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TRADE-OFF CONSIDERATIONS FOR ENVIRONMENTAL CONTROL SYSTEM ON BOARD OF HELICOPTERS

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ABSTRACT

Cabin air conditioning needs become always more mandatory both for better crew performances and for allowing larger heat rejection from avionic systems.
Conventional environmental control systems (ECS) of the bleed air type, modified from aircraft installations, are characterized always by larger penalties due to power extraction which, in case of helicopters, appears more critical than in case of aircraft engines.
In addition helicopter engines are capable of lower bleed air flows because of their own structures.
At present new ECS designs become more attractive, for their low power consumption, even if characterized by more complex structure, both in sense of hardware and of thermodynamic cycles. The present paper shows a performance comparison among ECS for this particular case of installation.
Two different typical helicopters, the former of 2-3 persons crew only, the latter of larger dimensions foreseen for passengers (30) have been taken into account as reference cases for evaluating system performances.
One of the most attractive concepts for energy saving appears cabin air recirculation; having this concept in mind, performance evaluation and optimization (with respect to power consumption, and cabin air ventilation needs) has been assumed as study task.
After a first comparison between simple bleed air and recirculation system, the attention of the analysis is focused on the latter ones cooling capabilities, and system weight evaluation, with respect to engine power penalties.
The study results show how the optimal ECS type often depends on board installation characteristics, mission profile and duration, number of passengers, and obviously type of helicopter.
By combining the recirculation concept with air and vapour cycle ECS, the system fuel and mass penalties can be minimized with a particular attention to the last generation helicopter engines.

1 INTRODUCTION

Performances to be met by helicopter Environmental Control Systems [ECS (o)] become always more stringent.
To fullfil the requested performances under even more critical mission conditions (duration, crew psycological stresses, contaminated environment, and so on) ECS's must be designed with special care depending on each particular application, with respect to cabin temperature control, cabin ventilation and avionic thermal conditioning.
At the same time the power penalty due to the ECS must be minimized to improve flight performances.
Aim of this paper is to compare the performances of different systems, keeping in mind their installation constraints and mission type, on the basis of the power penalty they impose on the engine.

2 SYSTEM DESCRIPTION

The ECS performances study here presented, for sake of simplicity, does not take into account the effects of presence of humidity in the air. As a consequence regenerative heat exchangers and water separators assemblies (whose presence is stricly connected with vapor condensation phenomena) are not taken into account in the system schemes analyzed.
Purpose of this paper, in fact, is not to show actual performances of an ECS optimized for a given mission, but to show general thermodynamic trends so that a preliminary choice of ECS type could be made early enough in the definition phase.
Conventional ECS's always use some amount of bleed air flow (from the engine compressor) wich, after cooling through a heat exchanger, is expanded in a cooling turbine and is sent into the cabin.
In the simplest system (turbofan) (Fig. 1) the cooling turbine mechanical power is utilized to drive a fan which circulates the external cooling air flow.
In the bootstrap system (Fig. 2) the bleed air flow follows a more complex thermodynamic evolution. The bleed air, after precooling, is further compressed by a compressor driven by the cooling turbine. Between compressor and turbine, another heat exchanger reduces again the air temperature.
Main constraints of these types of ECS depend basically on the minimum cabin air inlet temperature, because of crew comfort and danger of ice formation.

(o) Note: for a complete list of the acronysm used see at end to text.

This limit, fixed in this study at a temperature $T_F = 2°C$, suggests the use of low supply pressures only, such as those available from the first stages of engine compressor (L.P. bleed).
Because of decrease of these pressures when the engine is functioning at low throttle setting, normally L. P. bleed is not sufficient over the complete range of ECS working conditions. In addition it must be remarked that helicopter engines very seldom have LP bleed ports. Due to these considerations it becomes necessary to install, on a high pressure bleed line, a pressure reducing valve, which normally throttles the bleed air flow. High penalties for this type of control occur because of the large waste of compression power.
In order to show system performances, a coefficient of performance (COP) has been defined as:

$$COP = Q_{ref} / \Delta P_u$$

where :

Q_{ref} = refrigerating power supplied by the ECS

ΔP_u = mechanical power penalty at engine output shaft

In case of ECS using bleed air ΔP_u is the engine turbine power decrease caused by the reduced air mass flow through the engine turbine itself (this ΔP_u is approximatively the bleed air compression power multiplied by the inlet turbine/outlet compressor absolute temperature ratio).
The reason of this COP definition is based on the need of taking into account the effective engine power penalty in case of both bleed air and mechanical power extraction.
Performances for TBTF and TBBS (for different values of engine pressure ratios β) are plotted as COP versus throttling pressure ratio (ψ) in Fig. 3.
On this performance plot, such as on the following ones, cabin and ambient temperatures of 27 and 52 °C respectively have been assumed.
From the curves of Fig. 3 it appears how large (20 : 1) is the ratio of engine power to refrigerating power.
Two ways can lead to a reduction of the power penalties:

a) lowering the turbine outlet temperature, keeping the inlet cabin air temperature constant by recirculating the cabin air

b) reducing the engine power penalty by means of an air compressor mechanically driven by the engine shaft.

With the first method risks of ice formation can be lowered by use of a regenerative heat exchanger and of a water separator at turbine inlet.
With the second method the only power needed is that necessary for air compression (without the additional power penalties introduced by changes in the engine thermodynamic cycle); in addition the mechanically driven compressor can be designed according to the exact

requirements imposed by each single application.
If the compressor is coupled with the engine shaft its speed becomes less sensitive to engine loads variation than the one of the gas generator. Even if the dedicated compressor has an efficiency lower than the engine compressor, (values of 0.75 and 0.85 have been respectively assumed in the present study) the power absorbed by the ECS appears to be much lower. In Fig. s 4 and 5 recirculation ECS schematics are shown respectively for two versions: turbofan (RBTF) and bootstrap (RBBS): in Fig. s 6 and 7 the same systems but using a dedicated compressor instead of bleed air are shown.
To quantify the amount of recirculating air, the ratio ρ is defined as:

$$\rho = G_{ext} / G_{cab}$$

where

G_{ext} = air flow taken from the ambient

G_{cab} = air flow entering the cabin

Obviously the recirculation air flow is:

$$G_{ric} = G_{cab} - G_{ext} = (1 - \rho) \; G_{cab}$$

In Fig. s 8 and 9 performances of RBTF and RSTF, RBBS and RSBS are presented as curves showing the COP values against ρ (i. e. the external air flow) at different values of the pressure ratio β. Pressure ratio ranges are from 1.8 through 5 for the mechanically driven compressor, from 4 thru 15 for the case of bleed air. Lower values have been selected for the dedicated compressor because the higher COP's correspond to the lower β's. In addition compressors of small dimensions cannot give high pressure ratios at the expected rotational speeds.
It appears self evident by comparison of Fig. s 8 and 9 with Fig. 3 the advantage of the use of a mechanically driven compressor or of a recirculation system, even if the system becomes obviously more complex in its structure.
A limit to the lower values of ρ is fixed by the needs of cabin ventilation with external fresh air. If the number of passengers is not large this limitation appears of very little importance.
Mechanically driven compressor systems offer further advantages from the energy saving point of view. If the recirculation air flow passes through the compressor, the air flow taken from ambient can be reduced to the minimum imposed by ventilation needs; expecially in case of high external air temperature, the COP values significantly increase.
Compressed recirculation turbofan and compressed recirculation bootstrap system schematics are reported in Fig. s 10 and 11 respectively, while their performances (COP versus ρ at different pressure ratios) are plotted in Fig. 12.

From these diagrams it appears that pressure ratios suitable for such types of ECS are very low; in fact because the total air flow enters the turbine, no recirculation air mixing occurs before entering the cabin and the corresponding advanteges are lost. Performance curves are terminated when an inlet cabin temperature equal to 2 °C is reached. Higer COP values at low ρ values indicate the advantages of lowering the external air flow; the lower limit again will be imposed by cabin ventilation air needs.

3 COMPARISON

In Fig. 13-a performances of various systems are shown versus pressure ratio. Values in the range of 1 ÷ 5 are typical of dedicated compressor systems, bleed air systems are typically in the range of 4 ÷ 15.
Each system type presents a performance range whose boundaries are imposed either by ρ , or by the pressure ratio extremal values. In Fig. 13-b, for the same systems analyzed in Fig. 13-a, values of ρ are plotted versus pressure ratio.
The meaning of the diagrams is self evident; the pressure throttled systems appear as the less efficient ones as far as power penalty is concerned.
On the other hand the best one, CRBS, needs, for the same refrigerating power, about 1/5 of the power required by throttled bleed systems. Another comparison between the systems taken into consideration, with the addition of vapour cycle refrigerating systems, is shown in Fig. 14.
Power penalties for two different applications (typically a refrigerating power of 4 kW for a three man helicopter and a refrigerating power of 12 kW for a 30 passenger helicopter) have been evaluated for each system considered over the pressure ratio range typical of each ECS.
Performance curves have been computed taking into account an inlet cabin air temperature of 2 °C.
In the left side scale power penalty for the 4 kW systems is plotted; on the right side that for the 12 kW one.
On the abscissae scale, in addition to the ρ values, the effective external air flow are also plotted, assuming a cabin air flow rate G_{cab} = 0,12 kg/s for the first application, and G_{cab} = 0,36 kg/s for the second one.
On these scales the arrows indicate the minimum air flows for a correct cabin ventilation for each application.
It is self evident that the systems located on the left side of these values are unacceptable for cabin air conditioning.
Fig. 14 also shows the performance curve of a typical vapour cycle ECS. In fact, once the recirculation loop concept has been accepted, methods applicable for cooling the inlet cabin air flow may be

different from those in which direct air flow expansion is utilized. Because vapour cycle systems have higher COP values in comparison to air cycle systems, they are competitive even if their structure can appear more complex. In fact the performance curve of the vapour cycle ECS gives the lowest power penalty; but it must be taken into account that vapour cycle systems need a separate device capable of supplying the ventilation air flow; the corresponding power penalty has not been taken into account into the overall energy balance. Vapour cycle systems also can be analyzed with different recirculation ratios. In order to lower the engine power penalty it appears a good practice to maintain at a minimum value the ventilation air flow since its temperature (normally ambient temperature) is higher than the temperature of the recirculating air at cabin outlet.
Disadvantages of the vapour cycle ECS are greater complexity, and larger weights; nevertheless these aspects are largely overcome by the resulting lower fuel consumption.

4 FUEL WEIGHT PENALTIES EVALUATION

ECS's component weight is only one of the causes of the take-off weight penalty due to the system; in fact also the fuel mass corresponding to the power absorbed during the complete mission duration must be taken into account. This second item is often larger than the first one.
Trade off considerations must trend to minimize the sum of system and fuel weights.
Obviously simple and light systems, characterized by lower efficiencies, may become competitive in helicopters foreseen for short duration missions. On the contrary the other systems may be the optimum choice, for long mission applications.
In Fig.s 15 and 16 take off weight penalties for the systems above considered, for two refrigerating power levels, are plotted as a function of mission duration.
The curves have been calculated assuming an engine specific fuel consumption of 0,095 g/kW. s, typical for current engines. Simple bleed systems appear to be advantageous only for missions no longer than 0,5 + 1 h; on the other hand vapour cycle ECS's appear to be the best ones for mission duration over 4 h.
In the middle range, recirculation systems show the highest overall efficiency.
On the basis of the above considerations a realistic choice among the different systems can be done not only with respect to the helicopter type, but also to the typical mission duration for the aircraft on which the ECS must be installed.

5 REFERENCES

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LIST OF ACRONYMS

BS	boot-strap system
C	compressor
COP	coefficient of performance
CRBS	compressed recirculation boot-strap system
CRTF	compressed recirculation turbofan system
ECS	environmental control system
F	fan
HX	heat exchanger
PRV	pressure reducing valve
RBBS	recirculated bleed boot-strap system
RBTF	recirculated bleed turbofan system
RSBS	recirculated shaft boot-strap system
RSTF	recirculated shaft turbofan system
RVC	recirculated vapour cycle system
T	turbine
TBBS	throttled bleed boot-strap system
TBTF	throttled bleed turbofan system
TF	turbofan system

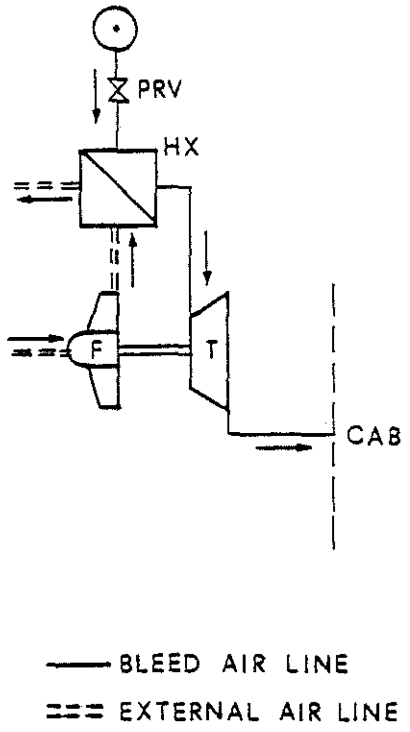

Fig. 1 - Turbofan ECS (TBTF)

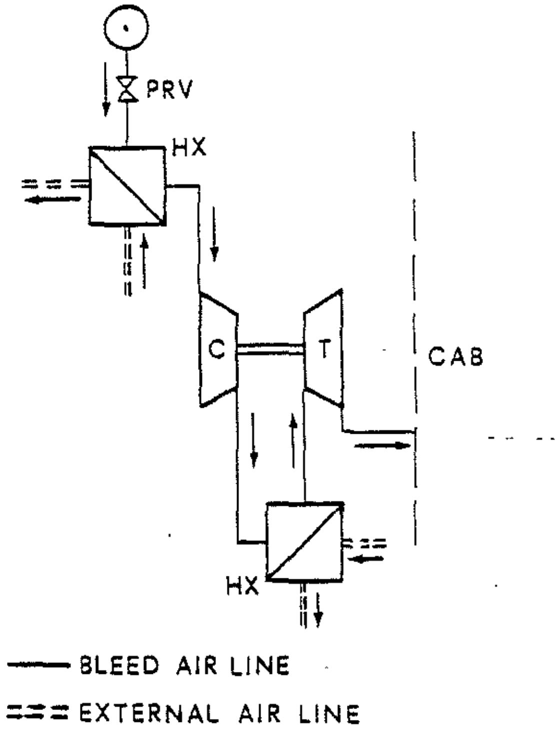

Fig. 2 - Boot-strap ECS (TBBS)

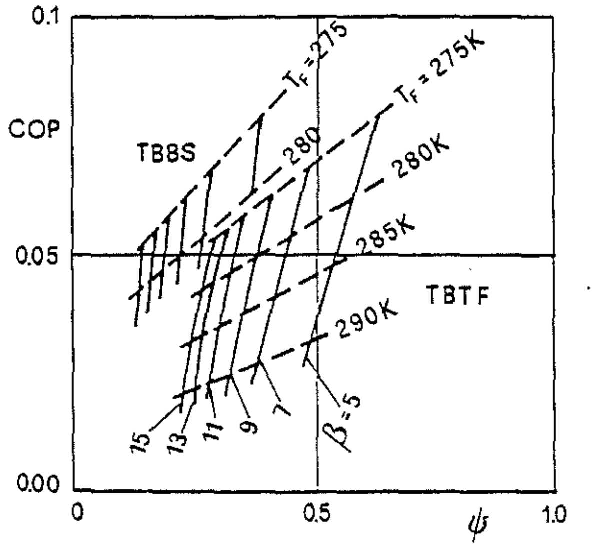

Fig. 3 - Throttled ECS Performances

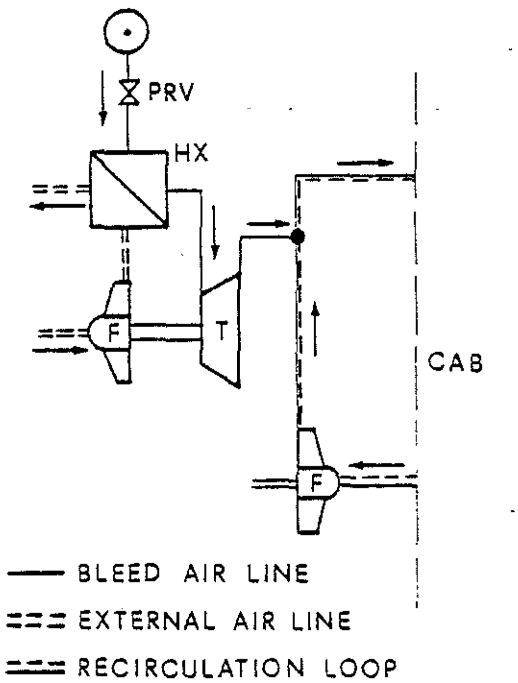

Fig. 4 - Recirculating Turbofan (RBTF)

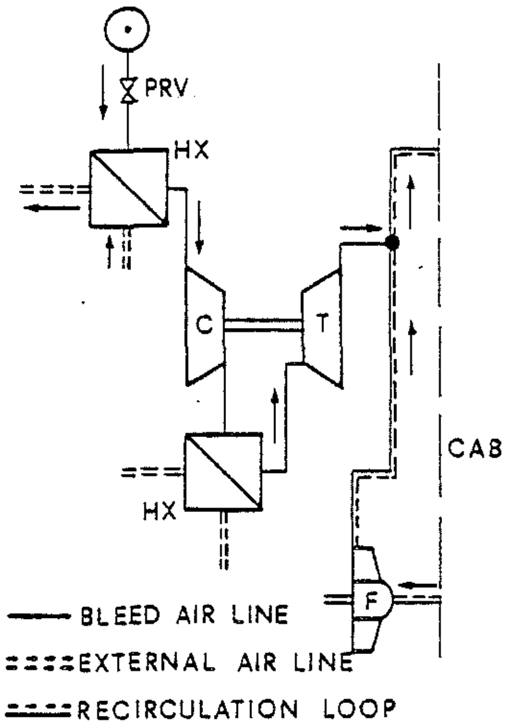

Fig. 5 - Recirculating Boot-strap (RBBS)

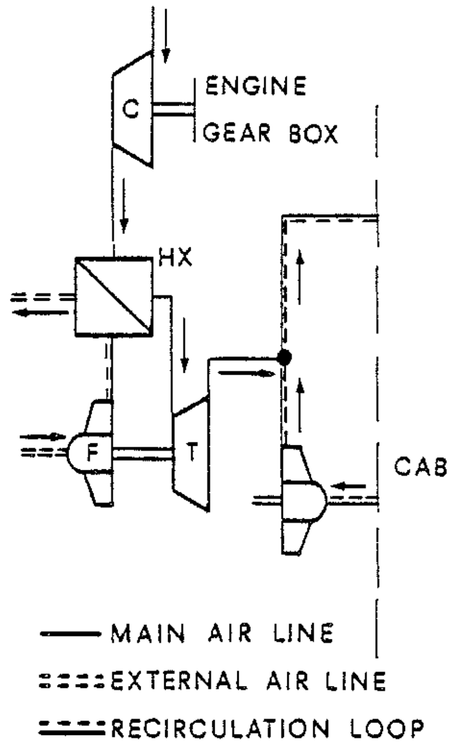

Fig. 6 - Recirculating Shaft Driven Turbofan (RSTF)

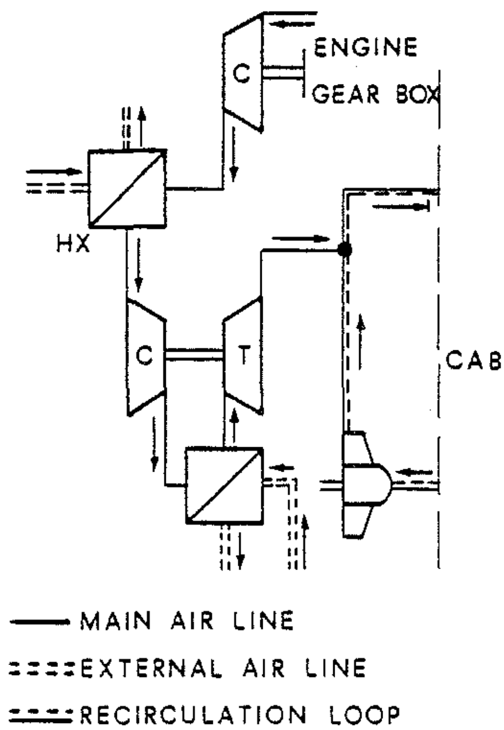

Fig. 7 - Recirculating Shaft-Driven Boot-strap (RSBS)

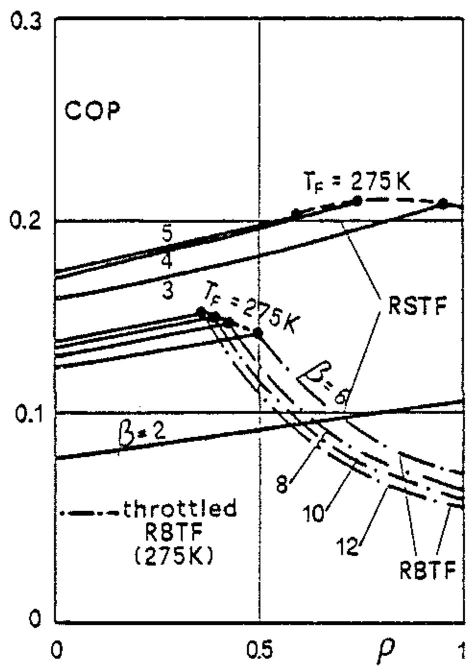

Fig. 8 - RBTF and RSTF Performances

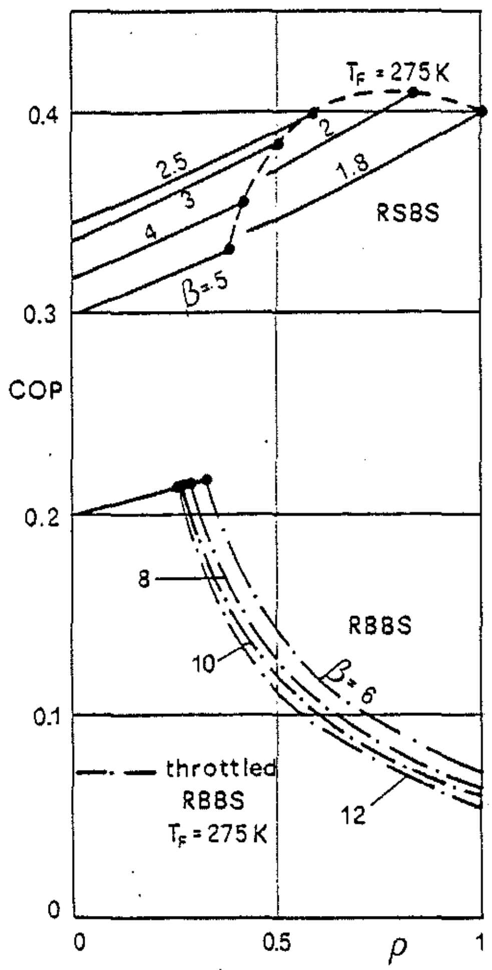

Fig. 9 - RBBS and RSBS Performances

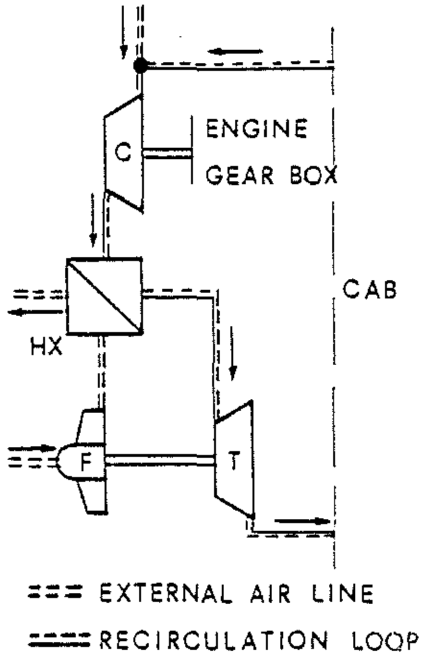

Fig. 10 - Compressed Recirculated Turbofan (CRTF)

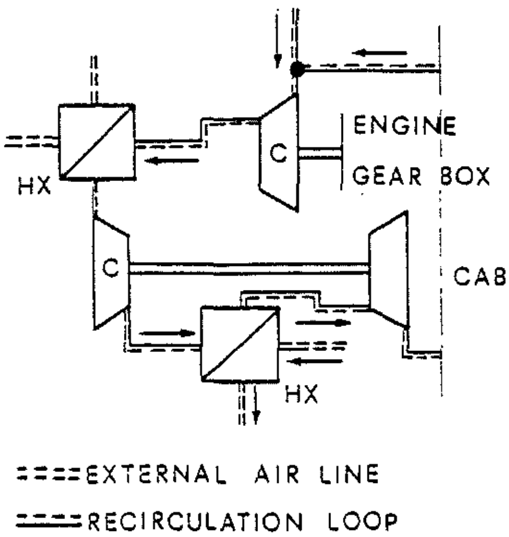

Fig. 11 - Compressed Recirculated Boot-strap (CRBS)

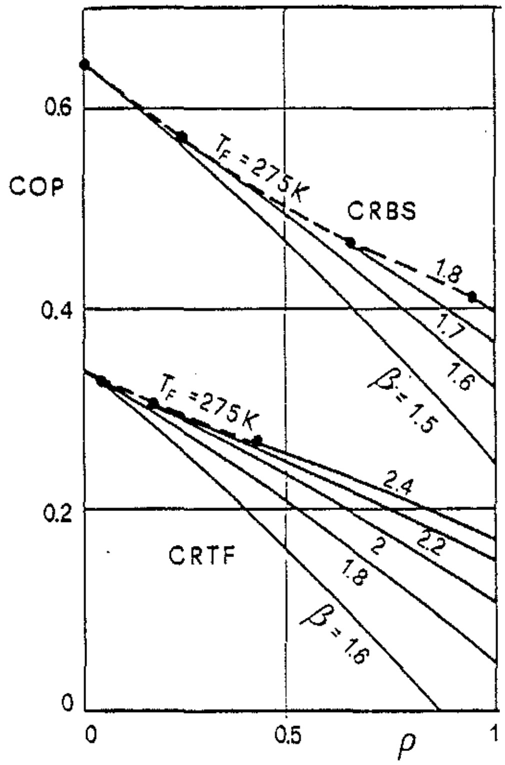

Fig. 12 - CRTF and CRBS Performances

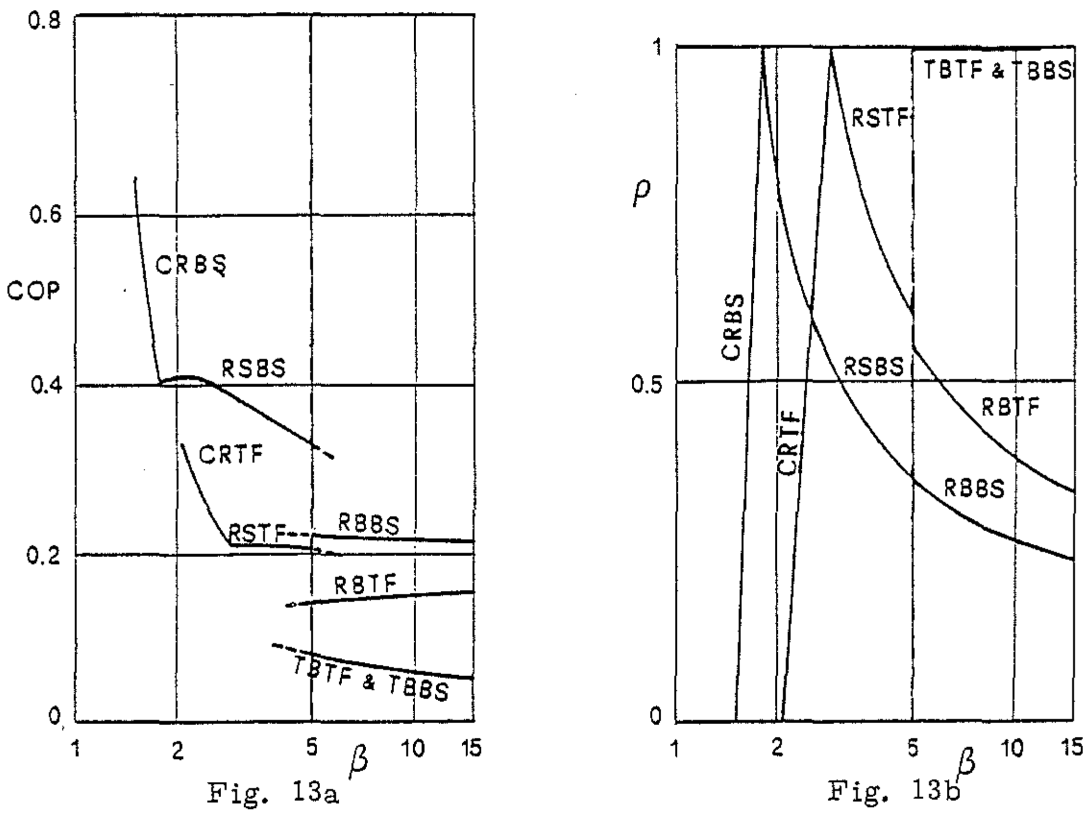

Fig. 13a

Fig. 13b

Performance Maps for various ECS configurations

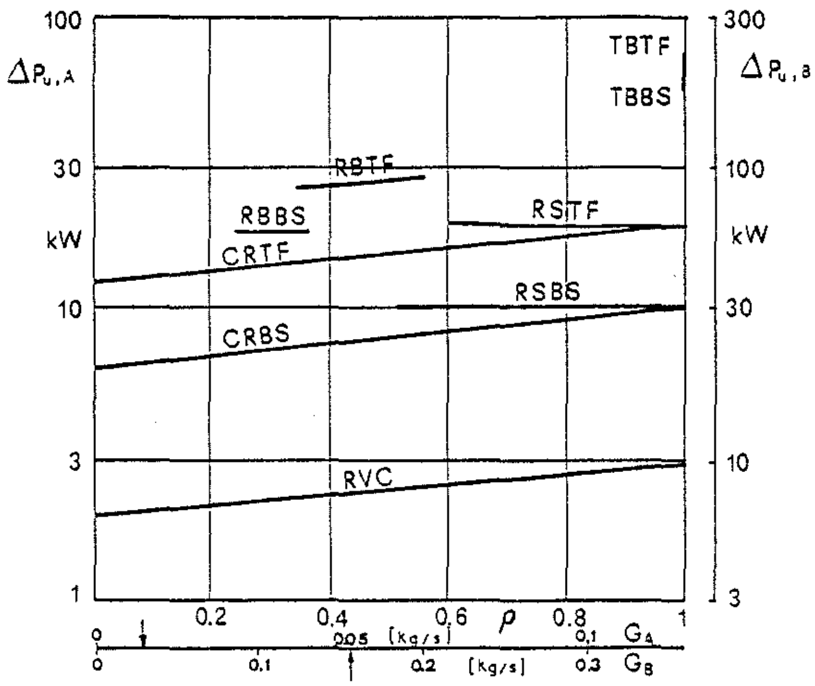

Fig. 14 - Power Consumption for two typical Helicopter ECS

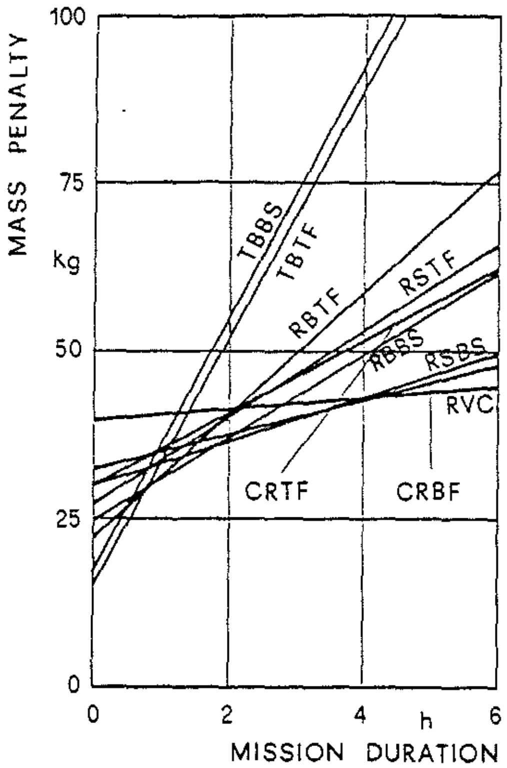

Fig. 15 - Mass Penalty for 4 kW ECS

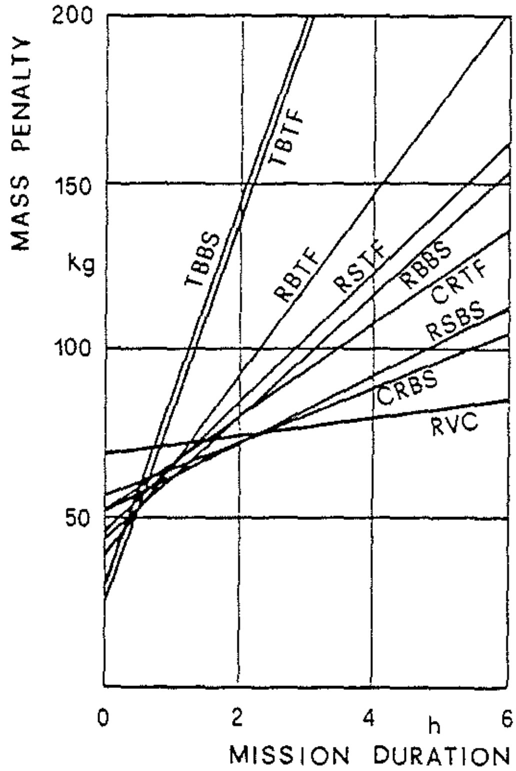

Fig. 16 - Mass Penalty for 12 kW ECS