamic process of an engine with rotating cells was presented as a cycle process in the PV Diagram. This presentation gives an easily conceivable picture of the details. An explicit expression for the total efficiency was not given. Furthermore, it was not intended in this report to give detailed evaluations of the aforementioned unsteady processes.

5. Test Data Already Obtained

The tests were carried out with a small engine, having an air mass flow which amounted to 1.4 kg/sec at full rpm. The turbine was rigidly coupled with the rotor, in contrast to the more recently recommended construction, shown in Fig. 1, of a turbine independent of the cell rotor.

The device was tested on the test stand with an electric dynamometer. The gas velocity, pressure, and temperatures at various spots were measured. The exact details can be found in a special unpublished report (RR-2, dated 15 Dec 1946, given to Lt. Dickey and Commander Miller of the U. S. Navy by the author of this report in early part of 1947 in Berlin). 1/ In the following, only a qualitative overlook about the run of the tests, the main difficulties, and the most important results are given. The testing of the engine began in April, 1946. The construction, according to that early design, did not give satisfactory results.

The maximum pressure ratio attained amounted to 2.4 at a combustion-chamber temperature of 2200°F. The engine was able to drive itself; the effective output was practically zero; the scavenging was not sufficient to remove all the hot-air remnants from the cells.

The evaluation of the test results showed that the insufficient working of the unit was the result of unforeseen occurrences in the partial processes 2 and 3. These occurrences had the effect that only a small part of the compressed fresh air flowed out of the combustion chamber, and that the energy attained in partial process 2 was considerably under the calculated values. Because of these results, various alterations, which were to be tested independently of each other were made on the unit.

1/ See Supplement A - AEL Translation 56

The revolution per minute for these tests were limited to 8000, that is, about 45% of the provided maximum revolution per minute, because of a deficient welding of the cell walls to the rotor.

In the following test program, the engines were permitted to run with the most effective alterations at various revolution per minute and various load conditions. Finally, whether the cell rotor could run without support of the turbine was to be tested. For this purpose the turbine was to be separated from the cell rotor.

Even the first tests with the altered unit showed essential improvements with regard to performance, to attained pressure ratio, and to efficiency. The attained pressure ratio amounted to about 3, the effective power to 16 hp. Individual details of this test run were reported by Mr. Schaefer in October, 1946. It must be considered here that the average circumferential velocity of the turbine, of 330 ft/sec, is insufficient for a pressure ratio of 3, and that the blades were admitted in an unsatisfactory manner.

The test program originally planned could not be carried out because the tests had to be stopped suddenly at the end of September, 1946. The engines had to be delivered by 1 October, without consideration of their condition and of the status of the tests. Because of the time shortage, it was impossible to bring the engines to the status of the last tests.

At the end of the last tests, the engine with the turbine removed was investigated. It was found that the cell rotor was able to run alone with a small excess performance (about 3 hp).

Herewith, conditions were fulfilled for a unit with a turbine running independently of the cell rotor. It can be assumed, in evaluation of the test results, that essentially improved performance and efficiency can be attained by such an arrangement. There were further important hints for improvement in other parts of the unit, but it was impossible to carry them out.

Extensive tests are required to permit an accurate judgment of the principle. As the described test results are not sufficiently broad. However, these test results can be considered to be favorable for the new constructions, because they at least represent the initial operation of a thermal-compressor engine.

6. Construction Details

a. The Cell Rotor

The exterior form of the cell rotor may vary according to its scope. For units with small exterior dimensions in respect to their performance, cell rotors with axial flow are best suited. For manufacturing reasons, constructions having cells parallel to the axis are preferred.

The average temperature of the rotor is essentially lower than the temperature of the hot gas in the cells, because of the effective inner cooling by fresh air. As a rough approximation, it can be said that the temperature of the rotor lies halfway between the temperature of the scavenging air and that of the hot gas in the cells.

The ratio of the inner diameter to the outer diameter generally lies over 0.5.

Thus, with cell walls having constant wall thickness, the following equation is valid for the tension (S):

$$S \leq \rho \cdot \frac{u^2}{2} \cdot 0.75$$

u = circumferential velocity of the cells

ρ = density of the material of the rotor

According to past project calculations, the circumferential rotor velocity of high-performance units does not go above the value of 820 ft/sec. This limit is approximately determined by the fact that the friction losses are proportional to the cube of the circumferential velocity, while the effective power at constant combustion-chamber pressure is directly proportional to the revolutions per minute. The stress caused by the centrifugal forces in the cell walls, at a circumferential velocity of 820 ft/sec, amounts to about 25,400 psi. This makes it possible to design cell rotors, which are easy to manufacture from sheet metal. The expected weight G of such rotors amounts to $0.09\,\gamma\,\mu\,d_0^3$

γ = specific weight of the material of the cell rotor

μ = ratio of the length of the rotor to the diameter

d_0 = outer diameter of the rotor

b. Bearings

The bearings of the cell rotor are under comparatively small load, because

(1) no axial forces (or only very small forces) occur

(2) the weight and the revolutions per minute of a rotor are less than the corresponding values of a compressor-turbine rotor.

The bearings are generally built into the walls 7 and 8 (Fig. 1.) Here it must be noted that the heat transfer on these walls is very high, and that special measures must be taken to cool the walls or the bearings.

c. The Combustion Chamber

For test engines, the combustion chamber has been mounted eccentrically in regard to rotor shaft. For test purposes, this design has the advantage of a simple disassembly, and offers the possibility of alterations on the combustion chamber without removing the other components of the engine. This kind of combustion-chamber mounting is very suitable in fields of application for which position and shape of combustion chamber has to be fitted for special installation conditions. For engines not submitted to special limitations in regard to their outer diameter, annular combustion chambers may be used.

It is especially noted that the temperature of the gas in the combustion chamber for attaining the desired pressure of about 4:1 or 5:1, lies between 2200° and 2750°F. For that reason, special precautions must be taken for protecting the combustion-chamber walls and the nozzle channels 14, (Fig. 1).

As the vanes in the channels are very thick in comparison to their width, a high heat transfer takes place from the vanes to the housing. This makes sufficient cooling of the vanes possible without a special cooling arrangement.

Various types of the cell rotor with radial and with partial radial gas flow should be discussed in greater detail, as well as devices of channels 14 and 15, with axial or part-axial flow. It appears, however, that such devices are less practical for aircraft application.

Further design details will not be mentioned, because they depend upon special application of the engine. For their discussion, project drawings are required.

7. Applicability for Aircraft

The described process of thermal compression was mainly provided for the construction of turbines of medium and small performance. The following two viewpoints were predominant.

a. Simplicity, Ruggedness, Dependable Operation, and Low Cost

The device has no stator blades. The turbine runs independently of the cell rotor. The cell rotor may be constructed so that no special supercharging fan is required. The revolutions per minute of the cell rotor and of the turbine is essentially less than the revolutions per minute of a normal gas turbine of equal performance.

b. Efficiency of the Engine

According to the thermodynamic calculations, it seems possible to reach a total efficiency of the engine of from 18 to 22% at a pressure ratio of from 4:1 to 5:1. Since the pressure ratio is not dependent upon the revolutions per minute, the influence of the revolutions per minute upon the thermal efficiency is less than with a normal gas turbine. With a normal turbine, the pressure falls with about the square of the circumferential speed. With a small turbine of normal design, it is practically impossible to reach a total efficiency of 20% without heat exchanger. The low thermal efficiency of a small, gas-turbine engine results from the low Reynolds Number and the poor unit efficiency of any small turbine and compressor.

The following points are important in considering the thermal compression process for application in aircraft:

(1) The characteristics of the engine at high altitudes

(2) The weight of the engine in relation to its performance

(3) The dimensions of the engine in relation to its performance

The characteristics of the engine in high altitudes are similar to those of normal gas turbines. The supply per weight is proportional to the specific weight of the intake air. The pressure ratio rises at constant combustion-chamber temperature at high altitude, as a result of the decrease of the absolute temperature T_0 of the intake air, corresponding to the equation:

$$P = P_0 \; T/T_0$$

The thermal compression engine is less sensitive to an increase of Mach number with altitude and to the resulting troubles of surging, breakdown, and low compressor efficiency than are conventional turbojets.

The weight and dimensions of the engine in relation to performance cannot be generally given. In calculating various projects, velocities of the scavenging air in the cells was assumed between 400 and 520 ft/sec. A free inlet area for the scavenging air of about 35 - 40% of the frontal area of the rotor was assumed. The precalculated weight of such engines, equipped with sheet-metal rotors, is about equal to or lower than the weight of gas turbines with radial compressors, of equal performance. The diameter of the cell rotor is about 10% to 15% smaller than that of a normal centrifugal compressor of equal mass flow. The ratio, μ , of length of the rotor to diameter with high-speed thermal compression engines amounts to about 0.6.

A main difficulty in using the described engines for aircraft is, in many cases, the location of the combustion chamber, which lies outside of the cell rotor.

Figs. 14 through 18 show in schematic drawings two engine types for aircraft. Test data available up to now are not sufficient to provide a base for accurate project calculations. For that reason, these illustrations first of all serve to give a picture of development possibilities, while the accurate layout will not be possible until after more extensive research.

In Fig. 14 is shown a small propeller turbine calculated for about 500 hp static sea level. The turbine runs independently of the cell rotor.

The following assumptions are basic for the design:

mass flow	10.5 lb/sec
velocity of the scavenging air	400 ft/sec
circumferential velocity of the cells	720 ft/sec
revolutions per minute of the rotor	11,000
revolutions per minute of the turbine	15,000
revolutions per minute of the prop shaft	1600
length of the cell rotor	7.8 in.
outer diameter of the cell rotor	15.6 in.
inner diameter of the cell rotor	9 in.

Section for scavenging equals 30% of the front area of the cell rotor.

Calculated weight of the engine, including the gear of the propeller, 500 lb.

In Fig. 15 the installation of the engine in a fuselage is shown; in Fig. 16 the installation is shown in a wing. In both cases the installation should be so arranged that the scavenging section lies outside the fuselage or the wing.

In Fig. 17 the cross section, and in Fig. 18 the length section of a turbojet engine is shown. This engine is calculated for a static thrust of 3000 lb. The following assumptions are basic for the design:

mass flow	55 lb/sec
velocity of the scavenging air	530 ft/sec
circumferential velocity of the cells	850 ft/sec
revolutions per minute of the cell rotor	7500
length of the rotor	15.6 in.
outer diameter of the cell rotor	26 in.
inner diameter of the cell rotor	14 in.
calculated weight of the engine, about	1000 lb

Section for scavenging equals about 40% of the front area of the cell rotor.

The engine for this purpose is especially simple, because the turbine can be eliminated. The axial scavenging blower is not altogether necessary, although it was provided in the design, as shown in Fig. 18, for the special purpose of enlarging the capacity of the engine.

The installation of the engine is shown in Fig. 18. It should be similar to the installation of the propeller turbine, as shown in Figs. 15 and 16. The gear box and the combustion chamber are installed in the wing or in the fuselage, while the scavenging sector of the engine lies outside the airframe. The scavenging section extends almost halfway over the circumference of the rotor (see Fig. 17). The expansion is provided in a large part by means of expansion waves.

In Figs. 17 and 18, it may be seen that the installation of the combustion chamber and of the gear box on the inside of the airframe is very important for judging the suitability of the engine. The combustion chamber and the gear box of the described project has a height of 1.1 ft, a length of 4.2 ft, and a front area of 4.6 sq ft. The frontal area on the outside of the airframe has a value of about 2.5 sq ft. The thrust per frontal area with regard to the outside of the airframe has the value of 1200 lb/sq ft. If the installation of the combustion chamber and of the gear box on the inside of the airframe is impossible, the ratio of the thrust to the frontal area is very unfavorable. This value would amount to 420 lb/sq ft.

c. Afterburning

The afterburning can be carried out in a way similar to that with normal jets. It seems advisable to inject the fuel for the afterburning into the cell rotor at definite places in the housing, but extensive tests are required for the evaluating of this process. The thermal compression jet engine is well suited for driving a ducted fan if a turbine with partial gas admission is added. The comparatively low speed of the partial gas admission turbine is favorable for a direct drive of the ducted fan. Due to the low speed of the turbine, the mass flow through the ducted fan can be much greater than the mass flow through the turbine. The fresh air for the high-pressure cycle can be taken now from the compressed air behind the ducted fan. Finally, all considerations of the well-known ducted-fan engines can be transferred to this suggested engine type.

Other fields of application for aircraft could be: small turbines - for starting engines, for driving accessories, electrical generators, etc. A possibility of applying the principle exists in the field of exhaust turbosuperchargers. The advantages would be independent pressure ratio of the revolutions per minute and comparatively low revolutions per minute. But it has not been ascertained whether the separation of the fresh air and the hot gas is possible. Special measures have been proposed, but until now they could not be tested.

8. Test Engine and Test Program

To supplement the tests already made, suggestions are provided for a new test engine, for the test installation, and for a test program. The design of the engine is based upon previously obtained knowledge. The layout should be made exclusively for the purpose of testing and measuring the partial processes. The size of the cell rotor must be suitable for efficient installation of the measuring equipment. A suitable diameter of the cell rotor is about 16 in. The ratio of the diameter to the length should be about 1.8 and the ratio of the inner diameter to the outer diameter should be about 0.6. These values are an average of the values of individual types for various application. The results of measurement so obtained can be applied to other conditions by recalculation.

Important requirements for the design of the test engine are:

(1) simple disassembly

(2) easy accessibility to the measuring spots

(3) possibility of varying the shape and position of the channels, 14 and 15, Fig. 1, and the possibility of timing the walls, 7 and 8, Fig. 1.

It would be best to equip the walls 7 and 8 with adjustable partial walls. By adjusting these partial walls, the overlapping of the partial processes can be investigated. The unsteady-flow process may be influenced by adjustment of the partial walls.

The combustion chamber of the test engine is purposely arranged eccentrically to the rotor, so that the chamber of the engine on the test stand can easily be mounted or dismounted. For the first tests, a bottled-gas combustion chamber is purposely used, because of its large combustion range.

In order to obtain a good adaptability of the test engine to all operational conditions which are possible with the various application purposes, the test engine may be built without a turbine. The scavenging air is supplied to the engine by a separately driven scavenger blower. The condition and the mass flow of the fresh air must be controllable before it enters the cell rotor. The condition of the hot gas in the jet and in the scavenging sector is also measured.

Figure 19 shows the recommended test arrangement. A separately driven supercharging fan 1 supplies the fresh air in definite amount and pressure to the test engine. The test engine consists of cell rotor 2, housing 6, and combustion chamber 3. The hot air either flows out freely or through a duct from the test stand. The rotor is coupled with an electric dynamometer. The dynamometer brakes or drives the rotor in a measurable way.

The tests should treat the following points:

(1) determination of the produced or absorbed power of the cell rotor dependent upon the revolutions per minute and the gas temperature

(2) determination of the kinetic energy and of the condition of the hot gas in the jet

(3) determination of the mass flow of the scavenging air and of the excess scavenging air dependent upon the revolutions per minute and the temperature

(4) determination of the total efficiency and of the individual losses in the four partial processes dependent upon the revolutions per minute and the gas temperature

(5) determination of the pressure ratio, dependent upon the gas temperature in the combustion chamber and in the cells, and upon the revolutions per minute

(6) investigation as to how far the procedures in the individual partial processes correspond to the precalculations; and as to which influence is possible by the variation of channels 14 and 15 and of walls 7 and 8, as shown in Fig. 1

(7) investigation of the unsteady flow in the cells

(8) investigation of the procedures in the transition from the one partial process to the other

(9) investigation of the best overlapping of the individual partial processes

(10) investigation of starting behavior

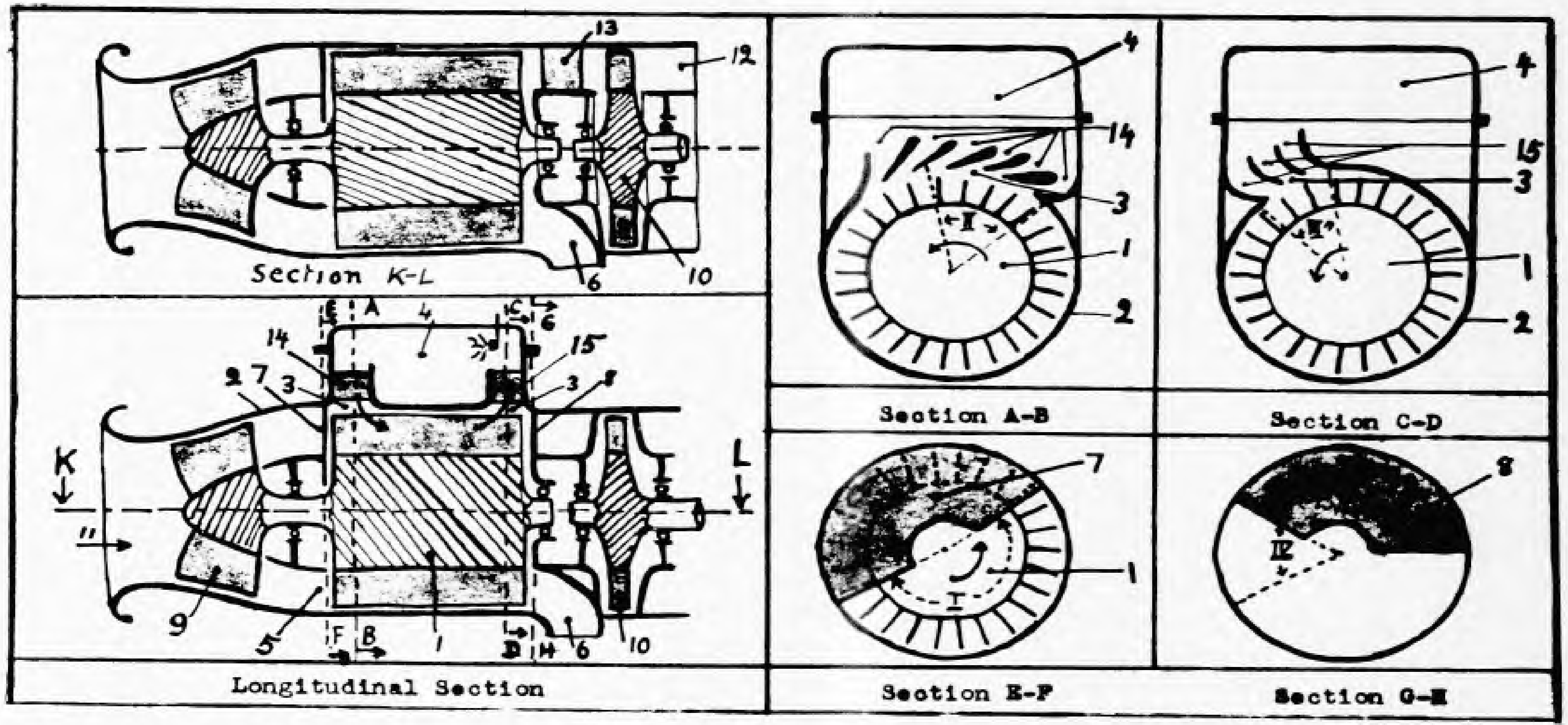
(11) investigation of the influence of the outside conditions

(12) investigations of the influence of the number of cells in the cell rotor

The required measuring devices and the location of the measuring instruments for these investigations will not be discussed in this report. They may be obtained from a special report about the test of engine RR-2.

Later tests, which are not in the range of this test program, may be concerned with variations of the dimensions of the cell rotors and with the different shapes of the cell rotor.

A judgment of the utilization of the principle of the various fields of application can be made according to the first test program, because an approximate conversion of the obtained results is possible for other dimensions of the rotor.



1. Cell rotor
2. Housing
3. Openings between cell rotor and combustion chamber
4. Combustion chamber
5. Inlet opening for fresh air into the cell rotor
6. Outlet opening for low pressure hot gas
7. Front wall of housing
8. Back wall of housing
9. Supercharging fan
10. Turbine for effective output
11. Fresh air inlet
12. Exhaust-gas outlet
13. Stationary vanes for turbine
14. Channels for hot gas flowing from the combustion chamber into the cells
15. Channels for compressed fresh air flowing from the cells into the combustion chamber

Fig. 1 - Gas Turbine with Constant-Pressure Combustion and Thermal Compression

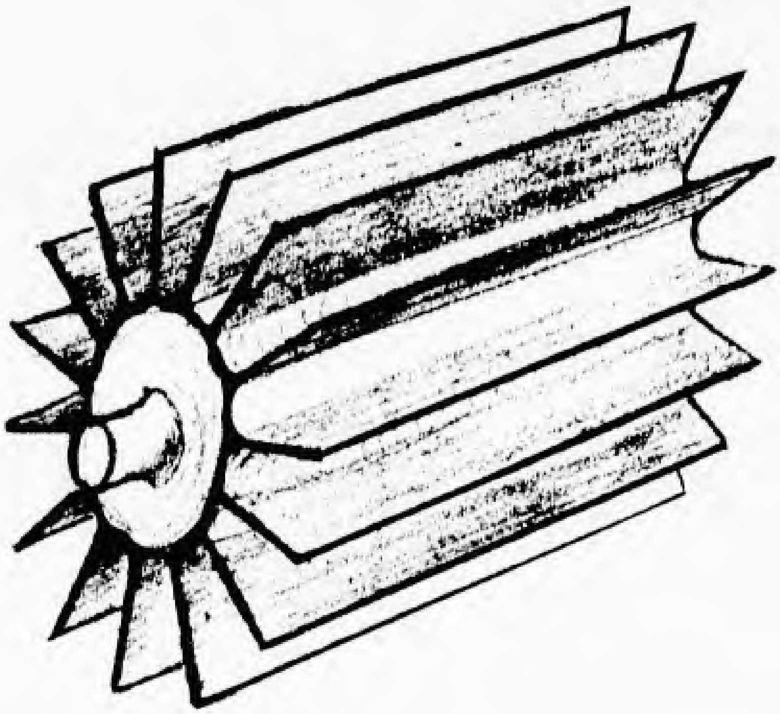


Fig. 2 - Cell Rotor

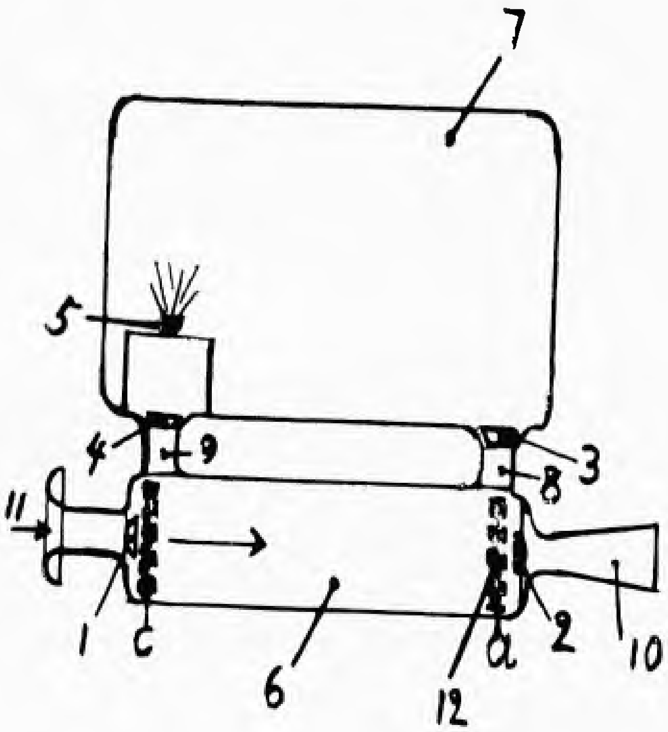


Fig. 3 - Partial Process 1

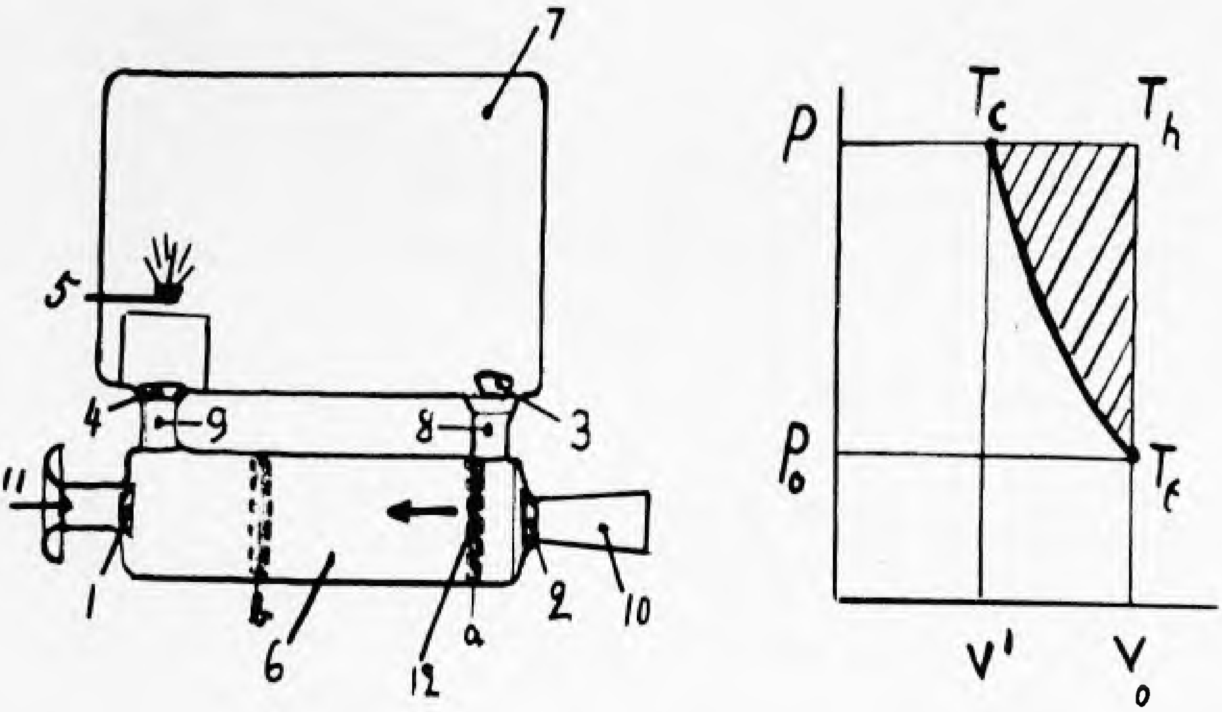


Fig. 4 - Partial Process 2

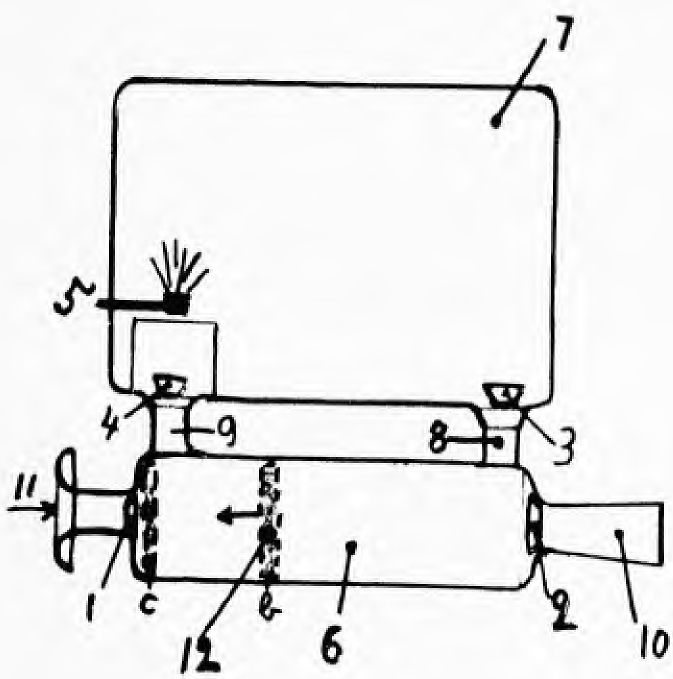


Fig. 5 - Partial Process 3

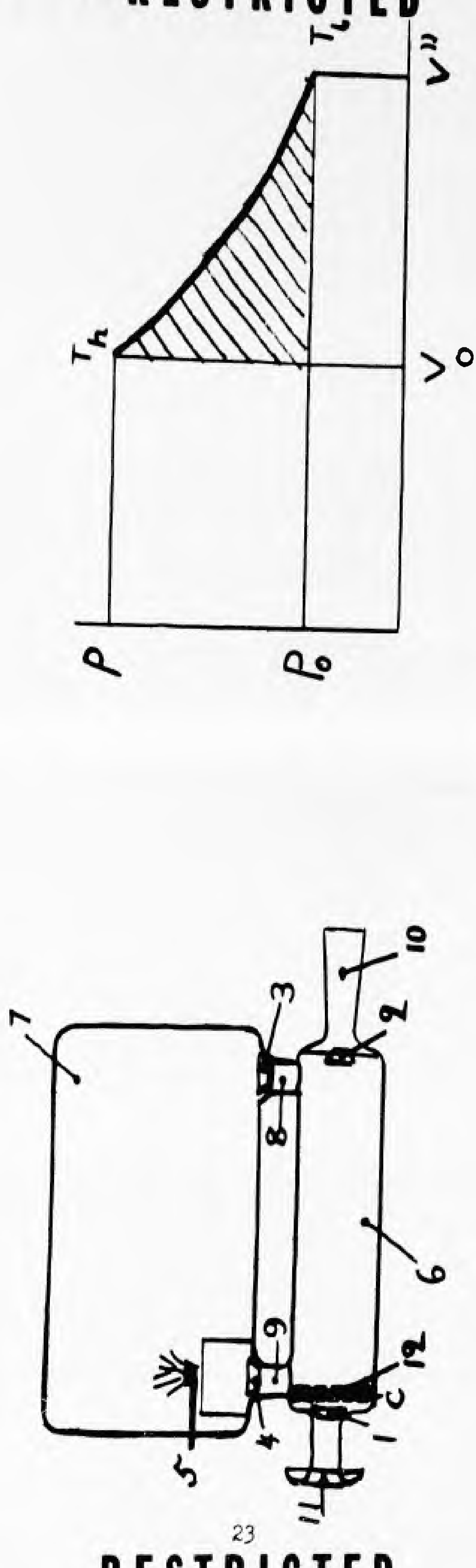
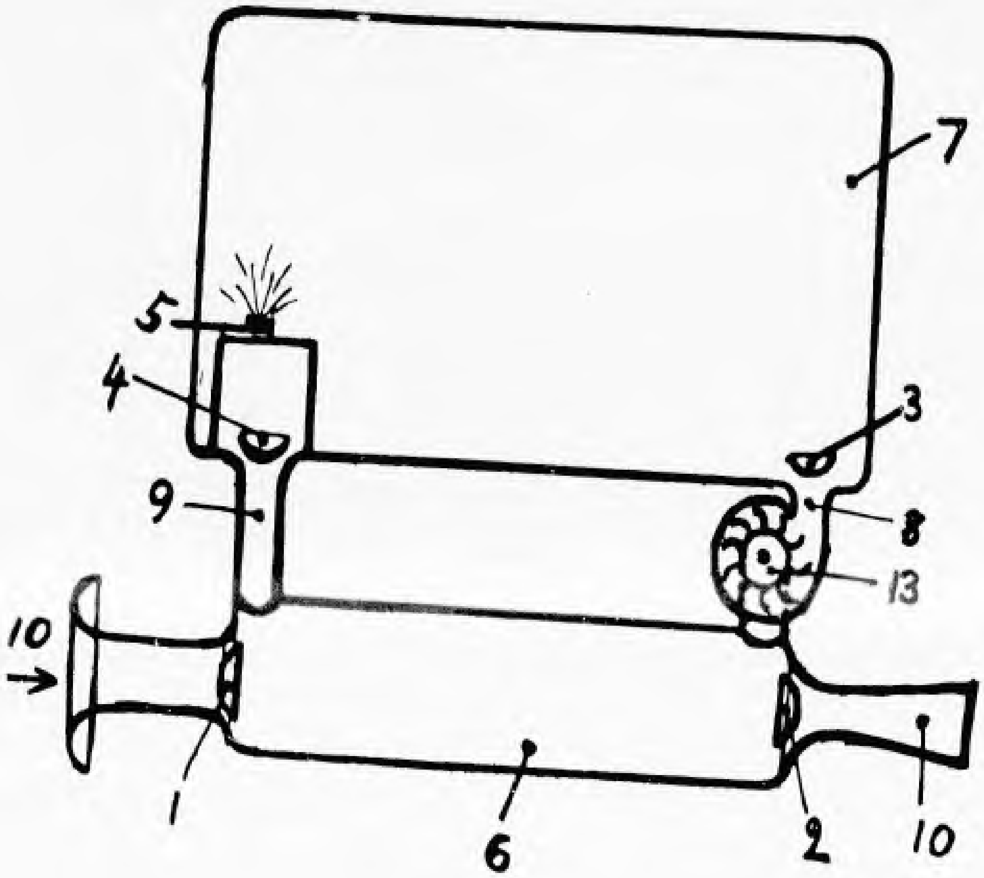


Fig. 6 - Partial Process 4



1,2,3,4. Valves
5. Fuel nozzle
6. Stationary cell
7. Combustion chamber
8. Channel for hot gas from combustion chamber into stationary cell (Same as 14, Fig. 1)
9. Channel for compressed fresh air flowing into the combustion chamber. (Same as 15, Fig. 1)
10. Outlet nozzle
11. Inlet channel
13. Turbine

Fig. 7 - Device with Stationary Cell

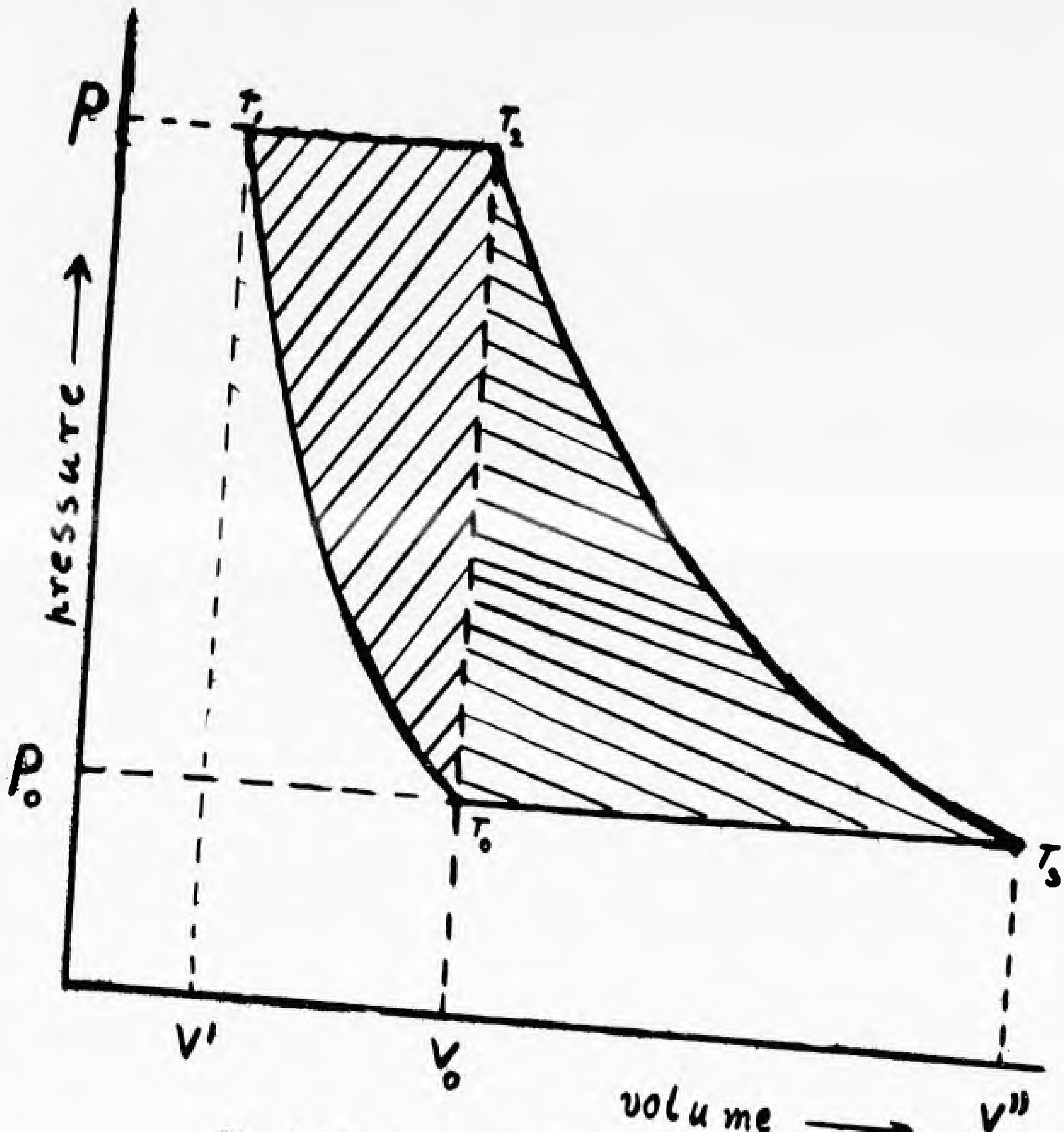
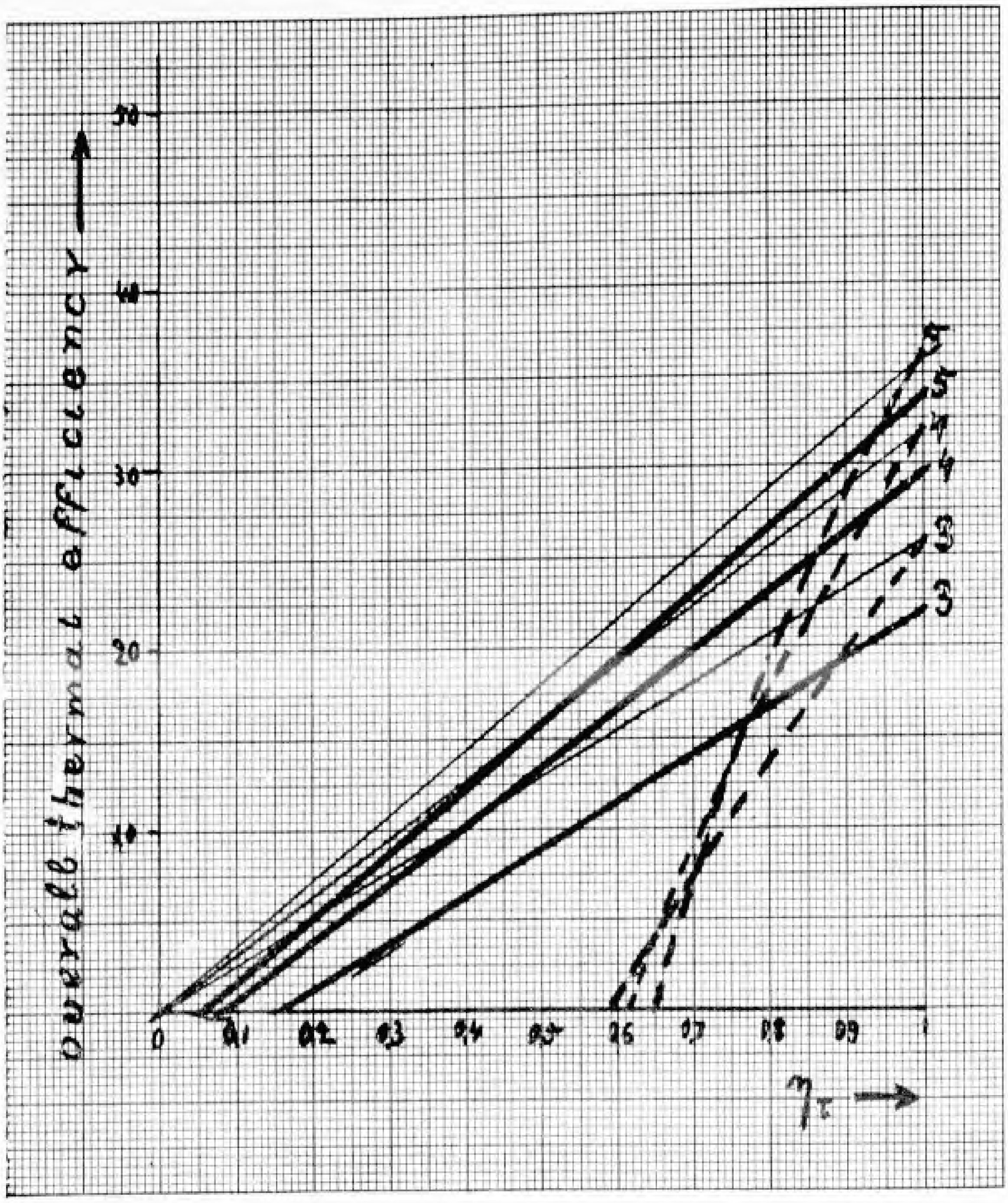


Fig. 8 - The Total Process in the PV Diagram



Pressure ratios 3, 4 and 5.

———— process with thermal compression

———— process with thermal compression without circumferential friction

------ normal constant-pressure cycle

Fig. 9 - Thermal Efficiency Dependent on η_τ

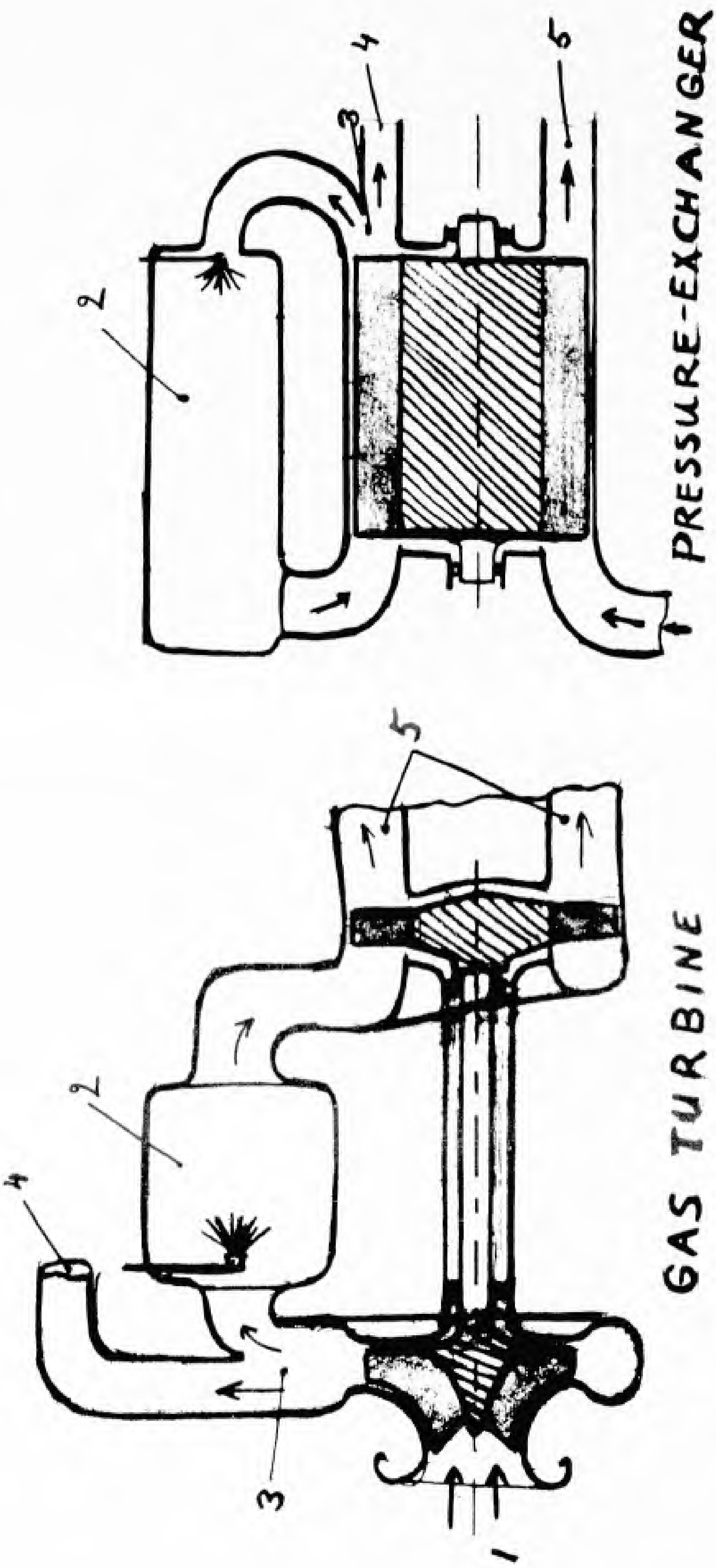


Fig. 10 - Pressure Exchanger and Gas Turbine with the Same Thermodynamic Process

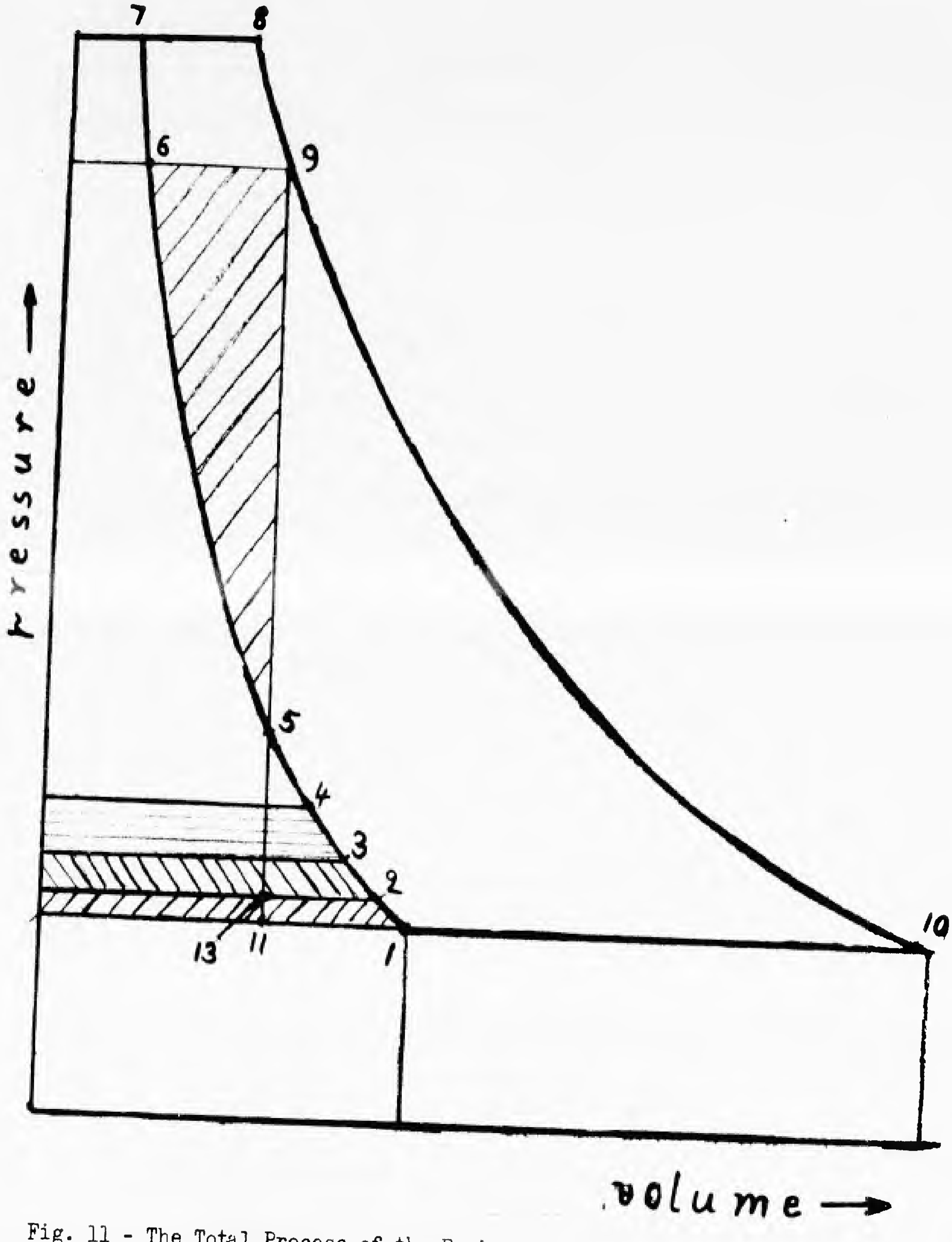
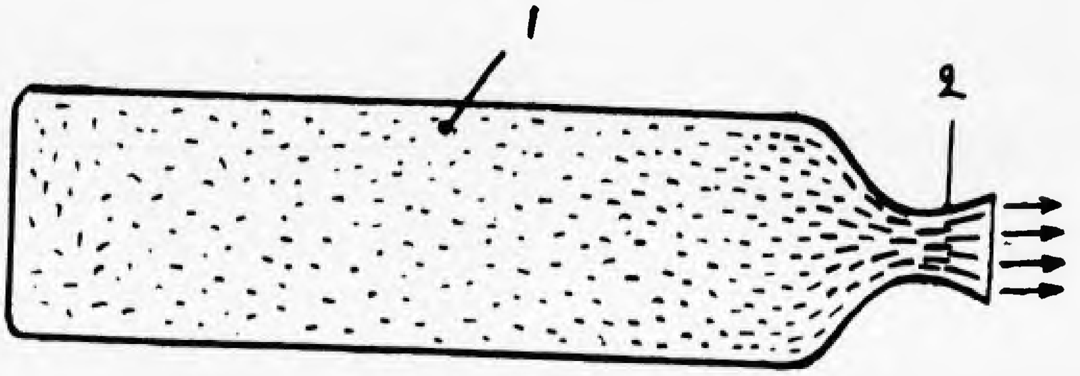


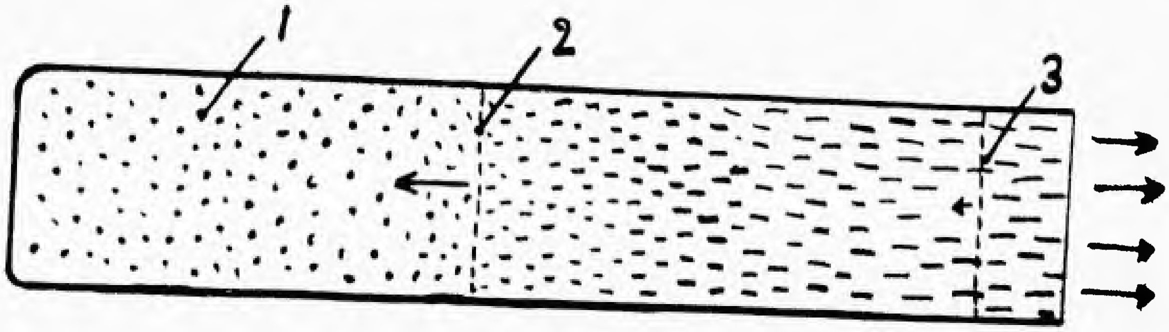
Fig. 11 - The Total Process of the Engine with Cell Rotor in PV Diagram



1. Cell
2. Nozzle

Fig. 12a - First Limiting Case of Expansion

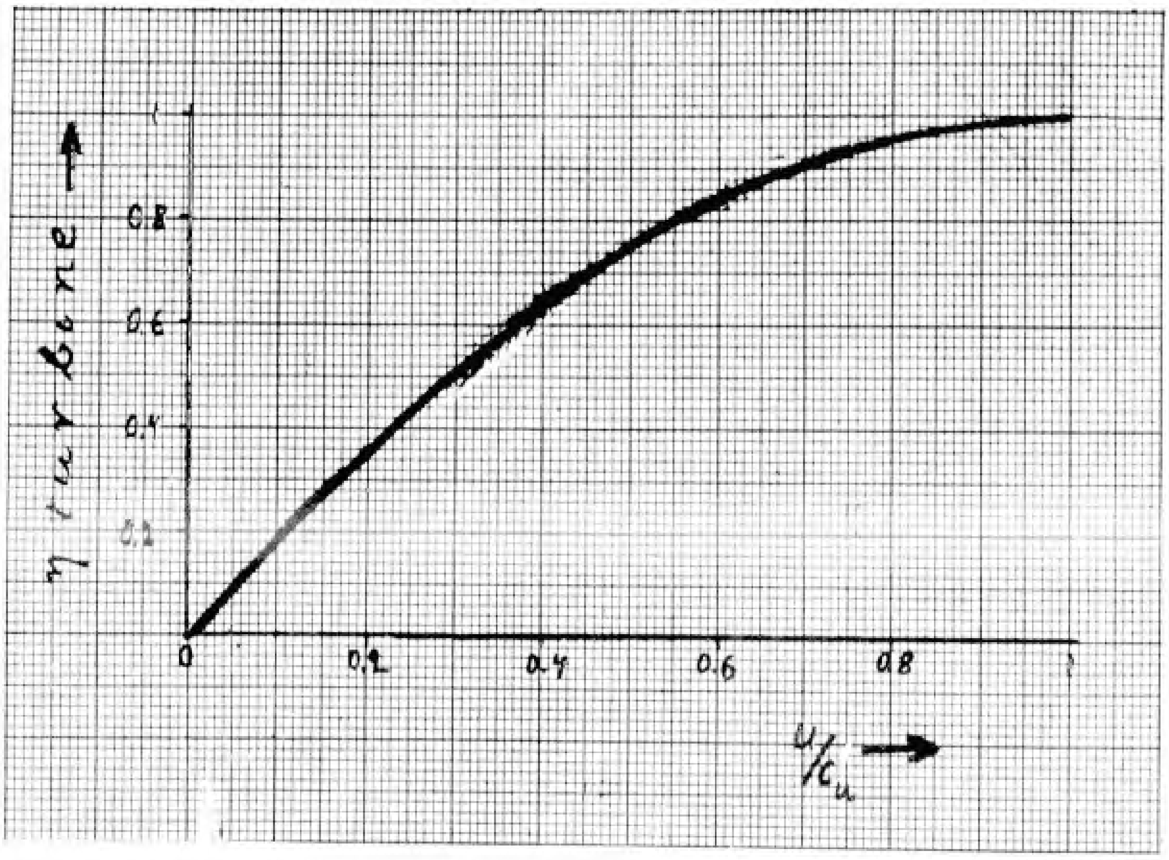
The hot gas expands quasi steadily by means of the nozzle 2. Inside the cell the velocity of the gas and the intensity of the waves is low.



1. Cell
2. Head of expansion wave
3. End of expansion wave

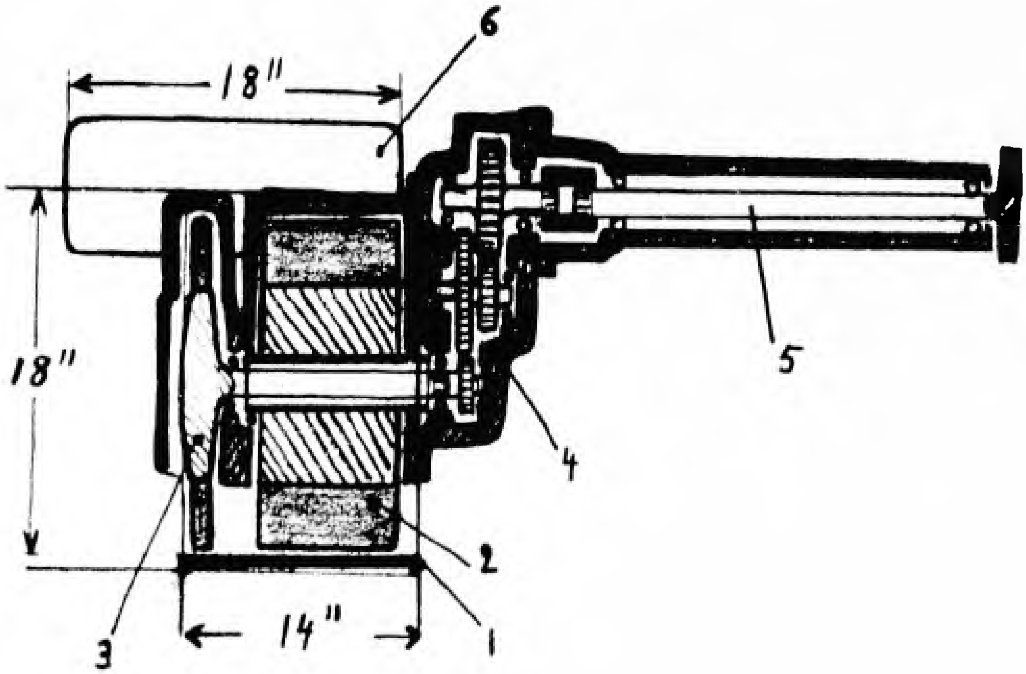
Fig. 12b - Second Limiting Case of Expansion

The expansion takes place by means of expansion waves, moving through the cell with sound velocity in the direction of the arrow.



u = circumferential velocity of the cell rotor
c_u = circumferential velocity of the hot gas

Fig. 13 - Turbine Efficiency of the Cell Rotor 3 in the Partial Process 2 Dependent on u/c_u



1. Housing
2. Cell rotor
3. Turbine
4. Gear
5. Propeller shaft
6. Combustion chamber

Fig. 14 - Engine Used as a Propeller Turbine

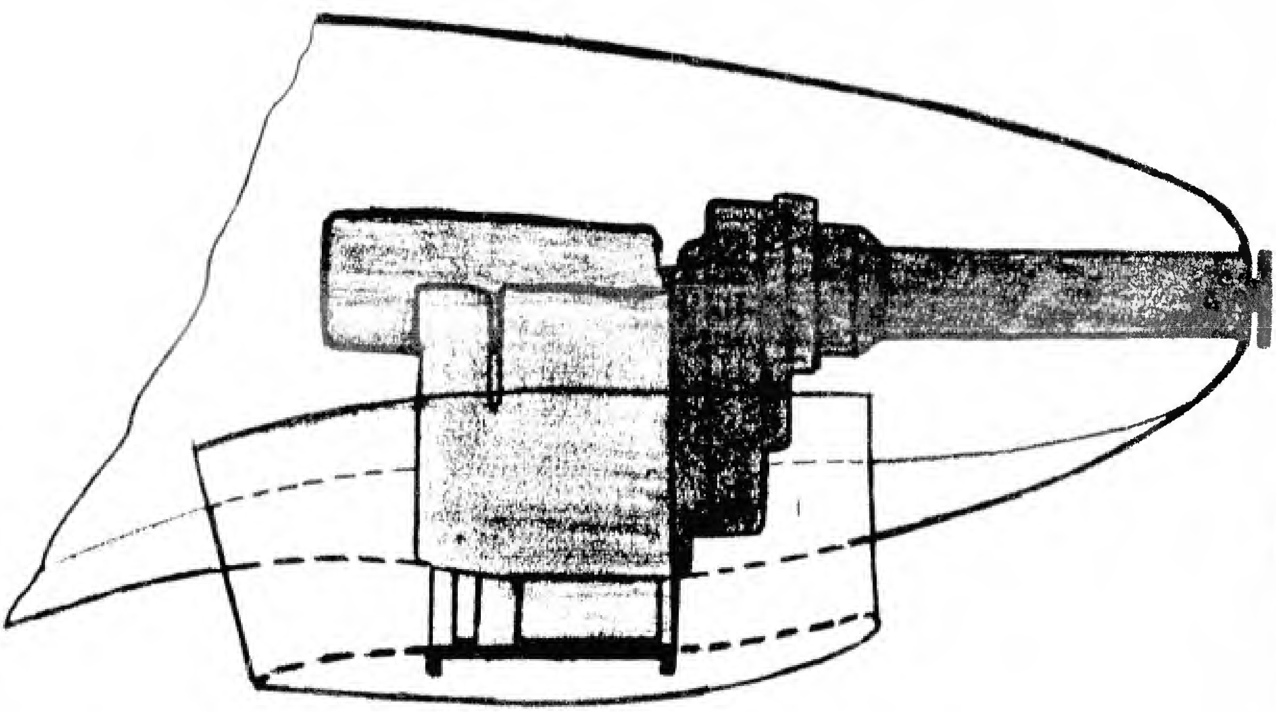


Fig. 15 - Example for the Installation of the Engine in a Fuselage

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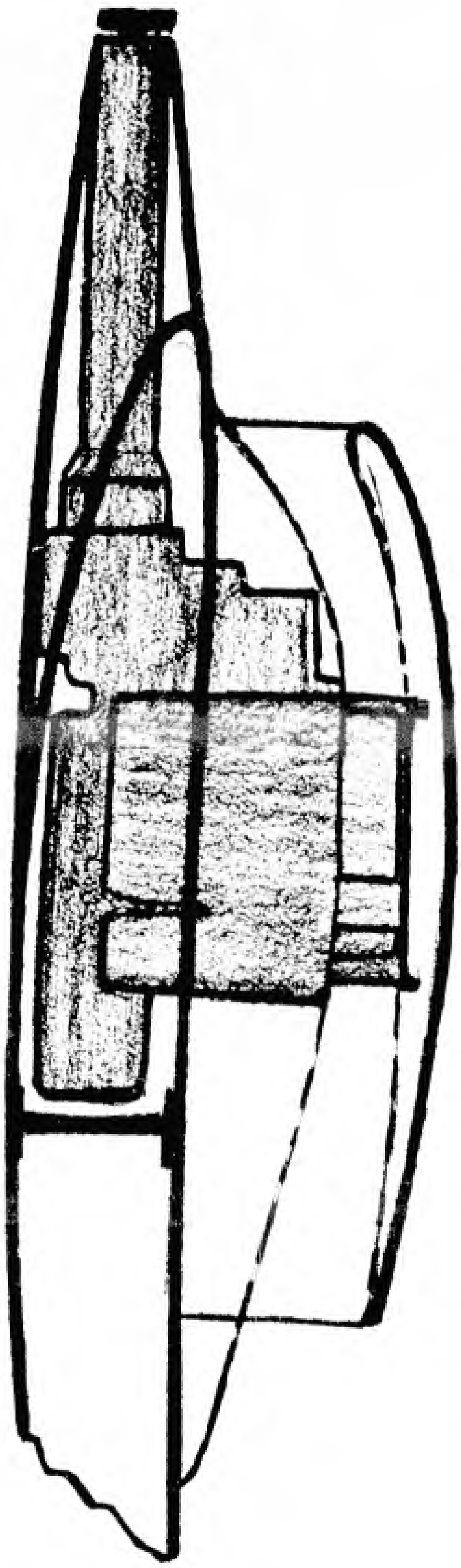


Fig. 16 - Example for the Installation of the Engine in a Wing

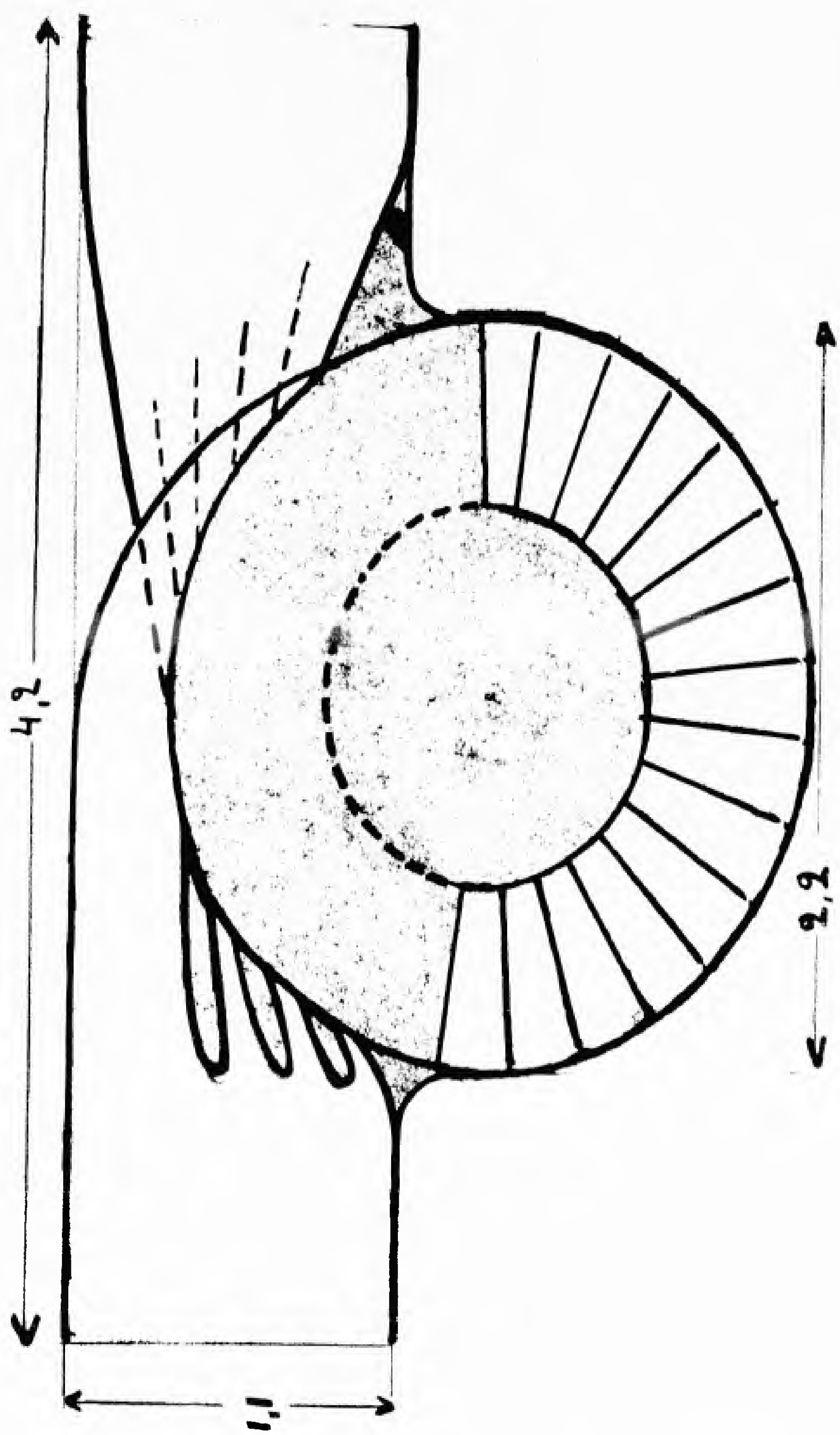
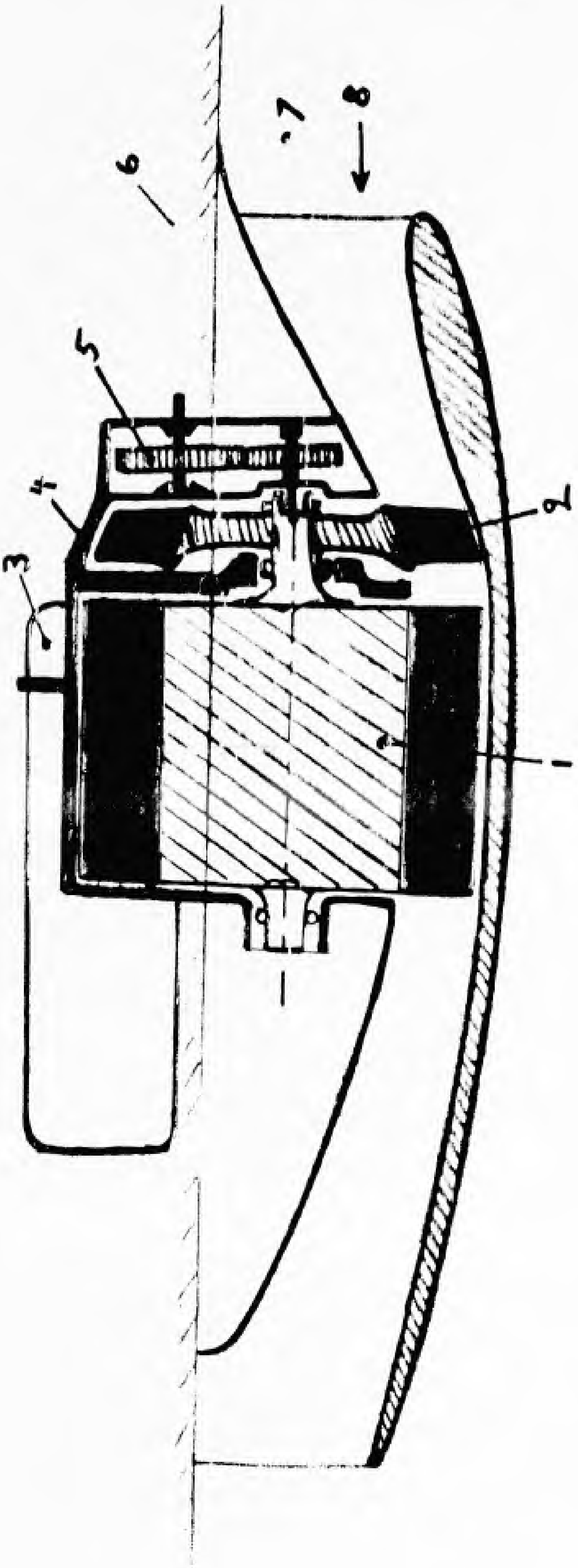
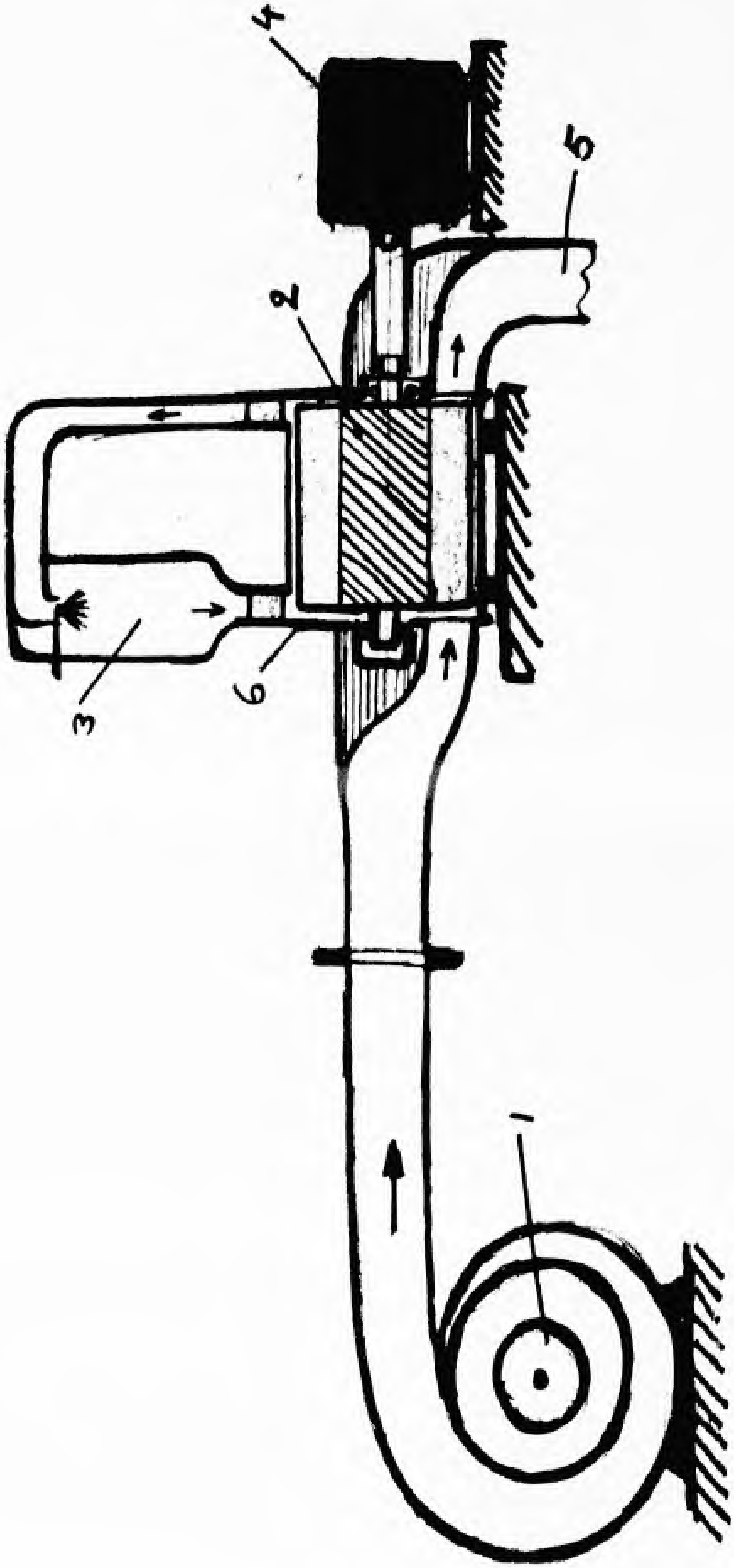


Fig. 17 - Scheme of TL Engine in Front View



1. Cell rotor
2. Supercharging fan
3. Combustion chamber
4. Housing of the cell rotor
5. Gear box
6. Inside of the airframe
7. Outside of the airframe
8. Fresh-air inlet

Fig. 18 - Scheme of TL Engine in Longitudinal Section



1. Supercharging fan
2. Cell Rotor
3. Combustion chamber
4. Dynamometer
5. Exhaust
6. Housing

Fig. 19 - Scheme of Test Stand

SUPPLEMENT A

The presented report is supplemented by two further reports translated by the Aeronautical Engine Laboratories, Naval Air Experimental Station, Naval Air Materiel Center Philadelphia:

(a) Report on the Development of a New Heat Energy Principle and Gas Turbine Processes with Pressure Produced by Heating of the Working Medium. AEL Translation 15.

(b) The Heinkel-Hirth RR 2 (Tuttlingen) Gas Turbine Engine, Using Thermal Compression. (Report by Heinkel-Hirth, Stuttgart-Zuffenhausen, December 1946). AEL Translation 56.

Reports AEL 15 and AEL 56 were not available in their English translation until approximately 4 months after completion if the main portion of F-TR-2186-ND. However, Dr. H. J. Pabst von Ohain consulted German text of these above referenced reports during the preparation of the main report. Several important theoretical problems vital to the thermal compression engine were not treated in these two Navy reports.

The original of AEL 15 was given to the Navy in October 1945, at Stuttgart, Germany. It discloses the general course of development in the field of thermal compression by H. Wolff, along with a brief theoretical description of the principle.

After receiving AEL 15, the U.S. Navy ordered the construction of some test engines by Heinkel-Hirth at Stuttgart-Zuffenhausen. The test results are given in the AEL 56. The theoretical analysis of the processes which are necessary for the evaluation of the test results also are included in AEL 56.

Important theoretical and engineering problems are investigated more completely in the T-2 Report, F-TR-2186-ND, than in the two Navy reports AEL 15 and AEL 56. F-TR-2186-ND is especially concerned with the following:

Unsteady flow processes

Comparison with the pressure exchanger

Application for aircraft

Suggestions for new test engines and test program

More detailed description of the method of operation

F-TR-2186-ND, in one volume, analyzes the problems cited above; establishes a technical history to September 1947, and presents a utilization program for the thermal compression engine.

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DIVISION (None)

ORIG. AGENCY NO. F-TR-2186-ND

PUBLISHING AGENCY NO.

Cancel Classification

TITLE: Report on a Special Gas Turbine Principle (Project No. LP-256)

AUTHOR(S): Pabst von Ohain, H. J.

ORIGINATING AGENCY: Analysis Division, AMC

PUBLISHED BY: Air Materiel Command, Wright-Patterson Air Force Base, Dayton, O.

DATE	DOC. CLASS.	COUNTRY	LANGUAGE	PAGES	ILLUSTRATIONS
March '48	Restr.	U.S.	Eng.	40	diagrs, graphs, drwgs

ABSTRACT:

The principle and the design of a gas turbine with constant-pressure combustion and thermal compression, in which the pressure is built up by the increase of temperature of the working substance, are described. The engine, except for its stationary combustion-chamber design, is very similar to the well-known constant-volume intermittently burning gas turbine with rotating combustion chambers. By means of a supercharging fan, fresh air enters the engine, is precompressed, and flows into the channels formed by the rotor blades to displace there the low-pressure hot gas. As soon as the rotor channels are completely filled with fresh air, ducts in the front and rear walls of the engine housing, leading to the combustion chamber, open. Gas from the combustion chamber flows into the rotor channels increasing the pressure there to the pressure prevailing in the combustion chamber.

CFSTI per SEG ltr, 24 Mar 66

~~DISTRIBUTION: Copies of this report obtainable from Air Documents Division; Attn: MCIDXD~~

DIVISION: Power Plants, Jet and Turbine (5) 29

SECTION: Design and Description (18) 2

SUBJECT HEADINGS: Gas turbines - Design (44076)

Pulse Gas Turbines

AD-A800 230

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