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# HYPERSONIC AIRCRAFT SECONDARY POWER CONCEPTUAL STUDY

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## Abstract

The increasing interest about the hypersonic aircraft is well known.

As many innovations are presented by these planes in the fields of aerodynamics, structures and propulsion, so the systems of the hypersonic aircraft will be very innovative; that is because of the great differences, from the traditional aircraft, in the mission and in the propulsion. In particular the propulsion will utilize ramjets or scramjets without any possibility of direct power extraction; so a traditional Secondary Power System, based on engine mechanically driven gearbox, which purely transfers mechanical power to hydraulic pumps and electrical generators, is not suitable for these planes.

Hypothetical secondary power systems based on A.P.U.'s or pneumatic turbines will be proposed. In particular the pneumatic turbines, fed by engine bleed air, are useful when engines operate as turbojet or ramjet: the first case is usual in the traditional planes, the second is studied in this paper and our results confirm that it is possible.

Unfortunately a secondary power system based on the engine bleed is not possible with scramjet or, obviously, with rocket propulsion; in these cases the solution may be given by Auxiliary Power Units, with turbines actioned by gas generators from combustion of fuel and oxidizer. An interesting solution is the possibility that the same turbine can also be fed by engine bleed air, if the propulsion allows that.

The possibility of an SPS based on the engine bleed will be considered. A simulation computer program that allows the preliminary sizing of this system for a given mission and a given secondary power load profile will also be presented. An example of calculation will be considered in order to validate the above said program.

## Introduction

As Secondary Power System (SPS) we mean a set of devices capable of providing, to all the sub-systems and accessories of the aircraft, electrical, pneumatic and hydraulic power during:

- flight
- pre-flight operations
- normal and emergency engines starting
- emergency conditions

Nevertheless, the functions developed by the SPS greatly depends on general characteristics of the aircraft, its architecture, its power plant and its mission profile(1).

In the aeronautical field the importance and the complexity of the SPS are increasing according to the progress of the aircaft. Some basic characteristics of SPS are common to all the aircraft so we can identify several consolidated solutions of SPS, but in the case of the hypersonic flight we must consider fundamental differences in the layout, due to the high flight altitude and to the kind of power plant (Figure 1); therefore the SPS schemes of conventional aircraft are not proposable for hypersonic planes.

In the following of this paper we will shortly describe several possible configuration for the SPS of an hypersonic aircraft; afterwards we will go deep into the SPS architecture based on the main engines air bleed. A calculation program will be presented also.

## Secondary Power System concepts for hypersonic aircraft

### Engine Bleed

Almost all of the turbojet aircraft have a pneumatic system which provides the aircraft with bleed air, generally coming from two different stages of the engine

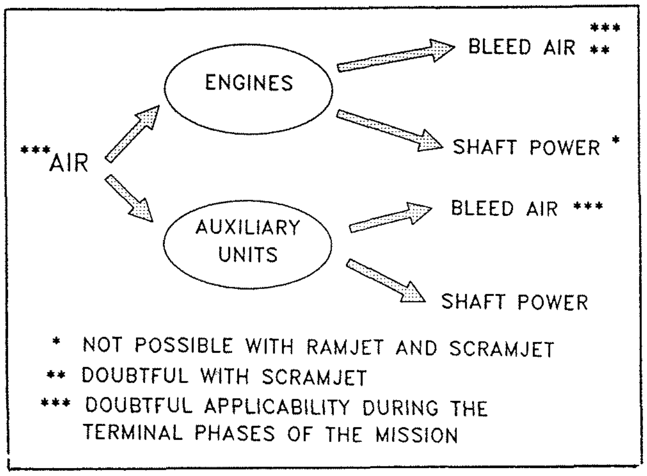


Figure 1

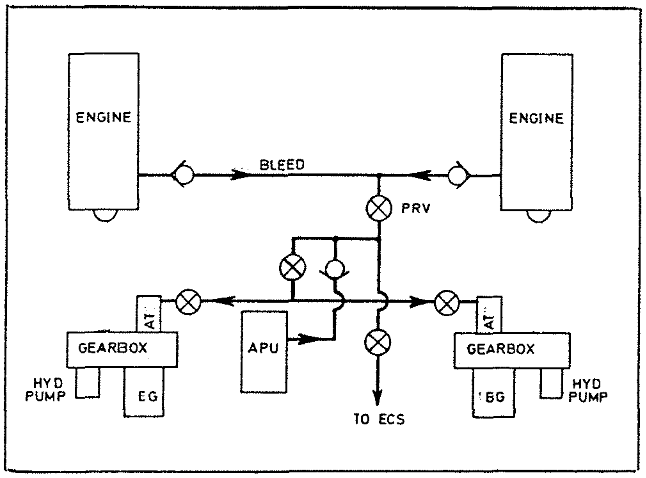


Figure 2

compressor. The bleed air could be direct to the enviromental control system, to anti-ice system, etc..., and could furthermore generate mechanic power by means of an expansion through devoted gas turbines (Air Turbine AT). This mechanic power can drive electrical generators, hydraulic pumps, and so on. Figure 2 shows the layout of a SPS based on the air-bleed. This kind of SPS could be considered for use on the hypersonic aircraft; nevertheless we must consider the following peculiar problems:

- It is not necessary to demonstrate the possibility of bleeding air from a turbojet compressor, whereas bleeding dynamically compressed air from the air intake of a ramjet represents an innovatory technology whose feasibility needs a verification.
- In the power plant of the hypersonic aircraft we often found the combined turbojet and ramjet engines therefore there will be a double system of valves in order to bleed air from the two kind of engines.
- Because of the large variation of the flight conditions there are large variations too in the pressure and temperature at engine bleed ports.
- At every instant of the mission the SPS need a continuative bleed in order to satisfy the hydraulic and electrical power demand.
- Absolute inapplicability of the air bleeding in the case of rocket propulsion and doubtful applicability in the case of scramjet propulsion.

### Auxiliary Power Unit (APU)

By the term APU we normally intend a system based on a small airbreathing turbine able to generate secondary power sufficient to satisfy the aircraft demand by means a fuel combustion and without power extraction from the main engines. In the traditional aircraft the APU is mainly employed in the pneumatic power generation but also in the shaft power generation: it may have its own gear-box or may be connected (mechanically, through a direct coupling, or pneumatically, through an air turbine) to the aircraft gear-box when the main engines are off. Using the APU we have some benefits as regards a larger indipendence on the ground infrastructures during pre-flight engines out operations. These advantages could induce us to consider an APU based SPS in hypersonic aircraft too; in particular we could hypothesize the installation of continuous operating APU(2): this permits to solve the problems concerning the secondary power supply when the engines are working as ramjet, scramjet or rocket (bad utilization of the bleed air and absence of shaft power).

Because of safety reasons more than one APU will be necessary in the system. For the hypersonic aircraft the adoption of continuous operating APU's doesn't permit the utilization of the traditional airbreathing APU because of the oxigen lack at highest altitudes and the thermodynamic problems inside the APU air-intake at hypersonic flight speed. In order to obviate these problems there were concieved the endothermic APU, that is a turbine fed by a gas generator in which fuel and oxidizer react (Figure 3). In this case some althernative problems also exist:

- impossibility of bleeding air from the APU,
- necessity of an on-board oxidizer tank,
- in the case of the utilization of hydrazine as pro-

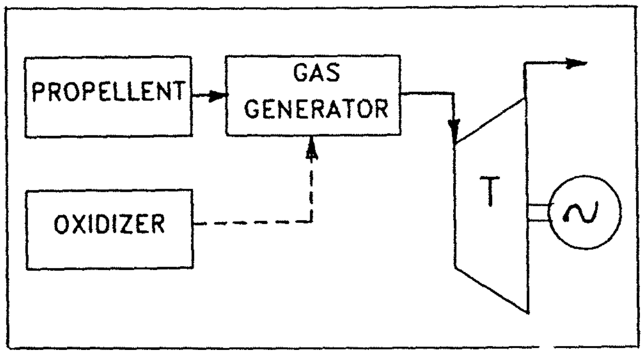


Figure 3

pellant there is the impossibility of the APU operation during the atmospheric flight because of the toxicity of the exaust gases. In any case the hydrazine is poisonous itself so its use is avoidable.

The last reason suggests the hydrogen employment as propellant, since it is proposed for main engines feeding too; alternatively we could consider the hydrazine APU, operating at high speed/altitude, joined with a traditional airbreathing APU or a main engines bleeding.

Super Integrated Power Unit (SIPU)

The last considerations lead to the integration of airbreathing and endothermic APU in an only system: this integration is certainly profitable on account of the reduction of the number of turbines, gearboxes, generators, pumps, oil systems, etc..
Figure 4 shows a SIPU scheme(3) in which we discern three different ways of working:

1. Airbreathing: combustion of hydrogen with atmospheric oxigen into a devoted chamber and a turbine driven by the combustion gases.
2. Gas Generator: hydrogen-oxigen combustion or hydrazine decomposition into a devoted chamber and a turbine driven by the resulting combustion gases
3. Engine Bleed: turbine driven by means of the bleed air coming from main engines.

Hypotheses of non-conventional SPS configuration

The previous SPS configurations, presented in the preceding paragraphs, could be seen as complementary rather than alternative: each of them could be considered preferable for particular type of applications:

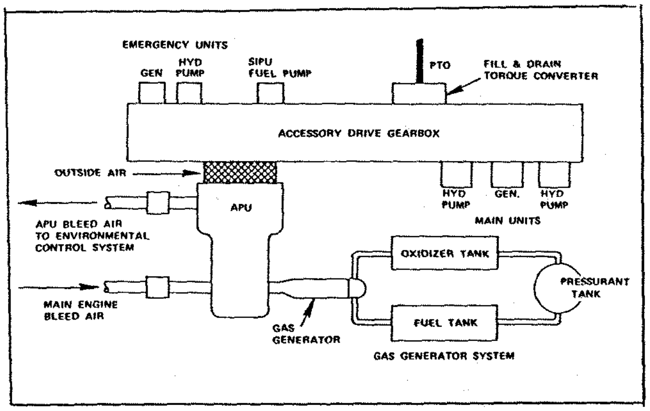


Figure 4

- The engine bleed system, probably less costly than an APU based system, is compatible with a limited range of Mach number: this is due to the above mentioned problems with scramjets engine operation. The engine bleed system results proper for hypersonic transport/combat aircraft (Mach < 7) and for the first stage of a TSTO aircraft. An airbreathing APU could be added to accomplish the pre-flight ground operations.
- The SPS based on the employment of multiple endothermic APU is utilizable in a wide range of Mach number, so it represents the best solution for a second stage of a TSTO aircraft.
- For a SSTO aircraft it's possible to consider an SPS architecture based on the employment of some SIPU: in this case we take advantage of the reduced fuel consumption obtainable by making use of the engine bleed or of some airbreathing APU modes during the low Mach phase of the mission.

All the above mentioned concepts represent a part of the possible solutions of SPS; with reference to this we also remind the solution based on the batteries (employed in low duration missions) and on the fuel cells.
We could also make the hypothesis of a secondary power generation using the hydrogen which is destined to the propulsion; at the moment this solution is under the consideration of the authors.
Now we are going to explain the results of a work that, for reasons connected with the interest of the Italian Aerospace Firms, concerns the study of an SPS, based on the air bleeding from engines, for the first stage of a TSTO aircraft.

## Preliminary design of the engine bleed SPS

In this chapter we will examine in detail the possibility to drawing power from the main engines of an hypersonic aircraft: this power extraction is carried out by the air bleeding. In order to do that we have carried out two computer programs for the evaluation, respectively, of the characteristics of the available engine bleed (mass flow, pressure, temperature,..) and of the deliverable mechanic power at the SPS turbines shaft.

### Bleed Program

This program is constituted by three parts:

1. definition of the mission profile
2. definition of the SPS power request
3. calculation, all through the mission, of the available bleed

Mission profile definition. The aircraft mission can be defined as a particular standard mission recorded on a data file, or by the Operator; in the last case he can freely fix the mission profile, point by point (time, Mach number, altitude): in this way it is possible to study a whatever duration mission cutting down the long cruise phases by few point and concentrating the attention on the crucial moment in which there are large gradient of the mission characteristics. The inserted data, relative to the mission, are altitude, Mach number, attitude, speed, acceleration of the aircraft during the time.

Finally it is also possible to define a single point mission in order to investigate the SPS behaviour only in a particular flight situation .

SPS power request definition. The global power demand of SPS is defined by the indication of the power absorption (mechanical, electrical and hydraulic) of the various aircraft sub-systems and devices at every moment of the mission.

Also in this phase it's possible to make use of a standard profile for the SPS power request or of a free fixed profile.

Calculation of the available bleed. This phase begins with the request of some data about the power plant and the aircraft characteristics.

As regards the propulsion system, in accordance with the recent studies on the hypersonic aircraft$^{(4),(5)}$, we consider a power plant based on combined turbojet and ramjet engines in a coaxial arrangement (Figure 5): turbojet engines with afterburner are used up to a particular Mach number, herein referred as "switch Mach". The value of this switch Mach is pertaining of the general design: it depends on the engines necessity, on the optimization of the mission fuel consumption, etc..., so we consider it as an input value for the program.

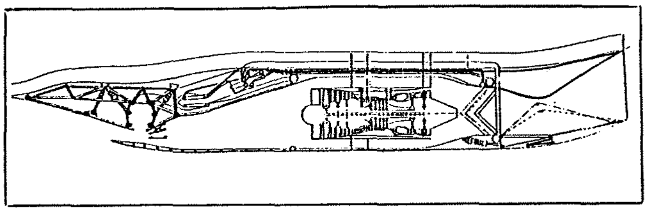


Figure 5

We do not consider rocket or/and scramjet propulsion because they are incompatible with the air bleed. The program also asks to the Operator some aircraft data, for example the number of engines, the cross section of the engine intake, the maximum pressure ratio of the turbojet compressor, the number of stages of the compressor and its efficiency, and so on.

On the basis of these data the program is able to compute the available bleeded mass flow rate and its physical characteristics.

Now we are going to explain the procedure of the bleed calculation, summarized in Figure 6.

The turbojet and the ramjet phases are analyzed saparately because the equations which describe the thermodynamic of the airflow are different.

Turbojet subsonic operation: applying the well-known equations of the thermodynamics to the airflow through the intake casing and the engine compressor, pressure and temperature are calculated at low and high pressure compressor stages. Using equations of the flight mechanics it is possible to calculate the necessary thrust in each phase of the mission and then the engine air flow.

Turbojet supersonic operation: the program considers the influence of the shock waves concerning the aircraft and its air intakes. We have supposed that the intake shock waves configuration , showed in Figure 7, keeps constant during each phase of the mission by means of a variable geometry ramps intake. The program assigns the available bleed as a percentage of the air mass flow rate: this percentage is fixed in such a way as to respect the correct working of the compressor and the fuel combustion stability.

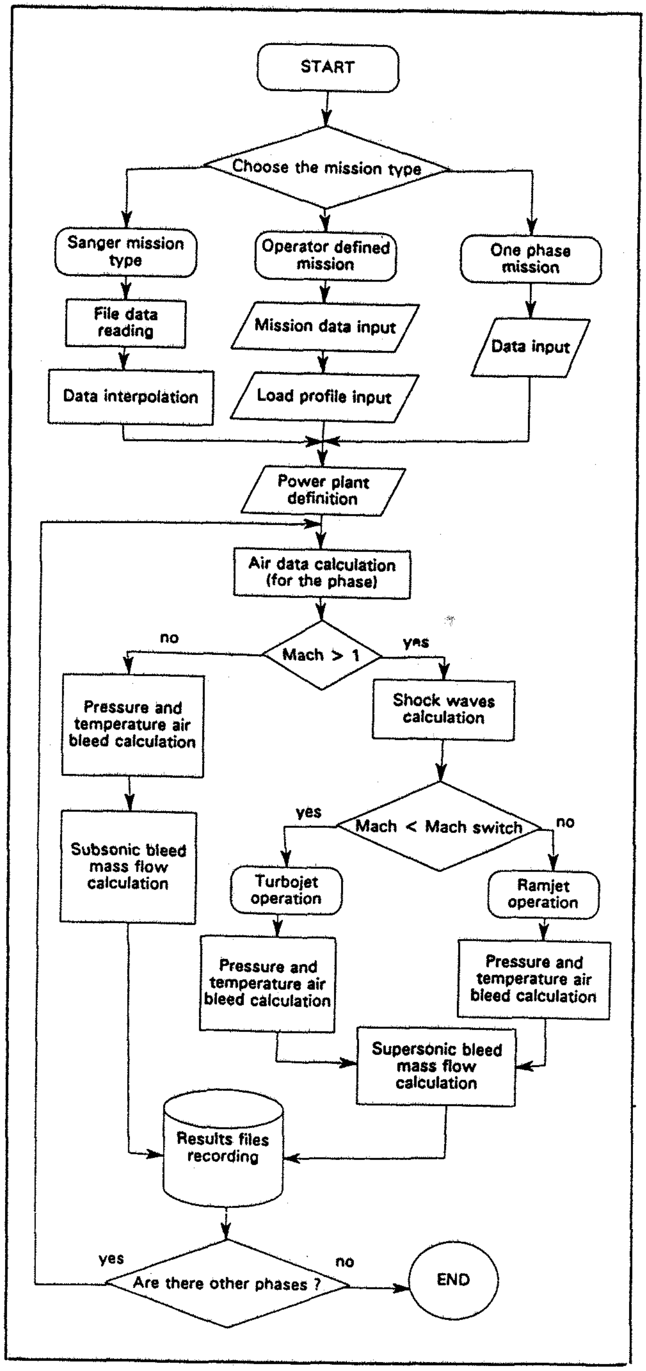


Figure 6

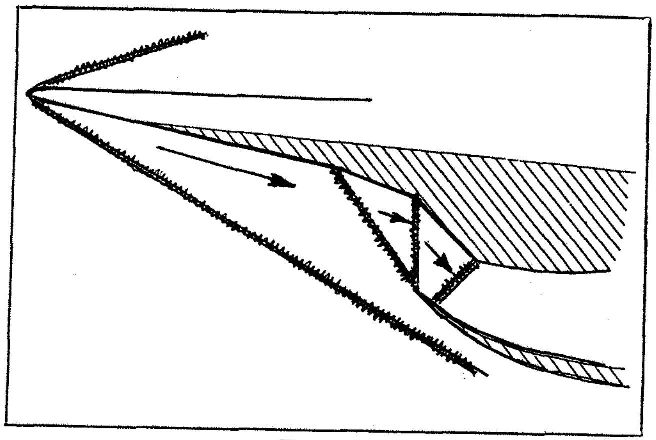


Figure 7

Ramjet operation: during the mission simulation, when the Mach number exceeds the switch value, the program selects the ramjet propulsion; the program knows the internal geometry of the air intake casing (in the ramjet mode) and calculates the thermodynamic characteristics of the air at the ramjet bleed valve (Figure 6).
We have supposed that the air bleed may occur up to a one per cent of the total engine air mass flow rate: we have inspected this limit as sufficient to satisfy the SPS demand and we think it is compatible with the correct working of the engines.
At the end of the mission the program shows the results and records on a file the data representing the maximum available bleeded mass flow compatible with the correct working of the engines for the mission completion.

Turbine program
This program estimates the power obtainable from the available air bleed fixed by the previously discussed "Bleed Program"; it is constituted by the following three parts:

1. definition of the bleed system
2. definition of the SPS turbine
3. calculation of the turbine power delivery

Bleed system definition. This routine allows a detailed definition of the bleed circuit, from the port valves to the SPS turbine inlet, in particular with regard to:

- system layout,
- length, diameter and roughness of each pipe,

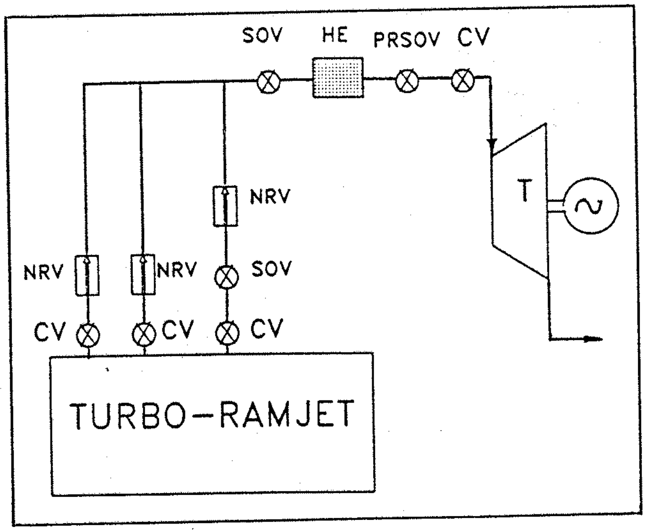


Figure 8

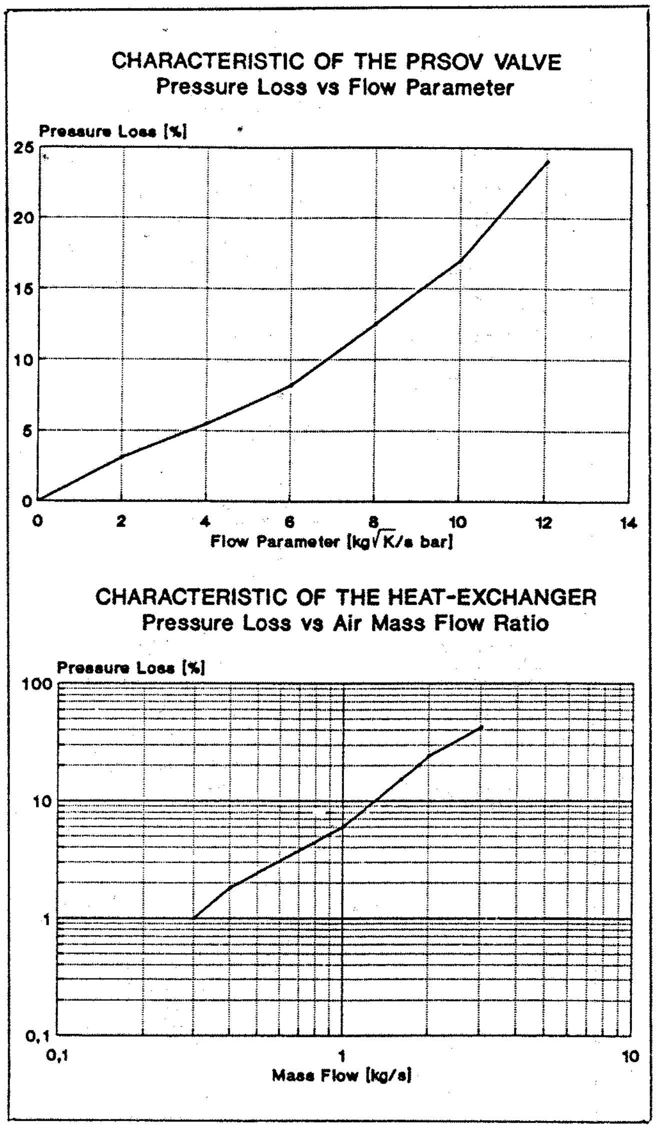
- technical characteristics for each components of the system (pressure reducing valves, heat exchanger, non return valves, etc..)

Figure 8 shows the typical configuration of the bleed system considered in our program; each component of this circuit has an appropriate behaviour: for example, Figure 9 illustrates the pressure loss behaviour assumed for the pressure reducer shut-off valve (PRSOV) and for the heat-exchanger (HE).

Now the Operator fixes some other data concerning the pneumatic turbine and the bleed system; these values, listed below, must be choosen on the basis of the Operator's technical experience or of some preliminary calculations:

- maximum percentage of bleed assigned to the turbine expansion when the bleeded air could also be used for other purposes
- temperature drop per length unit of the pipe
- pressure loss in the turbine exaust duct
- angular velocity of the turbine at the maximum efficiency conditions
- turbine efficiency at the design point
- air turbine contol valve characteristics: normally outlet pressure versus inlet pressure at a different values of the contol parameter (current or voltage).

Definition of the SPS turbine. A preliminary sizing of the turbine is possible in such a way that it could satisfy the demand of the SPS in a particular mission


CHARACTERISTIC OF THE PRSOV VALVE
Pressure Loss vs Flow Parameter

CHARACTERISTIC OF THE HEAT-EXCHANGER
Pressure Loss vs Air Mass Flow Ratio

Figure 9

condition: this represents the most significant working condition (design point) that does not necessarily coincide with the maximum SPS power request of the mission. The verification of the optimal working conditions of the turbine in the "design point" is not limited to check if the available power is greater than the necessary power, but involves several aspects:

- a safety criterion is complied which advises the Designer to oversize the turbine in order to take precautions from engines fault. For example, in an application, which will be presented in the following heading, we have hypotized an aircraft with six engines power plant; each engines feeds a devoted SPS turbine: the turbines are sized in such a way to allow the SPS to satisfy the aircraft demand up to two engine simultaneously out.
- There is a limitation on the turbine inlet temperature, by means of an heat-exchanger, in order to avoid a rapid deterioration.

If the "design point" condition isn't satisfied the Operator could change the turbine design characteristics till to reach a result.
At the end of this step the program shows and records the performance map of the upcoming turbine.

Calculation of the turbine power delivery. In each time the program reads the bleed characteristics (from the mission profile files), simulates the thermodynamic evolution of the air from the bleed valves up to the turbine inlet, and evaluates the available air mass flow rate. We have made the hypotesis that the turbine remains in the choked regime during all the mission: in order to make this the program operates on appropriate pressure control valves.
Knowing the thermodynamic conditions at the turbine inlet it's possible to evaluate the pressure ratio, the efficiency, and the delivered power. The program proceeds along the mission and ascertains whether the calculated power is lower than the necessary power, even if in an only point: in this case it's necessary to increase the air bleed mass flow rate through an appropriate adjustment of the pressure control valves; if this regulation should be insufficient the Operator must change the "design point" or the turbine characteristics and restart the procedure of the SPS turbine definition.
Figure 10 summarize the above mentioned procedure.

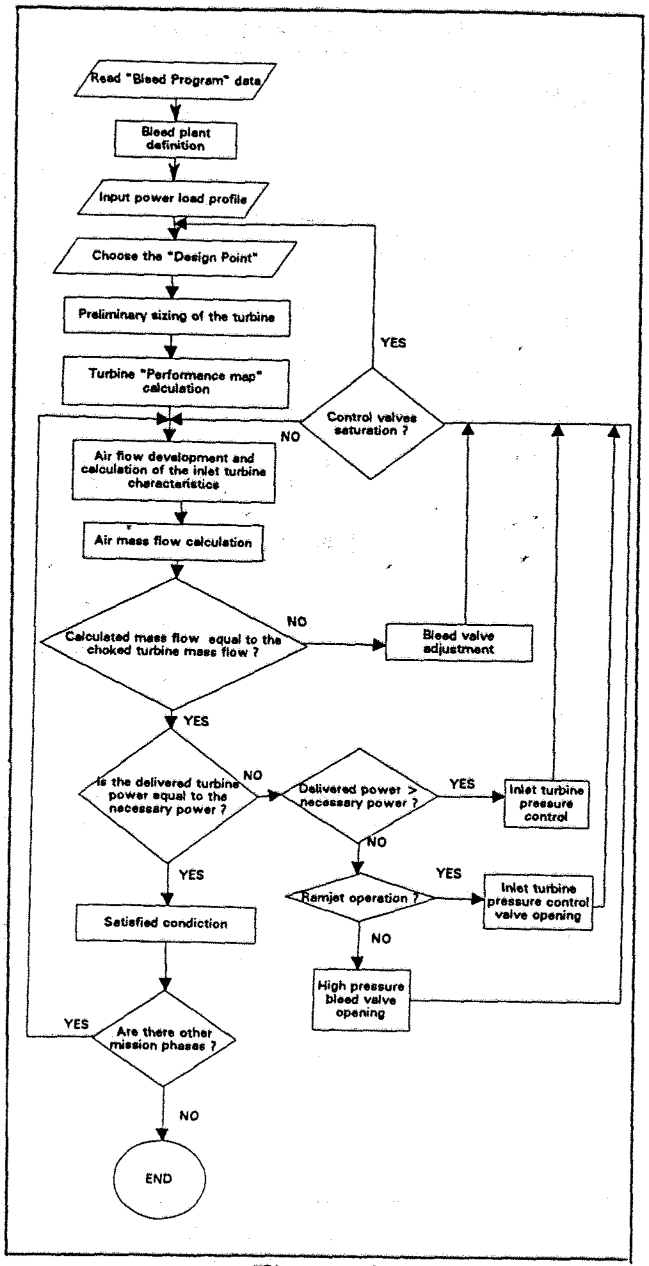


Figure 10

## Applications

In the following, the results obtained performing an application with the above mentioned program are presented; they have reference to a first stage of a Sänger type hypersonic aircraft with a mission profile put in Figure 11.

The output of the "Bleed Program" are summarized in Figure 12 which reports the characteristics of the one engine available air bleed: we notice the heat-exchanger intervention in the air temperature limitation.

The Figure 13 shows the (one engine referred) Secondary Power System load profile assignation.

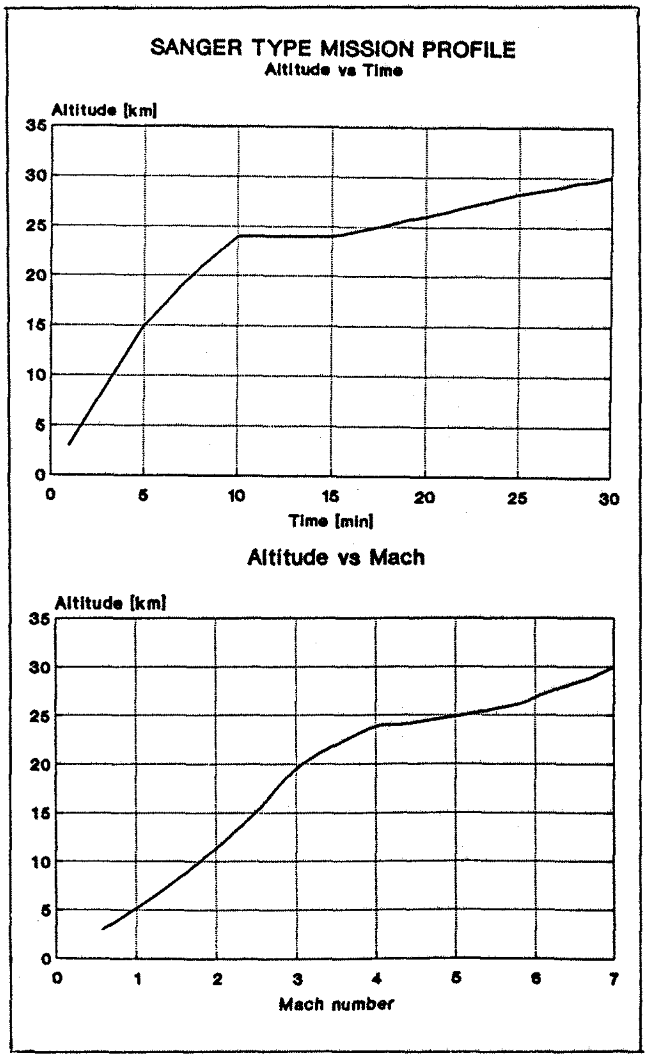


Figure 11

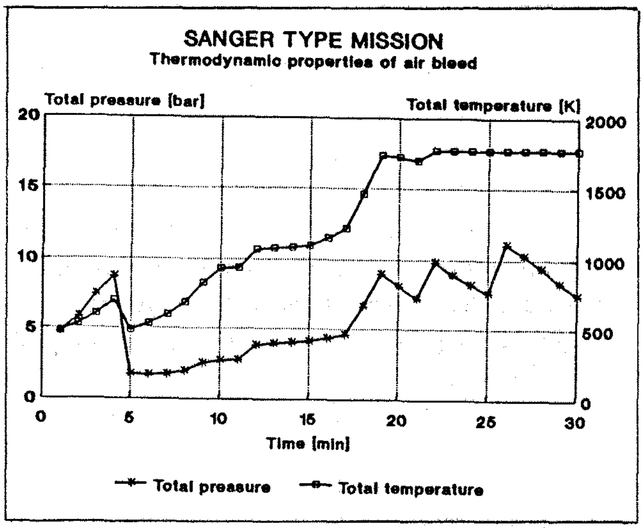


Figure 12

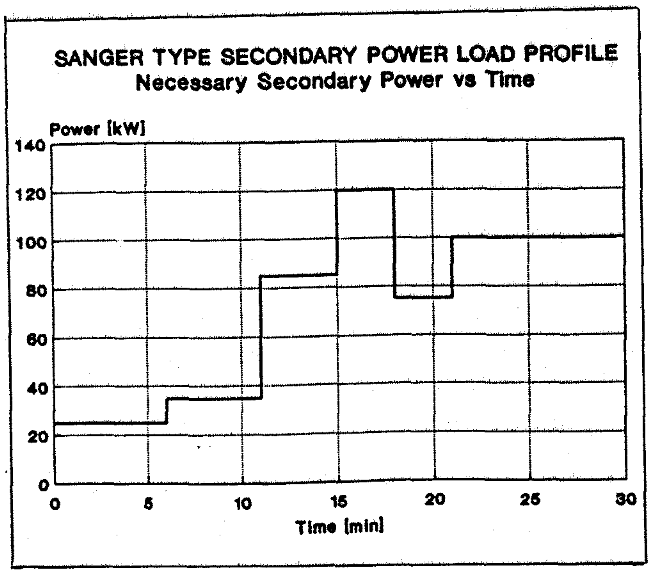


Figure 13

Figures 14,15 and 16 report the results of the "Turbine Program". In Figure 16 we notice that during the turbojet operation the turbine works with low efficiency and low pressure ratio: this is because we have optimized the turbine working for the ramjet operation, in which there is a greater power demand and a longer time duration.
Finally, Figure 17 shows the performance map of the turbine.

## Conclusions

On the basis of our calculations we underline that the bleed mass flow rate, necessary to satisfy the SPS power demand of an hypersonic planes, is very small compared with the engine mass flow rate: this encourage to further study in the light of an increase of the secondary power supplying.

## References

1. S. CHIESA, P. MAGGIORE, *Configurazioni Impiantistiche per Velivoli Transatmosfrici*, NT Tecnica & Tecnologia (Ed. AMMA Torino), No.2, 1994.
2. S. CHIESA, *Possibile Nuovo Ruolo per l'APU*, IX Congresso Nazionale AIDAA, Palermo, 1987.
3. A. D. LUCCI, J. A. WILLIAMS, B. L. McFADDEN, *Super Integrated Unit for Fighter Aircraft*, AGARD-CP-No.352, 1983.
4. D. E. KOELLE *SÄNGER II, a Hypersonic Flight and Space Transportation System*, 16th Congress of ICAS, 1988.
5. H. KUCZERA, H. HAUCK, P. SACHER, *The German Hypersonic Technology Programme Status*

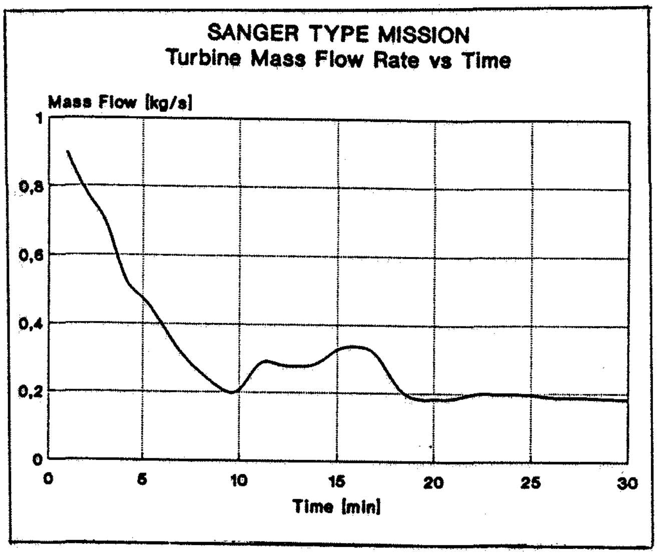


Figure 14

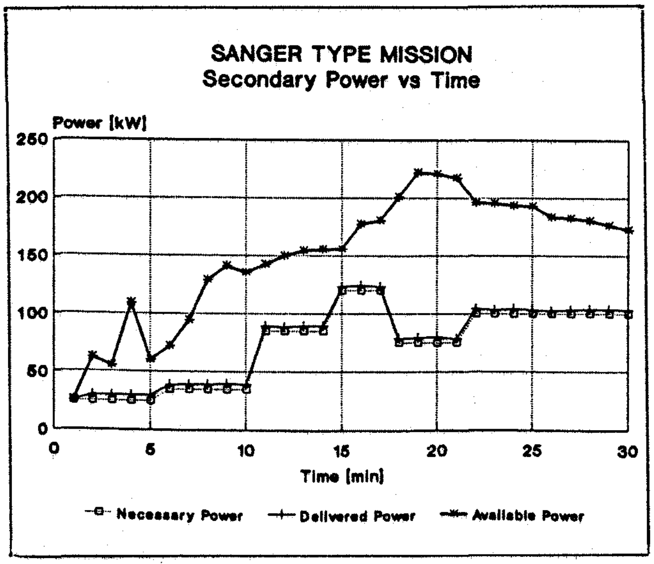


Figure 15

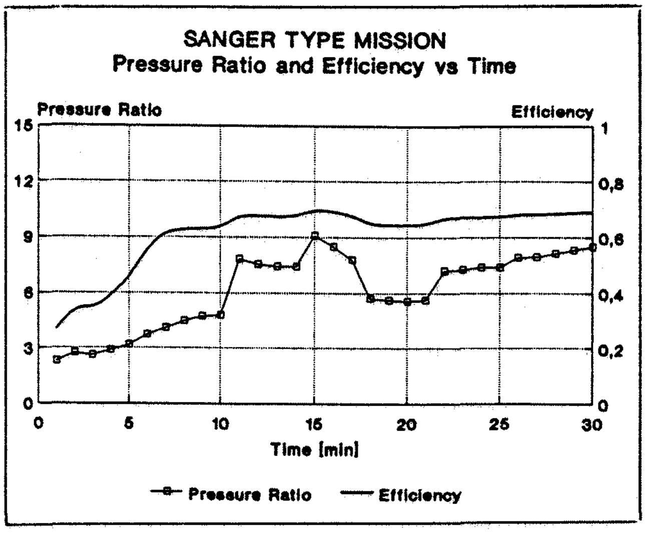


Figure 16

*1993 and Perspectives*, AIAA/DGLR 5th International Aerospace Planes and Hypersonics Technologies Conference, Munich, 1993.

6. S. TROLLHEDEN, H. STREIFINGER, *Secondary Power System for the Sänger First Stage Vehicle*, AIAA Paper, 1993.
7. C. BERNOCCO, *Secondary Power System per Aereo Transatmosferico*, Degree Thesis at the Polytechnic of Turin, Academic Year 1991/1992.
8. S. GIUSTO *Alternative per il Sistema di Potenza Secondaria di Velivoli Transatmosferici*, Degree Thesis at the Polytechnic of Turin, Academic Year 1992/1993.

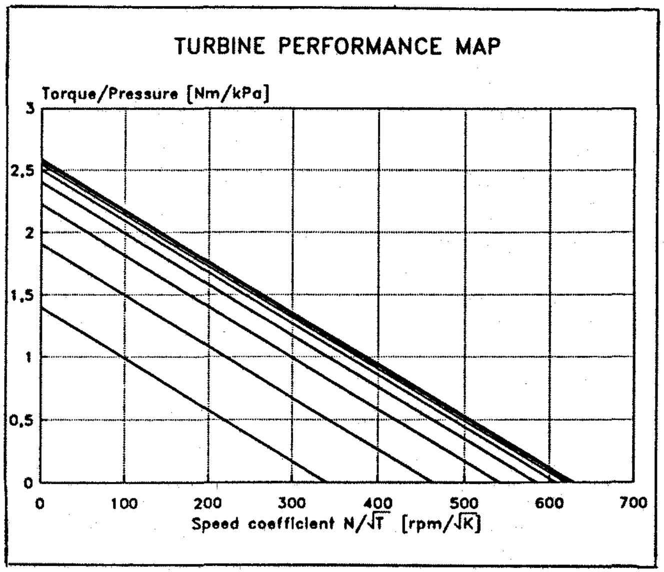


Figure 17