DETERMINING OF THE OPTIMUM SIZE OF TURBOFAN ENGINE FOR OBTAINING THE MAXIMUM RANGE OF MULTI-PURPOSE AIRPLANE

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Abstract

Aircraft range is one of the most important criteria of the assessment of the performance properties of an aircraft. For the needs of the paper the mathematical model of an aircraft (multi-purpose aircraft) and the engine which propels the aircraft was built (turbofan, two-spool, with jet mixer). For the analysis it was chosen so-called typical Breguet model and the conventional range. The models were modified as they should consider the characteristics of the engine in the non-dimensional form. The aim of the simulation research was to discuss the influence of the engine parameters (geometrical and thermodynamic) on the aircraft range, realized mainly in the subsonic and supersonic conditions. The decision which of these conditions can have a significant influence on the selection of the calculating point (i.e. the point which determines the geometrical dimensions of the engine) is difficult as there is no clear direction which aircrafts make up the important share in a mission or missions. It was decided that the parameter which connects the engine geometry with the range model is so-called non-dimensional coefficient of engine geometry which is the relation of the area on the inlet to the engine related to the wing area of the aircraft. It was shown that for various parameters of the engine cycle it is possible to show such a value of the non-dimensional coefficient of geometry which maximizes the aircraft range. The results obtained show opposite requirements as for the engine geometry for the subsonic and supersonic flight. On this basis the compromise solution was proposed to fulfil the requirements of the multi-purpose aircraft.

***Keywords**: airplane range, airplane and engine integration, engine cycle parameters*

1. Introduction

Aircraft range is one of the most important criteria of the assessment of aircraft performance properties. The calculations of the aircraft range depending on the flight conditions have been presented in [3]. For the needs of the research the model of range determination has been chosen for the constant flight and the constant coefficient of aerodynamic lift (i.e. the height of flight changes). The dependence which describes the range for the above limitations is known as the Breguet formula [3]:

$$x = \frac{EaM_a}{gc_j} ln \frac{1}{1-\bar{m}_{pal}}, \qquad (1)$$

where:
E - aircraft lift/drag ratio,
a - sound speed,
c_j - unitary fuel usage,
m_{pal} - relative mass of the burnt fuel

$$\bar{m}_{pal} = \frac{\Delta m}{m_s}, \qquad (2)$$

were:
Δm - mass of the burnt fuel during the flight,
m_S - primary aircraft mass.

2. Model of aircraft range determining

As it results from the analyses conducted in [1, 3], the increase of the flight height according to (1) is slight, so in the further considerations the flight with the range (1) is considered as the horizontal flight. This formula allows determining the aircraft range, when all the fuel will be used for the flight with the Ma speed. In the balance the mass, the fuel consumption for the take off, climbing and other manoeuvres, e.g. turn is not considered. However, the range (1) can be a benchmark as for the quality of parameters selection of the engine to the aircraft as the engine parameters "are included" in the functions c_j and m_{pal} . It is assumed that all the fuel reserve will be used after the flight.

Relative fuel mass is determined from the equation of masses balance (3):

$$\bar{m}_{pal} = 1-(\bar{m}_{płat} + \bar{m}_{ZN} + \bar{m}_u), \tag{3}$$

To simplify the considerations one can assume that the relative participation of the particular elements of the take off aircraft mass are known, then it is possible to determine the maximum range, considering the engine model only on the basis of cj parameter. It is the easiest and not so well-known approach. Then it is assumed that the engine mass in equation (3) is the function of the thermo-gas-dynamic parameters of the engine, it is possible to find the maximum range as the function of the engine mass connected with the thermodynamic process realized in the engine.

The model of turbofan, two-spool engine with jet mixer and afterburner has been shown in [2, 5-9]. Therefore, it is beneficial to decrease the engine mass in order to increase the fuel mass (the rage increases) or to increase of the mass of armament on the board.

According to [4, 9], the engine unitary mass is described as:

$$\gamma_{sil} = \frac{m_{sil}}{K_{sil}}, \tag{4}$$

where:
m_{sil} - engine dry mass,
K_{sil} - engine thrust.

From the definition of the relative mass of the power unit (ZN) which consists of the i-engines one can notice that:

$$\bar{m}_{ZN} = i\bar{m}_{sil} = \frac{im_{sil}}{m_s}. \tag{5}$$

By using the relation presented in [9] the equation (5) can be written as:

$$\bar{m}_{ZN} = \frac{g\gamma_{sil}\bar{K}_{sil}S_{ZN}}{\psi_s}, \tag{6}$$

where according to [9]:
S_{ZN} - relative engine size,
Ψ_S - non-dimensional coefficient of wings loading.

By substituting (6) to (3) and then to (1) we can obtain the formula for the range depending on the unitary mass of engine:

$$x = \frac{EaM_a}{gc_j} ln \frac{1}{(\bar{m}_{pal} + \bar{m}_u) + \frac{g\gamma_{sil}\bar{K}_{sil}S_{ZN}}{\psi_S}}. \tag{7}$$

Aerodynamic lift/drag ratio of aircraft E is defined as [1, 3]:

$$E = \frac{c_Z}{c_X}, \tag{8}$$

where:
c_z - coefficient of aerodynamic lift,
c_x - aerodynamic coefficient of resistance force.

From the polar line equation [3] it is possible to determine the aerodynamic lift coefficient as:

$$c_Z = \sqrt{\frac{c_X - c_{D0}}{K}} , \tag{9}$$

where c_{D0}, K - airplane polar coefficient.

In the horizontal steady flight the aerodynamic resistance coefficient is:

$$c_X = \frac{2\bar{K}_{sil} S_{ZN}}{k M_a^2} . \tag{10}$$

By substituting (10) to (9) and then to (8) we can obtain the relation for the aerodynamic lift/drag ratio E as the function of non-dimensional parameters of the engine and aircraft:

$$E = \frac{\sqrt{\dfrac{2\bar{K}_{sil} S_{ZN}}{k M_a^2} - c_{D0}}}{\dfrac{2\bar{K}_{sil} S_{ZN}}{k M_a^2} \sqrt{K}} . \tag{11}$$

Now we can start to do research on the influence of the engine parameters on the aircraft range by changing the flight conditions. It is important to remember that the engine parameters must be chosen in order to fulfil the flight requirements. There is one condition that the numerator in the lift/drag ratio formula E (11) is positively determined, which means:

$$\frac{2\bar{K}_{sil} S_{ZN}}{k M_a^2} > c_{D0} . \tag{12}$$

The calculating conditions for the engine were chosen as for the take off ($H=0$, $Ma=0$). Engine parameters for the determined flight conditions were determined from the model of speed and height characteristics of the engine presented in [6, 9]. The aim of the calculations was to find the values of the engine parameters for which the range determined from (7) considering (11) achieves the maximum values.

3. Results of calculations

In Fig. 1 there have been presented the differences in the range of subsonic and supersonic flight and the influence of the geometric parameter of an engine, i.e. the S_{ZN} value on the maximum value of the range. The theoretical range of an aircraft during the subsonic flight achieves its maximum for the low values of S_{ZN} (almost half lower than the required values of parameter for the supersonic flights). During the supersonic flight the range decreases significantly and its extremum, as a S_{ZN} function shifts towards higher values of S_{ZN}. The supersonic flight is possible from such values of S_{ZN} for which exists (12). Very important information which results from the conducted calculations is the fact that the range expressed by the equation (1) has its extremum as for S_{ZN}.

Multi-purpose aircraft performs its tasks in the wider range of speeds and flight height. It is difficult which of these conditions have an important impact on the choice of calculating point as there is no unambiguous opinion which flight stages have the biggest participation in the whole mission or missions. To search the clues for such conditions may be done by an analysis of heights or speeds influence on the aircraft range for the previously defined engine type. In Fig. 2 there have been shown the results of the influence of flight conditions (subsonic flight and supersonic flight on the chosen heights) and the choice of the parameter S_{ZN} on the theoretical range. It turns out that in case of some chosen parameters of the engine comparative cycle which are the same for each task (Ma, H), the change of the flight height has a significant influence on the range as the function of S_{ZN} parameter. Within the subsonic flights the bigger the flight height, then the range maximum

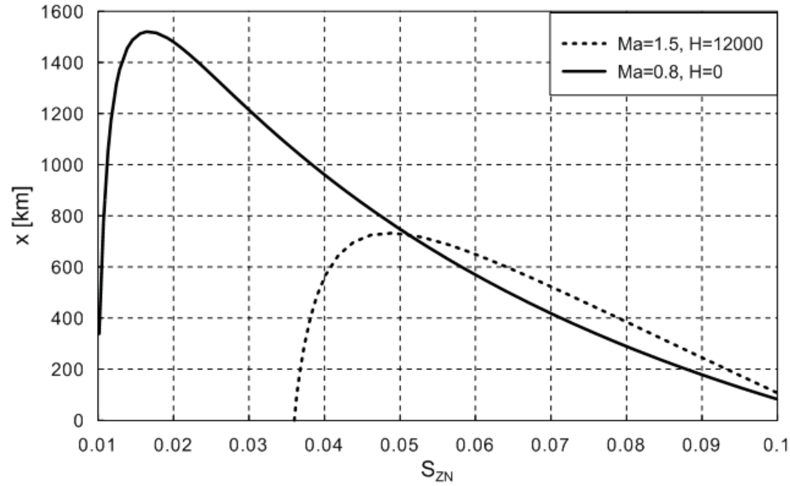

Fig. 1. Influence of the parameter of engine adjustment to the aircraft S_{ZN} on the theoretical range for the subsonic flight (full line) and supersonic flight (broken line)

shifts in the direction of lower values of S_{ZN}. The bigger calculating height of the flight, the bigger the theoretical range. For the supersonic flight the values of S_{ZN} which maximize the range change in a much significant way as in case of the subsonic flight. For the supersonic flights at big heights, close to the maximum ceilings of the present multi-purpose aircrafts it is important to choose lower values of S_{ZN} (below 0.05) than for the supersonic flights at small heights. The course of the relation $x=f(S_{ZN})$ can be explained in the following way. For the values of $S_{ZN}=S_{Znopt}$ the mass share of the engine in the total balance of the aircraft mass is very slight, but increases the mass share of the fuel, thus the range increases rapidly. Above S_{ZNopt} the engine mass increases, but the fuel quantity decreases, thus the range drops.

An interesting subject is to decide on the influence of the engine calculations on the aircraft characteristics. In order to solve this problem the notion of conventional range has been developed as:

$$x_U = \frac{EaM_a}{gc_j}. \tag{13}$$

It is the simplified criterion as to the Breguet range as it does not consider the mass change of an aircraft during the flight but it gives the possibilities of qualitative and physical assessment of the influence of engine characteristics on the basis parameter of engine efficiency, which is the range.

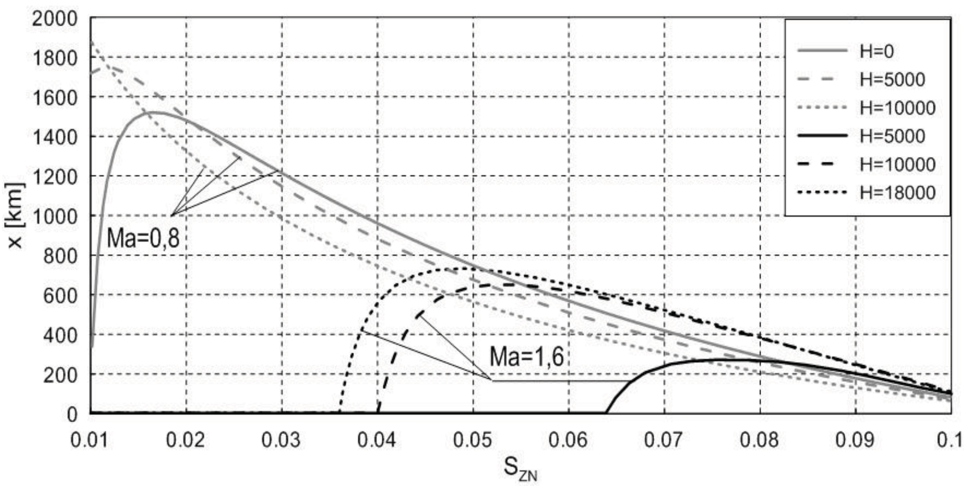

Fig. 2. Influence of S_{ZN} and flight conditions (Ma, H)on theoretical range

The influence of the calculating point choice of an engine is very significant for the course of its speed and height characteristics as well as the mass and geometry. This problem has been widely discussed in the literature of the subject for the airlines for which this point is chosen for the flight conditions (height and speed at the best ceiling and the best flight speed, which result from the optimization of the fight trajectory). For the multi-purpose aircraft it is difficult to show such conditions that are why there is a trial to determine the influence of the choice of calculations for various flight tasks. In Fig. 3 there have been shown, as graphs, the changes in the conventional range for three calculating points of the engine (in the Fig. marked as P.O.), when the range is realized in the conditions of supersonic flight at various heights.

The conclusions are the following:

1. the choice of the calculation point has no significant influence on the maximum value of the conventional range in the same flight conditions,
2. the bigger is the speed and the height of an aircraft, then the value of engine adjustment to an aircraft S_{ZN}, at which the conventional range has the maximum range, shifts towards lower values of S_{ZN}.

In the formula for range determining (1) there is the aerodynamic drag ratio of an aircraft E which is one of its most important characteristics. The drag ratio as (11) connects the characteristics of the power unit and an aircraft and it can be one of the assessment criterion of engine and aircraft adjustment for the given flight conditions.

Traditional approach to the engine designing process consists in the research on the influence of variables of the comparative cycle on the internal characteristic. The presented engine models and the aircraft range, as well as drag ratios are the additional criteria as for the quality assessment and choice of the engine characteristics for an aircraft. It is important that in the presented relations (6, 11) the engine models and aircraft have been integrated. The further calculations have been done which aimed at showing the influence of the engine parameters on aircraft range calculated on the basis of the Breguet model. The results of the calculations have been shown in Fig. 4 and 5.

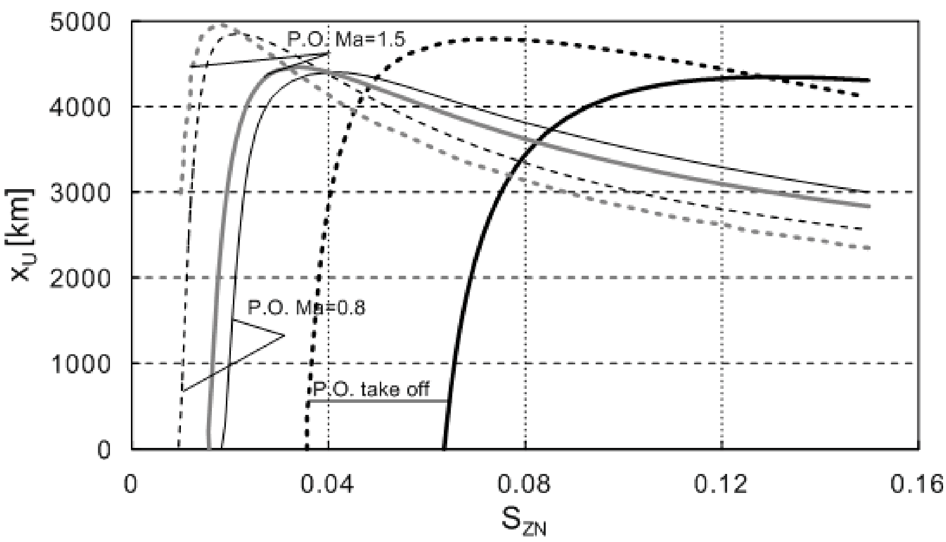

Fig. 3. Influence of choice of engine calculation point and S_{ZN} on the conventional range of aircraft performed for Ma=1.5 H=5000 (full line) and Ma=1.5 H=18000 (broken line)

The growth of T_3 , despite the fact that increases fuel consumption which leads to the range decrease, increases the unitary engine thrust k_j, which together with the temperature growth increases faster than c_j, and causes the range growth (Fig. 4 and 5). When the μ increases at the same time c_j, which slightly increases the range but the unitary thrust drops. This drop is compensated by the increase in S_{ZN} which shifts the range maximum in the direction of higher values of this coefficient. For all the considerations has been presented Fig. 5 which considers only the influence the parameters of the engine cycle on the range determined for the value S_{ZN}=0.05 and the subsonic flight conditions.

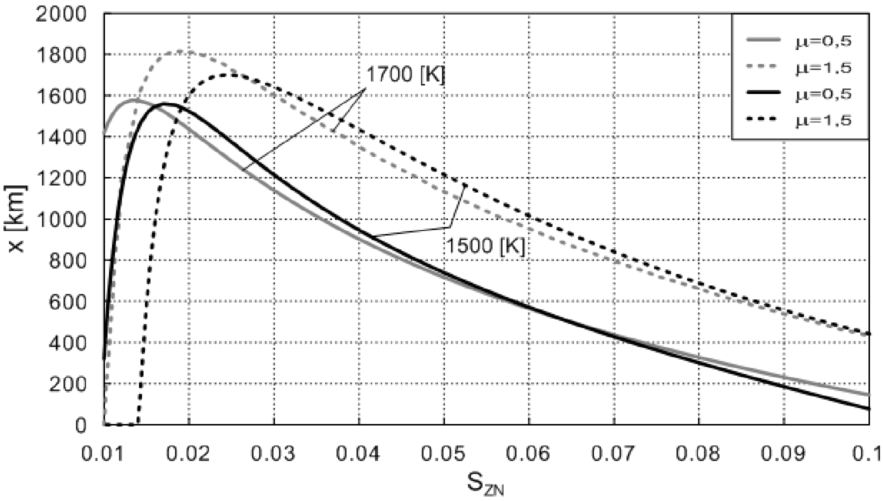

Fig. 4. Influence of bypass ratio μ and temperature before turbine T_3^* and change SZN on the range x for the subsonic flight (Ma=0.8, H=0)

For the accepted value S_{ZN}=0.05, higher than S_{ZNopt}, the temperature growth caused the range decrease which results from the fuel consumption. The unitary thrust in the accepted range of changes of the total compression of the compressor is constant and the aircraft drag ratio decreases (the thrust decreased and the aerodynamic resistance did not change), therefore the range decreases. The second reason of range decreases while compression increases results from the growth in the engine mass. Accepted for calculations model of engine mass as the function engine cycle parameters takes the compression growth as the effect of increase in the number of ratios of the compressor.

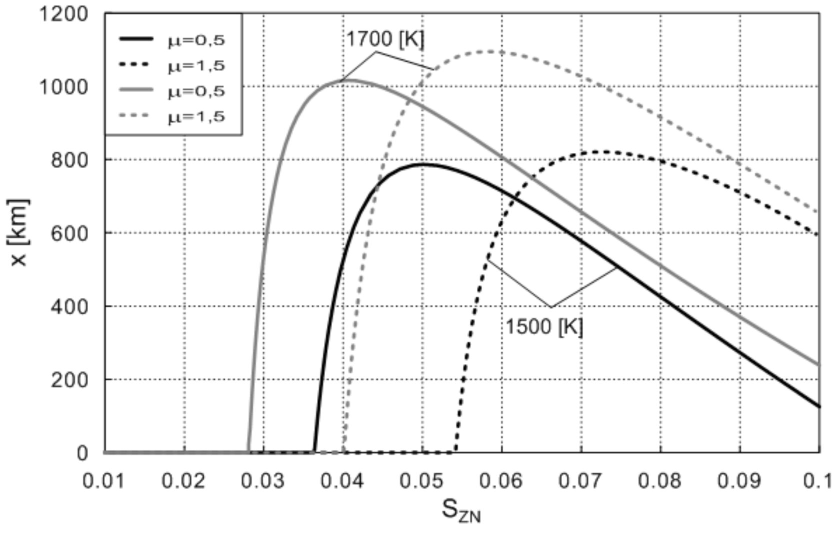

Fig. 5. Influence of bypass ratio μ and temperature before turbine T_3^* and change SZN on the range x for the supersonic flight (Ma=1.6, H=18000 m)

This way the increase in the engine mass causes the decrease of the fuel mass (it results from the equation of the balance of aircraft masses (3) and in consequence the range decrease. For instance, for the airliners which are propelled by the turbofan engines in case of the compression increase there is also the growth of bypass ratio μ and relatively moderate increase of total temperature before the turbine T_3 .

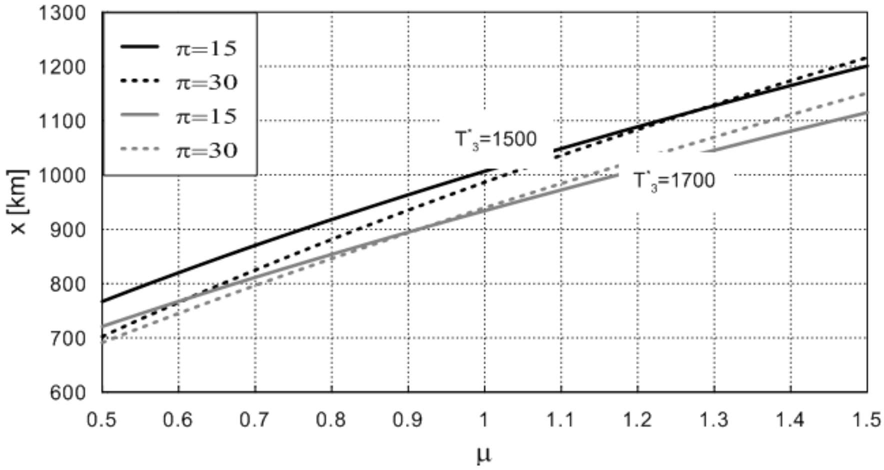

Fig. 6. Influence of engine cycle parameters on the range x (subsonic flight)

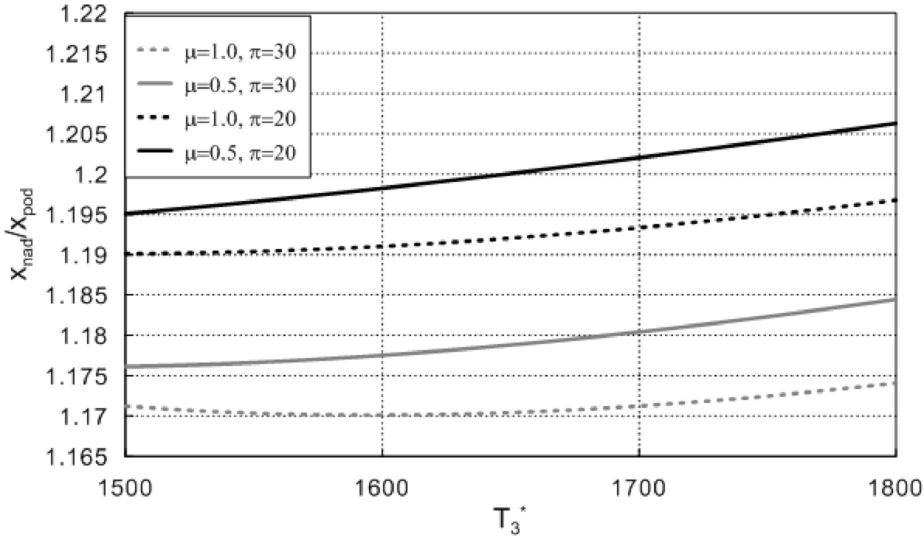

Fig. 7. Influence of temperature T_3 and μ as well as π for the relative range x_{pod}/x_{nad}. Subsonic flight Ma=0.8, supersonic flight Ma=1.6, H=12000 m

Thanks to such a concept we can obtain small values of the unitary fuel consumption at subsonic flight speeds. For the turbofan engines with the jet mixer which can be found in the manoeuvre aircrafts - multi-purpose ones such requirements as for the parameters differ depending on the task. Significant differences are visible when we want to „reconcile" the take off of the subsonic and supersonic flight.

In order to find the optimum engine parameters for the aircraft which during the mission flies both at subsonic and supersonic speed the calculations were made. For the same engine thermodynamics parameters, the aircraft range at supersonic speed will be bigger for the engine with the lower bypass ratio (Fig. 6, Fig. 7). It is connected with the fact that the engine efficiency at supersonic flight increases as the bypass ratio decreases. The increase of temperature before the turbine influences on the increase in the supersonic range to the subsonic one, but the growth the total compression of the compressor decreases this effect in a significant way (especially by the increase in the fuel mass). The increase of the bypass ratio has an impact on the increase in engine economics while performing subsonic flights which is the result of the decrease in (15). Thus, the lower bypass ratio improves the range characteristics of the aircraft as most of the tasks are realized on the supersonic ranges (fighter aircrafts, air interception tasks). On the other hand for the engine of the aircraft which supports battle field (little range, subsonic flight speeds, low ceiling of flight and manoeuvre) should be chosen the higher values of bypass ratio.

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