ON THE FUTURE OF JET PROPULSION IN SUBSONIC TRANSPORT AVIATION

By

M. Roy*

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Having to choose a subject for this talk and remembering the high reputation of the Scientists and Engineers of this country in the field of internal combustion engines I have chosen the "future of jet propulsion in subsonic transport aviation" because of its intrinsic technical and economical interest.

My subject will be limited to *subsonic or high subsonic aircraft* because this kind of vehicle will remain the most important and universal mean of aerial transportation both for passengers and for freight until an unforeseeable datum.

At first, I must confess that in my country I have been a pioneer of jet propulsion since 1928 and continuously worked on this matter since these long bygone days. Therefore my relevant reflexions and feelings of to-day are based on a continuous thinking and a long co-operation with many very competent engineers of various countries.

Concerning the recent history of our present subject let me remind you of some significant facts as follows:

(i) just before the end of W. W. II the jet propulsion appeared on some fighter aircrafts of both parties. Two years later the classical group "propeller and reciprocal engine" had totally disappeared among this class of *military aircraft;*

(ii) in 1946, very few people were confident in the future of jet engine in *transport aviation* though I was then sharing the firm views on this point of my British friend Sir John WHITTLE;

(iii) some years later indeed our preassessments became a reality;

(iv) during the last decade the "turbofan" has brought the subsonic transport aviation the most significant economical progress.

Since the end of W. W. II the technology of all components of the turbojet engine has been continuously improved. In a parallel progression the

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[*] Member and former President of the French Academy of Sciences

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domain of the operational altitude, velocity and range of the jet aircraft has been largely expanded.

This progress of what we call in France "performances" has been enormous both in military and in civilian applications.

Before commenting on the recent and subsequent technolgical advances I would briefly remind the usual representation of the evolution of internal flow through a one-flow turbojet engine.

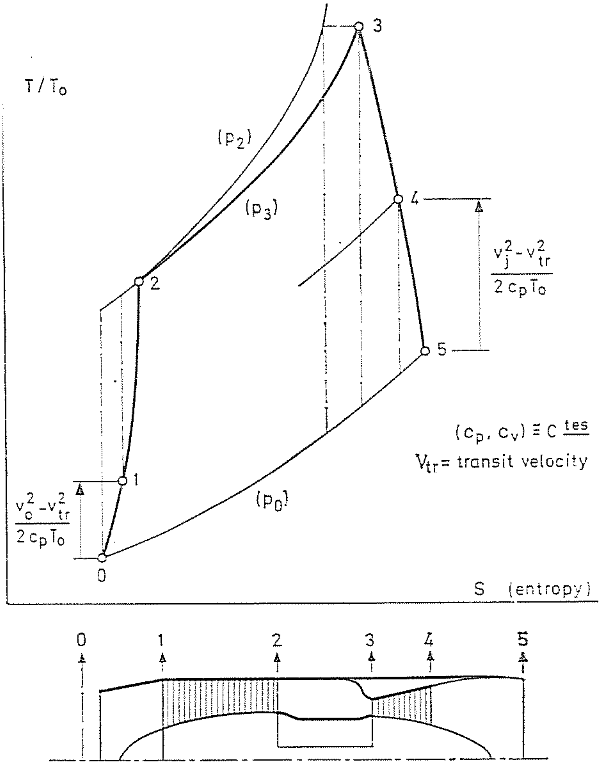


Fig. 1

With the simplifying assumptions $(c_p, c_v) \cong C^{tes}$ of our "simplified theory" elaborated in 1944 and still convenient for the present purely comparative evaluations, the said evolution is represented in Fig. 1, by the successive curved segments $0 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 5$ from ambient air captation *0* to burnt gases exhaust *5* at the same ambient pressure.

Our additional assumption $v_{tr} = C^{te}$ means that in the intermediate stage between each two successive components (air-intake, compressor, combustor, turbine, nozzle) the axial mean velocity v_{tr} of the passing flow-called here "*transit velocity*" — has a constant fixed value. So all these stages 1 to 4 of the evolution are isokinetic (same kinetic energy) with the exception of the extreme stages *0* at the air-intake and *5* at the exhaust nozzle *4* → *5*. Without going deeper in details it may be observed that such an isokinetic part of the global evolution makes possible a clear distinction between the two main deficiencies of the combustor as:

(i) during 2 → 3, uncomplete release of the fuel's calorific power and

(ii) the loss of isentropic enthalpy's fall until ambient pressure p_0 occurring in *3* by depression along 2 → 3.

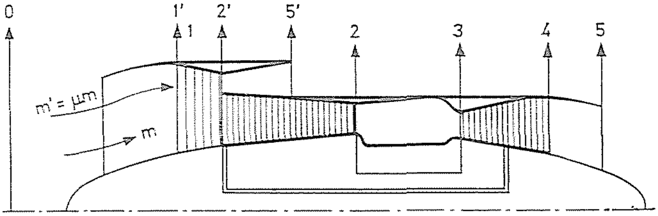


Fig. 2

It may be stressed here that the jet propulsion is very sensitive to this second kind of deficiency in the combustor.

Fig. 1 implies that the isobaric lines of *burnt gases* are translated on the enthalpic diagram so that the representative point of the combustor outlet is coincident with the point $3(p_3, T_3)$ of the isobaric line $p = p_3$ for *pure air* as it is fully and happily permitted by the simplifying assumptions adopted.

In order to compare and to appreciate the recent and the expected progress some evaluations may be presented.

These evaluations are selected among very many calculated particular cases because of their really instructive signification.

By definition, the primary flow of any considered *two-flows turbojet* has the same internal evolution as the said *basic one-flow turbojet* (Fig. 2), used as reference in all the present comparative evaluations.

In order to comply with requests of the near future, the basic engine is defined

(i) by a high pressure ratio ($p_2/p_1 = 25$) and

(ii) by a high absolute temperature T_3 at the turbine-inlet ($T_3 = 1730°\mathrm{K} = 273 + 1457°\mathrm{C}$) when running at full-power in the conditions of start on ground.

Each considered two-flows engine adds to this basic engine a secondary flow using increased mass flow of low-pressure stages of the global compressor, with stages corresponding to a fraction ζ of the global isentropic increase of enthalpy through the global compressor. This secondary air-flow is directly evacuated into the atmosphere, according to the simplest kind of a two-flows turbojet which offers the advantage of eliminating any thermodynamical connection between the primary and secondary exhausts.

It is actually conform to the so-called turbo-fan which has prevailed in transport aviation during the last decade.

Nevertheless and without renouncing to the exhaust autonomy comment will have to be made later on the possible interest of a moderated heating of the secondary flow by a "secondary combustion".

Two cases of functioning will hereafter be considered as characteristic for subsonic transport aviation:

(i) the case noted *GS*, relating to the functioning on Ground ($T_0 = 288°K$) and at the *S*tart of take-off, in principle at full power and at the highest rotational speed;

(ii) the case noted *CS*, relating to the *C*ruise flight at high *S*ubsonic speed, evidently in the stratosphere ($T_0 = 216°K$; Flight Mach Number $M_0 = 0.94$). For the start case *GS* a high "transit velocity" $v_{tr} = 200$ m/s has been adopted, as requested for the very compact jet engines of the future. For this case this velocity is also adopted for the exhaust of primary flow i.e. there is no variation of kinetic energy through the exhaust nozzle of primary and purely subsonic flow in the case *GS*.

The choice of all these *basic conditions*, suggested by the needs of the time to come, has an interesting result: it is possible to maintain for the compressors and the turbine the same and best efficiency in both cases *GS* and *CS* respectively, simply by

(i) reducing T_3 by 188° in case *GS* decreasing then from 1457 to 1269°C; and

(ii) reducing all internal velocities by 6% both the transit velocity and all the rotational speeds of a two-spool or multi-spool engine.

In cruise flight this fortunately permits an advantageous reduction of the high charge which the engine has necessarily to sustain during the short take-off time.

Consider now the two *predominant* progress factors of the turbofan, such as:

(i) elevation of the temperature T_3 at the combustor outlet; and

(ii) efficiency of turbomachines (compressor and turbine).

Firstly it may be stressed that the actual result of increasing T_3 must be evaluated by taking into account not only its possible effect on the distortion of T_3 itself before each turbine bucklet but also the expense of energy for the cooling medium and the disturbances due to the flow of this medium along the boundaries of the acting flow. Therefore in case *GS*, the high value *1630°K* (1457°C) has been chosen for T_3 which is certainly little optimistic for the next future if not for to-day. In fact, a slight change of such a high value would not much modify our present evaluations taking $(T_3)_{GS} = 1630°\text{K}$ as a fixed basis.

Nevertheless in my personal opinion, from now on the most efficient technological progress of the turbofan will proceed from an increase of the proper efficiency which may be operationally realized by its compressors and turbines.

For the sake of acceptable simplicity, let ϱ denote *an overall mean value* of the efficiency of any compressor and/or turbine and *three steps of advance* of ϱ will be admitted along the following period:

(i) step Y, meaning "*Yesterday*" of about *1968—73 where* $\varrho = 0{,}84$ for the high global pressure ratio $p_2/p_1 = 25$ adopted and considered as a fixed basis;

(ii) step M, meaning "To-*Morrow*" or about *1978 where* $\varrho = 0{,}88$;

(iii) step N, meaning "*Near* Future" or about *1983 where* $\varrho = 0{,}92$.

The evaluations M and N in comparison with Y may give a very convenient idea of what can be hoped in a not too distant future.

In order to appreciate comparatively the most important characteristics of actual and future turbofans in these three steps of technological progress Y, M, N, the turbo-fan of step Y with dilution $\mu = 6$ is taken a *reference* giving a not too bad idea of what the turbofans presently used in medium and long range transport aviation are.

Denoting *the dry engine weigth*, the *weight of fuel consumed in one hour* for example, the *thrust* of the reference turbojet by W^*, $(C^*, F^*)_{GS \text{ or } CS}$ respectively, it will be compared to any other turbofan (of step Y, M or N; and with $3 \leqq \mu \leqq 12$) *assumed to give the same thrust in cruise flight*, i.e. $F_{CS} = (F^*)_{CS}$. Then, this arbitrary turbofan will be characterized by its

(i) *dry weight index* $I_w = W/W^*$,

(ii) *fuel consumption index* $(I_c)_{GS \text{ or } CS} = (C/C^*)_{GS \text{ or } CS}$,

(iii) *thrust ratio* $R = (F)_{GS}/(F)_{CS}$, the ratio of thrusts in cases GS to CS at a cruising flight altitude of 11-km, the said ratio R being significant for the disponible mean acceleration during the take-off for a fixed $(F)_{CS}$ and a given initial total weight W_0 of the concerned aircraft.

Before presenting the annouced result it has to be mentioned that comparing our reference turbofan (step Y, $\mu = 6$) with the one-flow turbojet giving the same thrust F^*_{CS} by the same internal evolution as of the primary flow of the turbofan, this one offers about the *same dry weight*, a *gain of 67% on specific fuel consumption in the case GS*, and a *corresponding gain of 41,7% in the case CS*. Beside these advantages, lastly a *relative gain of 40,5%* on the thrust ratio R is to be noted. These excellent characteristics of operational superiority of the reference turbofan explain fully the *triumph* obtained by this kind of turbojet in the field of transport aviation during the last decade.

The quoted results are given in Table 1.

Table 1

Dilution μ-		3	6	9	12
Dry Weight Index I_w =	Step *Y*	1.063	1.0	1.033	1.11
	M	0.842	0.797	0.787	0.825
	N	0.702	0.643	0.629	0.643
Case GS Consumption Index $(I_c)_{GS}$ =	Step *Y*	1.437 (2.90)	1.0 (3.23)	0.827	0.836
	M	1.20 (2.30)	0.838 (2.60)	0.655	0.583
	N	1.055 (1.94)	0.713 (2.155)	0.634	0.727
Case CS Consumption Index $(I_c)_{CS}$ =	Step *Y*	1.163	1.0	0.982	1.014
	M	0.922	0.803	0.747	0.736
	N	0.787	0.655	0.602	0.574
Thrust Ratio R =	Step *Y*	4.67 (5.67)	5.78 (7.52)	6.84	8.01
	M	4.48 (5.51)	5.58 (7.24)	6.45	7.42
	N	4.30 (5.26)	5.32 (6.83)	6.16	6.92

Nota — Numbers between brackets refer to the case of a secondary flow heated by a secondary combustion to 515°C.

Fig. 3 illustrates the variation of I_w and $(I_c)_{CS \text{ and } GS}$ vs. μ in the respective steps of progress *Y*, *M*, *N*.

Fig. 4 gives the corresponding information for the thrust ratio *R*.

It clearly appears from Fig. 3 and 4 that:

(i) in the recent step *Y*, the dilution $\mu = 6$ has been excellently adapted to the best use of the operational turbofan;

(ii) *new important gains are still to be realized in the next technological steps M* and *N*, these gains being then favoured by a progressive and respective increase given to μ from about $\mu = 6$ to about $\mu = 9$ and $\mu = 12$.

In the preceding table and figures the dilution $\mu = 3$ has been intentionally considered, and the numerical values between brackets given for $\mu = 3$ and $\mu = 6$ are relating to the case of the secondary flow being heated by a secondary combustion at its highest pressure to the relatively modest temperature *515*°C. The interesting possibility offered will be considered hereafter.

Despite of the sensational progress of transport aviation during the last decade, *this progress remains astonishingly far from those expectable from technological possibilities.*

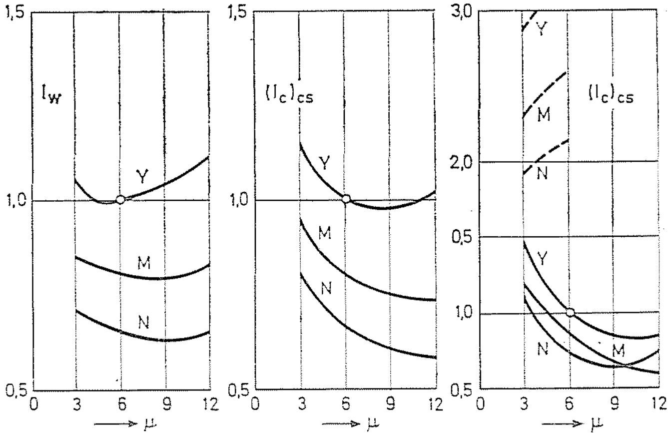


Fig. 3

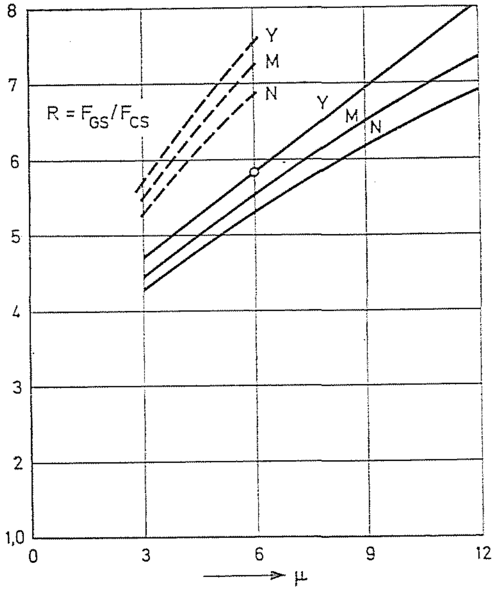


Fig. 4

The next and largely realizable advance would be obtained by better satisfying *more severe exigencies*, namely:

(i) all-weather flight safety;

(ii) decrease of total cost per unit of transportation;

(iii) flexibility of the transportation capacity, in order to improve mean use of the offered loading capacity;

(iv) drastic reduction of the take-off and landing lengths;

(v) and above all, drastic reduction of pollution, especially noise, on and near the airports.

Considering Fig. 3 and 4 it may be noted that increasing the dilution above $\mu = 6$ in the case *GS* the secondary exhaust becomes lower and lower subsonic, the primary one being already subsonic as stressed above.

Consequently *the global exhaust noise during the take-off and landing could be noticeably reduced.*

The thrust ratio R — seen in Fig. 4 — is then increasing and permits also the reduction of *the take-off and landing lengths.*

These important advantages reinforce the interest in increasing the dilution $\mu = 6$ of the reference turbofan in the technological steps M and N, a good representative of the recent step Y.

Now a quite different way of progress, namely a *sharp reduction of noise and rolling lengths at airports*, will be considered.

This consists in letting *contribute the exhaust jet, here mainly the secondary one to the lift*, not only in itself by orientable exhaust nozzle but also by the use of an especially appropriate wing on the aircraft.

Since twelve years at least as you know many and very different kinds of V-STOL aircraft have been studied and/or tested, especially in U.S. and likely in the U.S.S.R. too.

All the contemplated pure *VTOL.* are in fact costly, noisy and of limited speed and range, even the helicopter which has indeed *not yet any challenger* in many special cases but not in the widest field of transport aviation.

The *STOL aircraft* is more promising because of being *compatible with the fundamentally simple use of fixed wings and engines if the exhaust of these engines is conveniently utilized in the proper direction during take-off and landing.*

Numerous and interesting attempts are known to have been made in the recent years in order to use orientable or deviated exhaust jets to act on a single or multiple flap and thereby increasing the circulation around the wing and consequently its lift. This field of research seems to me the most promising if a clearer analysis is made of the concurring but mutual effects of

(i) the diffusive impulse of the utilized jet and

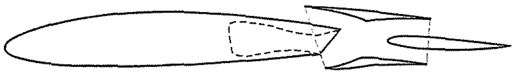
(ii) its orientation.

Shortage of space does not permit to comment in detail these very important points.

Nevertheless Fig. 5 gives a scheme to illustrate how the conception of an *integrated system of wing and turbofan* could be realized.

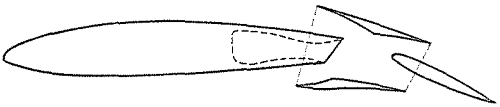
On a major part of the span and its rear part the wing receives internally the secondary and compressed flow of the turbofan (eventually with a moderate heating limited for example to 515°C as mentioned in the above table and figures).

For a good compatibility with the offered small transit section the

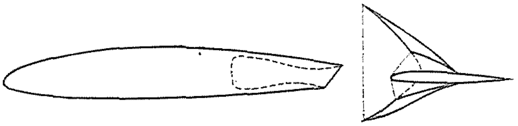


(1) Ground : acceleration from start

(2) Cruise : normal flight



(3) Take - off



(4) Landing : reverse thrust

(1) and (3)	Possible use of secondary heating till 515 °C
(2) and (4)	Normally without sec. heating

Fig. 5

inducing secondary exhaust *flow must be delivered at a sufficiently high pressure*, this condition explaining why the case $\mu = 3$ has been retained above. This inducing jet acts between two small upper and under flaps analogous to the walls of an "ejector" operating in front of a rear and separate flap. This one and the ejector walls are appropriately orientable as a classical flap.

With the possibility for such a wing-flap and ejector to induce a tertiary flow of external air with a mass flow rate 4 to 5 times that of the inducing flow, a value of 12 at least for the *global dilution* of the turbofan so integrated with the wing-flap ejector may be contemplated, with correlated and substantial effects in reduction of noise, increase of circulation around the wing, direct contribution of the finally inclined jet to the global lift, *all these consequences being easily controllable by the combined orientation of the ejector and flap and by a moderate and additional heat supplied to the inducing secondary flow by the secondary combustor mounted beside or even inside the wing.*

It is essential to stress that my *conception of such a new* utilisation of an appropriate turbofan, i.e. the use of a rather low internal dilution e.g. $\mu = 3$ and of a moderate and controllable secondary heating, must be *closely integrated into the design and the functioning of the associated wing-flap ejector.*

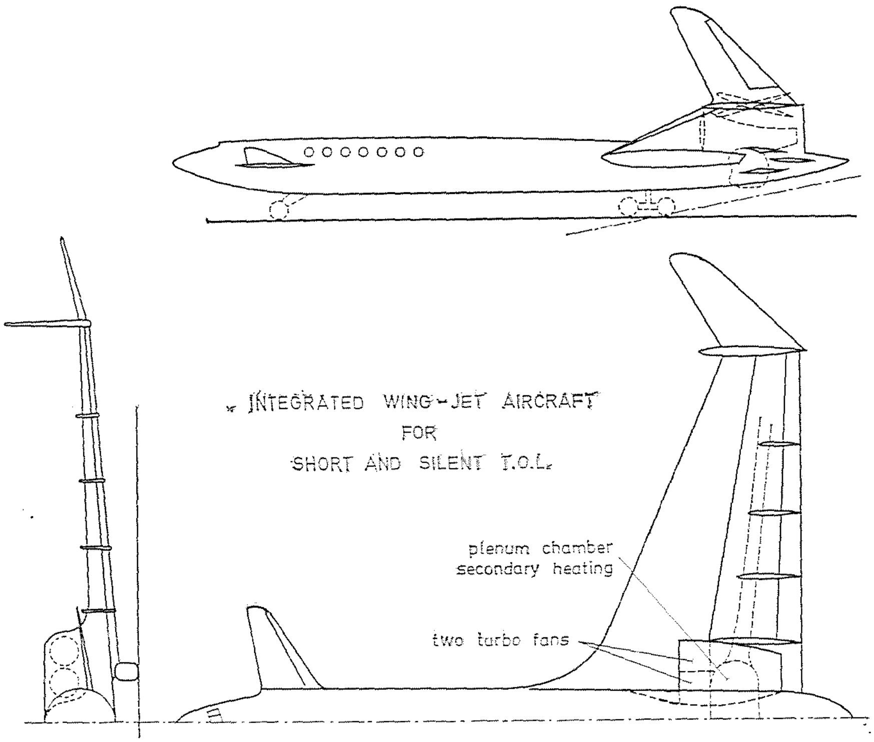


Fig. 6

The best formula of the corresponding aircraft may be a "canard" (Fig. 6) suppressing any interference of the mixed internal and external flows behind the wing with any other part of the aircraft and reducing unfavourable interaction due to the vicinity of the ground.

For illustrating the possible transformation of the usual transport aviation which could result from my unorthodox conception it may only be said that such a future subsonic transport aircraft is likely to take-off and land silently on parallel and very short runways, thus at a very high frequency. This would solve the paramount problem of facing an enormous increase of the traffic capacity of actual airports, thanks to *short and silent take-off and landings.* In the near future this kind of technological revolution would certainly greatly favour an enormous and cheap expansion of the air transportation for all possible customers by any weather and in all countries.

Summary

Parametric development potential studies on the thermodynamic cycle of transport aviation turbofan engines are showing substantial weight and consumption gain possibilities without increasing turbine inlet temperatures due to the expected improvements in compressor turbine efficiencies. Best results may be obtained by increasing the dilution, too, from present day value of about 6 to about 12. Ejector induced tertiary flow over special wing-flap combination may give very short take off/landing distances and significant noise reduction.

Such advantages would open an immense field of fruitful development to the proposed integral concept of a new combination wing-turbofan aircraft for subsonic transport aviation.

M. Roy 86, Avenue Niel. 75017 Paris. France