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LIMITATIONS IN THE OPERATIONAL RANGE OF TURBOJET ENGINES,(U)

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FOREIGN TECHNOLOGY DIVISION

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LIMITATIONS IN THE OPERATIONAL RANGE OF TURBOJET ENGINES

by

Jan Borgon, Dr. Eng.

Some limitations in the operational range of turbojet engines governed by the durability of the engine components, by the range of stable operation of the intake channel compressor and the combustion chambers and by the capacity of the fuel pumps.

The available thrust of turbojet engines is used to various degrees during their use. The working characteristics and operating limits of all the components vary as a function of the operational range.

Procedures for control of the maximum operational limits of turbojet engines and turbojet engines with afterburners are most often based on the principle of maintaining the maximum permissible (or close to the maximum permissible) values for such parameters as the rotational speed, the temperature of the gases in front of the turbine and the temperature of the gases in the afterburner chamber. Such control procedures will not only assure maximum thrust, but also protect the engine from mechanical and thermal overloads. Analysis of the operating conditions of individual parts of an engine however, shows that the control procedures do not completely account for the possible loads on the individual components and points of the engine in every case. Hence, additional limitations are imposed on the operating range of the engines (Fig. 1).

Strength Limitations

Strength limitations are usually involved with flights conducted at low altitudes, at high speeds and at low temperatures of the surrounding air. The limiting parameters can be:

- *the net torque of the engine;*
- *the maximum rotational speed of the disc (rotor) n and the maximum temperature of the gases in front of the turbine T_g^*;*

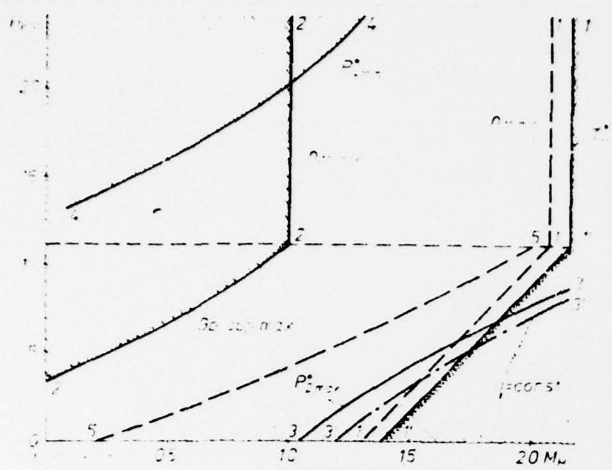

Fig. 1. Regions of possible limitations in the operational range of turbojet engines: line 1'-1' - limitation due to T_H^* max; 1-1 - limitation due to the range of stable operation of the compressor, on line 1-1 $n_{zr} = n_{zr}$ min; 2-2 - limitation due to $n_{zr} = n_{zr}$ max; 3-3 - beginning of limitations due to durability, governed by the pressure behind the compressor $P_2^* = P_2^*$ max; 3'-3' - limitation due to the dynamic thrust $q_{max} = (k/2)P_H M$; 4-4 - limitation of the possibility of using the afterburner due to minimum pressure of the gases behind the turbine P_4^*

- the air pressure behind the compressor or the dynamic thrust (ram effect) denoted by the flight number M and others.

Limitations in the maximum rotational speed of the rotor and the maximum temperature of the gases in front of the turbine are the most characteristic for turbine engines. These parameters exert a very marked effect on the durability of the turbine blades which in turn determines the reliability of the engine during operation in the maximum range. An increase (e.g., during operation of the engine in the maximum range) in the rotational speed n of 1%, when the critical cross section of the nozzle F_{cr} = const, reduces the safety factor by 5 - 10%. This is a consequence of the increase in stresses from centrifugal forces and the lessening of durability in the material of the blades from the persistent strain due to their elevated temperature.

The limitation due to the maximum permissible air temperature in front of the engine intake T_H^* max (T_H^* = overall temperature) also belongs to the durability limitations. This limitation is governed by the fact that, together with an increase in the temperature T_H^* the air temperature along the compressor increases and as a result of this, the temperature of the blades and other parts which make up the compressor increases. As is well known, an increase in the temperature of a material results in a reduction in its resistance to persistent strains (loads). Accordingly, the maximum value of the flight number M (which T_H^* is a function of - Fig. 1) is limited due to the reliability of engine operation. The permissible temperature T_H^* is a function of the durability properties of the materials used. Its permissible value is not large for light alloys (of the duraluminum type) and correspondingly higher for alloys of titanium and steel. The limitation due to T_H^* can also be related to limiting conditions of the engine's oil or cooling systems.

Limitations Due to Stable Operation of the Compressor

The inevitability of this type of limitation is due to the fact that for engines with definite control procedures the stable operation of the compressor varies during flight. This limitation, above all, concerns turbojet engines with unregulated, axial compressors.

As is well known, the stable operation of an unregulated, axial compressor is possible in a definite interval of variation of reduced rotational speed n_{zr}. In control procedures that are based on the assumption n = const or $n \simeq$ const, the reduced rotational speed

$$n_{zr} = n\sqrt{288/T_H^*} \qquad (1)$$

varies accordingly together with the change in temperature T_H^* over a rather wide range. Together with an increase in the flight number M_H, the temperature T_H^* increases in accordance with the equation:

$$T_H^* = T_H\left(1 + \frac{k - 1}{2} M_H^2\right) \qquad (2)$$

where T_H is the static temperature, and k is adiabatic index.

Consequently, for n = const the value of n_{zr} decreases.

If the reduced rotational speed under standard conditions on the ground (T_H = 288 K) is assumed to be 100% then at an altitude, for example, of H = 11 km, for $M_H = 2$, it decreases to 86% and for $M_H = 3$, to 69%. An increase in flight altitude to 11 km, particularly under conditions of low flight speed and at low temperatures of the surrounding air, can lead to an increase in n_{zr} to as much as 115% relative to the calculated value. As is evident in Fig. 2, such a change in n_{zr} can be sufficient to cause unstable operation of an unregulated, axial compressor, since its range of stable operation approaches zero at this time.

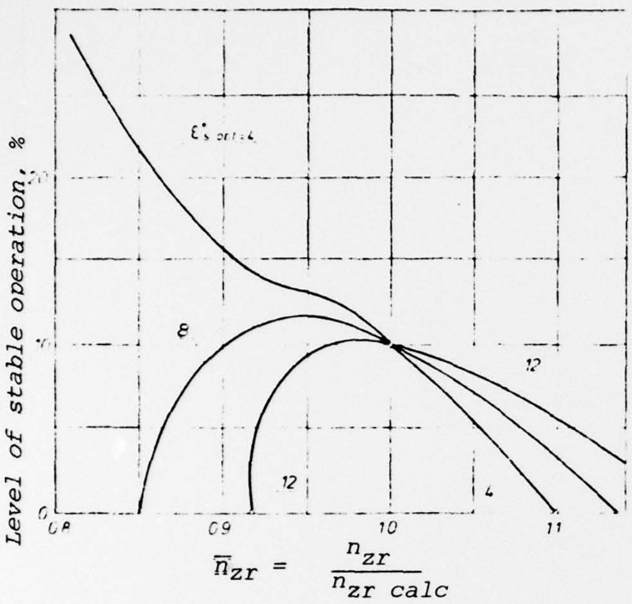

Fig. 2. Change in the level of stable operation for a turbojet engine with an unregulated, axial compressor as a function of $\overline{n}_{zr}$ for various calculated compressions ε^*_s calc

Limitations Due to Stable Operation of the Intake Channel

The most widespread limitation of this type during flights at high supersonic speeds prohibits removal of the engine control lever beyond the position which corresponds to the maximum range. This limitation is governed by the fact that when the engine control lever is removed the relative flux density in the compressor intake decreases, requiring a reduction in the capacity of the intake channel by regulating it. Under conditions of high, supersonic flight speeds the control elements must already be in the extreme position, which establishes minimum capacity.

A further reduction in capacity for such a position of the control elements is already impossible. Removal of the engine control lever in this situation can cause pumping out of the intake channel. To protect the intake channel from the possibility of unstable operation caused by accidental or unnoticed removal of the engine control lever, a special blocking system is usually provided which does not permit displacement of the engine control lever below the position which corresponds to the maximum range under specific flight conditions (the above defined air speed).

Limitations Due to Stable Operation of the Afterburner Chamber or the Main Combustion Chambers

The operation of the combustion chamber largely depends on the characteristics of the air supplied to the chamber and the composition of the air-fuel mixture. As follows from the characteristics which define the stability of the afterburner chamber operation, during an increase in flight altitude, a reduction in speed and a reduction in the rotational speed of the rotor, the range of stable operation of the afterburner chamber tapers off due to a change in the total excess air number

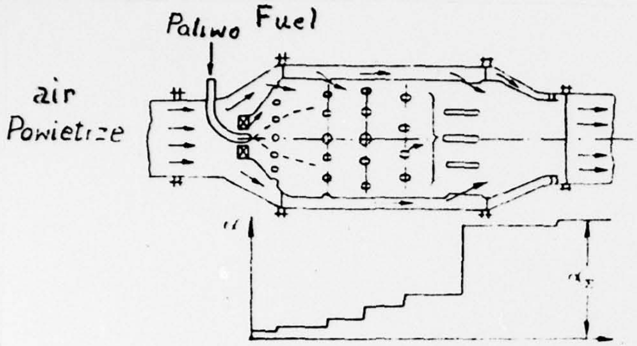

Fig. 3. Change in the excess air number a through the main combustion chamber

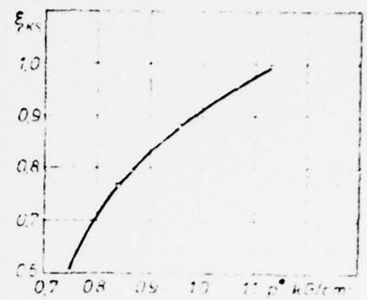

Fig. 4. Effect of total pressure behind the compressor P_2^* on the combustion completeness factor ξk_s

α_Σ *(α_Σ - excess air number in the intake section of the afterburner chamber: Fig. 3) which is represented by the equation:*

$$\alpha_\Sigma = \frac{G_{air}}{(G_p + G_{pd})L_0} \qquad (3)$$

where: G_{air} is the air consumption per second, G_p the the fuel consumption in the main combustion chamber per second, G_{pd} the fuel consumption in the afterburner chamber per second, and L_0 the theoretical amount of air needed for combustion of 1 kg of fuel.

Under certain conditions, e.g., for some types of engines (for α_Σ < 1.2-1.3), vibratory combustion (Fig. 6) may appear in the afterburner chamber which often leads not only to damage of the chamber but also to fatique damage of other parts of the engine.

This phenomenon gives rise to definite limitations. During flights at high altitudes, when the engines are operating with the afterburner, operating instructions very often prohibit throttling back the engines from full afterburning to minimum afterburning or a rapid change (in the rate of acceleration) from the maximum limit to the afterburning limit since the depletion or enrichment in the mixture caused by this can lead to a flameout in the afterburner chamber.

Experiments have shown that the value of the pressure of the air supplied to the chamber exerts the greatest influence on the operation of the combustion chamber. A decrease in the pressure value leads to a deterioration in the conditions

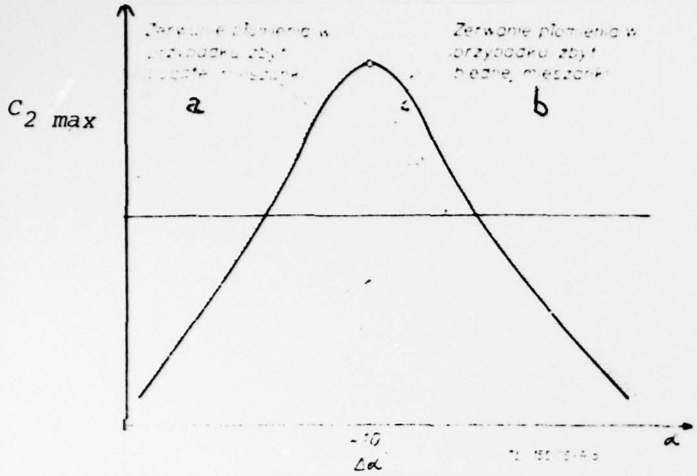

Fig. 5. Characteristics of the operational stability of the combustion chamber: $C_{2\ max}$ - maximum speed in the intake section of the combustion chamber; a - excess air number in the combustion zone of the chamber; $\Delta\alpha$ - range of stable combustion. Legend: a) Flameout when the mixture is too rich; b) flameout when the mixture is too poor

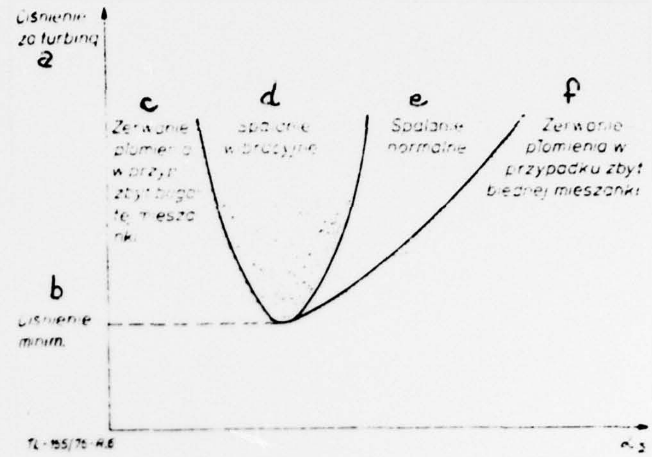

Fig. 6. Limits of normal and vibratory combustion of fuel in the afterburner chamber. Legend: a) Pressure behind the turbine; b) minimum pressure; c) flameout when the mixture is too rich; d) vibratory combustion; e) normal combustion; f) flameout when the mixture is too poor

for mixing, a reduction in combustion rate and to incomplete combustion (Fig. 4). During flights at high altitudes the spraying of the fuel deteriorates owing to a decrease in fuel pressure in front of the nozzles. Under these conditions a flameout can occur along with automatic shutoff of the combustion chamber.

The pressure of the gas introduced into the chamber is adopted as a criterion which limits the flight altitude (in terms of combustion chamber operation). This pressure diminishes together with an increase in flight altitude and a decrease in air speed. Ensuring that the total pressure behind the turbine P_4^* is such that $P_4^* > P_{min}^*$ and for the main chamber that the total pressure behind the compressor $P_2^* > P_{min}^*$ is a condition for stable behavior in the combustion process in the afterburner chamber. When calculating the characteristics of an engine the pressures P_2^* and P_4^* are determined for various flight numbers M_H and various altitudes H, thus determining the range of this type of limitation presents no problem.

Limitations (involving operation of the afterburner chamber) are also possible which consist of the fact that turning on the afterburner is prohibited during flights at high altitudes and low speeds, i.e., within certain limits in speed and altitude when $P_4^* < P_{4\ min}^*$. The reason for such limitations (restrictions) consists of the fact that the certainty of fuel ignition in the afterburner chamber depends more on the total pressure behind the turbine P_4^* than on stable combustion of an operating afterburner. Consequently, for aircraft flying at high altitudes with low speeds, restrictions on engine operation with the afterburner engaged are not always imposed, although turning on the afterburner is prohibited under certain conditions. For many modern aircraft, in order to avoid installation of an additional P_4^* pressure indicator or a special signaling device which responds at the limiting values for pressure P_4^* and thus eliminates the need for monitoring by the pilot, the conditions under which the afterburner can be turned on are established by a less precise, but simple method - by simply supplying in the instructions the appropriate altitude and speed readings within whose limits the afterburner can be turned on or should not be turned on. For many types of engines turning on the afterburner is prohibited during the takeoff run, during takeoff or immediately after liftoff of the aircraft. This is explained by the fact that when the afterburner is turned on, due to premature opening of sections of the nozzle which is controlled relative to the moment of supply of fuel to the afterburner nozzle, a brief drop in thrust occurs which is very dangerous for the pilot and the aircraft under low flight speed and altitude conditions.

Limitations Due to the Output of the Fuel Pumps

Limitations of this type are of a structural nature, related to inadequate output of the fuel pumps under certain conditions of aircraft flight.

The pumps of the main fuel system and the afterburner fuel system are designed for a specific, maximum feasible fuel consumption that is established from the safety requirements of all the most important aircraft flight limits. The creation of a sizeable fuel output reserve is unsuitable since this entails an increase in the size and weight of the fuel pumps.

Under certain conditions however, it is possible that that the pump of the afterburner fuel system or the main fuel system will attain its maximum possible output and a further increase will be impossible. In this situation, assuring that $n \approx$ const for turbojet engines or that $n \approx$ const and the gas temperature in the intake section of the afterburner $T_d^* \approx$ const for turbojet engines with afterburners *becomes impossible owing to inadequate amounts of fuel being supplied to the combustion chamber. This leads to a change in the characteristics of the power unit, and above all, to a decrease in thrust which results in a sudden deterioration of the flight characteristics over a defined range of speed and flight altitude.*

The greatest fuel consumption for turbojet engines and turbojet engines with afterburners corresponds to flights conducted at a low temperature in the surrounding air, at low altitudes and high speeds. These conditions precisely limit the range of restrictions owing to an inadequate amount of fuel being supplied. Determining the limits of this range does not present any problem, since when the engine characteristics are calculated all of the parameters required to find the fuel consumption value for a turbojet engine and a turbojet engine with afterburner are determined for various flight altitudes and speeds. Calculating the characteristics in the limitation region depends on the engine control requirements in this region.

Not all of the above-mentioned limitations concern each actual type of turbojet engine. Depending on the type of engine, its method of control, the aircraft in which it is installed, the conditions under which it is used and other factors, the number of operational limitations can be greater or smaller.

For the aircraft as a whole, still other limitations are involved, e.g., with respect to the minimum operational speed, the stability and control of the aircraft within defined intervals of flight speed and altitude, etc.

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