TWELFTH EUROPEAN ROTORCRAFT FORUM

Paper No. 89

AIR CYCLE ENVIRONMENTAL CONTROL SYSTEM FOR HELICOPTERS: A TRADE-OFF STUDY

A. MANNINI - G. SARRI
MICROTECNICA S.p.A. TORINO - ITALIA

V. MARCHIS
POLITECNICO DI TORINO

September 22 - 25, 1986

Garmish - Partenkirchen
Federal Republic of Germany

Deutsche Gesellschaft fur Luft-und Raumfahrt e.V. (DGLR)
Godesberger Allee 70, D-5300 Bonn 2, F.R.G.

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ABSTRACT

A comparative analysis for Air Cycle Environmental Control Systems for helicopters application has been performed to find out the most suitable configuration depending on the various aircraft's and mission's parameters. The trade-off evaluation has concerned the simple cycle, the bootstrap cycle and the simple/bootstrap cycle.

Assuming as fixed parameters the same performances for the Environmental Control System, which can be summarized as cooling airflow supply temperature and removed thermal load, the choice of one air cycle machine presents some advantages or disadvantages over the other two. This has been underlined in terms of: System Weight Saving, Energy Saving, Overall Dimensions, Reliability, Maintainability.

The study here presented, derives from the experience of **Microtecnica** in all ECS types mentioned before.

Performances and behaviour of the complete Environmental Control Systems (Heat Exchangers, Valves, Water Separators and Pipes) have been simulated by means of a well tested computer program, which has to be considered the ideal test rig for the present study.
The effect of weight and power saving due to the best configuration has been then enhanced by the evaluation of the consequent fuel saving as function of the mission's time.
The impact of reliability and maintainability on the machine estimation has been also investigated.

As sample case, the Environmental Control System for the **EH 101 Agusta/Westland helicopter** has been considered. The result of the trade-off study, for this application, is that the simple/bootstrap system can meet, better than the other ones, the specification requirements.

1. INTRODUCTION

The present paper describes some design procedures performed during the definition of an Environmental Control System (ECS) for application on the **Agusta / Westland** helicopter EH 101, and particularly in the trade-off phase among the various system configurations suitable for application. Optimization of system design involves not only performance criteria, but also component installation, mass, reliability, maintainability, and life cycle costs.
The choice of the "best solution" is often a compromise, in which the experience of the designer plays a fundamental role: the solution appears strongly dependent on design requirements and constraints.

In the case here considered, the attention was focused on an air system . In the example of the paper it was specifically requested by the Customer. He preferred this philosophy against the vapour cycle, for easier installation and higher reliability. Nevertheless, other considerations out of our interest (e.g. coefficient of performance COP and energy saving criteria) could lead to the vapour cycle selection.

A trade-off analysis among various ECS is shown in another paper presented at the Eight European Rotorcraft Form on 1982 (M.Andriano,A. Mannini, V. Marchis - Trade-off Considerations for Environmental Control System on board of helicopters. Paper No. 54).

Even if all computational efforts were done with the aid of a powerful computer package capable of simulating ECS performances in the most various configurations, in the following emphasis is placed not on numerical simulations, but on design and trade-off philosophies here utilized for obtaining the most convenient solution.
Reliability, maintainability, minimum weight and power consumption are the leading guidelines which, in addition to system performances goals, were used in evaluation of scores for the ECS systems in competition.
From the optimization analysis, some general philosophies can be drawn. It must be remarked that the final configuration, which has been determined for the particular case here considered, cannot become a figure suitable of generalization.
Different design "scenarios" obviously need a quite new examination of the problem.

The present work has the main purpose to show a method of design trade-off, illustrating how the various parameters play a role in the design, and how the different, and often inhomogeneous, evaluation scores, have to be taken into account.

2. HELICOPTER ECS

Helicopter Environmental Control Systems are, in certain aspects, basically very similar to those for use on aircraft (civil and military). However the designer during the ECS selection phase, has to take care of some peculiar aspects of the flight envelope of this aircraft, which can affect the final choice.
Power budget on the helicopter is very critical. Power extraction, both as bleed air and as mechanical or electrical power, is strongly penalized. ECS designers have to take into consideration this important aspect, in order to minimize power consumption.

In some flight conditions, like as the hovering, the obvious requirement of the energy and weight saving is the most stringent one. Any extra weight not strictly needed, and any fraction of power not directly used for the lift generation, is a waste of performance.
Various are the differences between helicopter flight characteristics and airplane ones.
All helicopter flight is performed at lower velocity than for airplane. This fact could have a big effect on the selection among the various possible ECS (at fixed performances) and on heat exchangers sizing. Designer cannot now take advantage from the aircraft velocity to obtain dynamic recovery for the air flow generation on the coolant side of the heat exhanger.
The use of fans is mandatory and careful selection is needed in order to optimize system installability and helicopter aerodynamic design (i.e. air intake size), by minimizing both weight and power extraction.

Among the different configurations of air cycle ECS, tipically three are the candidates in a trade-off:

- simple air cycle (turbofan) ECS,
- bootstrap cycle ECS,
- simple/bootstrap cycle (three wheel) ECS.

All these systems have in common a pressurized air supply, bled from engine compressor, an air cooling system performed via compact heat exchangers, and water separator systems for removing condensed water in air after turbine expansion.
As already mentioned, refrigeration of air supplied to cabin is performed by expanding the air flow through a turbine.

In turbofan system (Fig. 1) mechanical power generated by turbine is utilized for driving a fan, which circulates air through cold side of heat exchanger.
On the contrary, bootstrap systems (Fig. 2) use the turbine power for increasing bleed pressure, by means of a compressor. In this case, cooling air flow is induced by an electrically (or hydraulically) driven fan.

Three wheel ECS (Fig. 3) make use of both fan and compressor, which are placed on the same turbine shaft.

General consideration about functioning of these ECS configurations can be summarized as in the following:

- at low bleed pressure turbofan ECS shows low performance figure in comparison with the other two;
- low pressure drop on heat exchanger coolant side means large cross sections and hence higher heat exchanger dimensions and weight;
- efficiencies of turbomachines influence differently overall system performance;
- presence of humidity in air strongly influences system performances;
- systems must adapt itself to different working conditions (flight envelope) without entering in critical functioning (e.g. overspeed);
- control must be performed according stability and confort criteria.

3. A SAMPLE CASE: ECS FOR AGUSTA / WESTLAND EH 101 HELICOPTER

The trade-off study performed for the ECS of EH 101 (which **Microtecnica** is going to supply to **Agusta / Westland**) has been selected as case example.

The aircraft is of conventional single 5 - blade main rotor, single 4 - blade tail rotor configuration, powered by three GENERAL ELECTRIC engines.

Leading characteristics include:

Lenght, rotors turning	22.9 m
Lenght, folded	15.85 m
Main rotor diameter	18.59 m
Tail rotor diameter	4.00 m
Cabin lenght	6.50 m
Cabin width (at floor level)	2.39 m
Cabin height (on centre line)	1.82 m
Weight (maximum)	14200 kg
Disposable load	6599 kg
Speed VNo	157 kts T.A.S. S.L. I.S.A.

EH 101 is designed and developed jointly by Westland and Agusta for Navy use with requirements of large dimensions but also agility appropriate to landing within the confine space of small ships.

It must possess a great endurance and must operate in severe weather conditions. It will be available also in the civil transport version for 30 passengers.
For both versions a cooling capacity of 7.5 kW (sensible heat load) at design point is requested, while the split of the cold air between crew / passengers and avionic compartments will be done according to the specific needs.

A sufficient amount of bleed flow from the engine is available for ECS purpose.

Fig. 4 shows the three views of the helicopter.

4. SYSTEM OPTIMIZATION

Provided that the Customer specification requires an air cycle system, the trade-off study has been performed among the three different philosophies mentioned at Para 2.

In order to achieve an optimal design for each ECS configuration, single component performances have been investigated.
During the preliminary phase, some component characteristics and structures have been assumed to be the same in each configuration. In particular, equal water separators and collectors, equivalent piping, and valves have been used. In addition, in the three systems, two heat exchangers (primary and secondary) with parallel coolant side flows have been installed.

According to these assumptions, parameters to be taken into account in the optimization process are:

- compressor efficiency (if any),
- turbine efficiency,
- fan efficiency (if any),
- primary heat exchanger effectiveness,
- secondary heat exchanger effectiveness,
- flow vs pressure drop characteristic of primary heat-exchanger (cold side),
- flow vs pressure drop characteristic of secondary heat-exchanger (cold side),
- electric fan characteristics (only bootstrap system).

A statistical investigation (cluster search) over operating ranges in the three systems has been adopted as a first guess analysis in finding optimal ranges of design parameters.
The above mentioned design parameters have been assumed to vary (randomly and with uniform frequency) within fixed ranges, according to present state-of-the-art constraints.
System goal has been set in cooling performances, as air temperature entering the cabin, and air mass flow.
In the multi-dimensioned space of design parameters, regions can be identified, where target system performances are achieved.

A special computer program, developed in **Microtecnica** is capable of simulating, in the most various conditions, ECS systems. This program has been used in connection with an optimization program to identify (if any exist) optimal regions.
Typical results are those reported in Fig. 5 where projections of the multi-dimensioned region on 2 variable plane (in our case example, primary and secondary heat exchangers effectiveness) is reported.

Black points indicate where design conditions allow to obtain air temperatures lower than 5°C. In this case, the concentration of the black points in the right side of the diagram, but spread over the vertical axis, shows that the desired system efficiency can be achieved virtually with any value of primary heat exchanger effectiveness, provided that the secondary heat exchanger effectiveness is reasonably high.
Fig. 6, on the other hand, shows a situation where neither the x parameter nor the y one have particular influence on the system result.
The black points, in fact, are spread over the diagram without any concentration.

5. ECS TRADE OFF

By means of the typical optimization procedure previously described, which operates by varying ranges and mean values of design parameters, a preliminary selection among the three systems above mentioned is possible.

For the particular application of the EH 101 helicopter, this leads to exclude the turbofan cycle. Too high performance is requested to turbofan system components (mainly turbine and heat exchanger) in order to achieve the target.
In fact, by focusing our attention on turbine performances (and fixing therefore the other components characteristics to the same average values for the three systems), the analysis shows that efficiency in the turbofan cycle must be about 30% higher than either in bootstrap or three-wheel ones. In particular this leads to a system not feasible (see Fig. 7).

A lower value of turbine efficiency for the turbofan cycle could be sufficient if higher heat exchangers effectiveness is allowed. However the complete problem analysis shows that with the present state-of-the-art components the turbofan cycle is not suitable for this application.

This result has not a general signification, but it depends on the present application for the EH 101 helicopter. It is in particular due to the very low bleed pressure available at the engine ports. It is possible to see that increasing the bleed pressure the difference in performance among the simple cycle and the other two drops until, in same conditions, the turbofan becomes advantageous.
Therefore, from now on the comparative analysis will carried on between the bootstrap and the simple/bootstrap cycle.

By means of parametric analysis performed via " cluster techniques " optimum average values (for the parameters stated in the previous paragraph) have been compared. They allow same performances for the two systems. Results are shown in Table I.

Both Fig. 8 and Table I show the differences of the efficiency values of the same components of simple/bootstrap cycle and bootstrap cycle for the same system results.
From these values it points out that about the same components performances are requested, but the simple/bootstrap cycle needs slightly higher efficiencies (in particular turbine). That is due to the lower pressure ratio available for the turbine that depends on the fact that the turbine work is not used by the compressor only (as in the bootstrap system), but also by the cooling air fan. However the differences are, for this application, very small (less than 5% for the efficiencies and the pressure ratio) and therefore the only large difference between the two systems is the presence or not of the electric fan and related motor.

From the reliability point of view, it shall be noted that ECS system, excluding air cycle machine, is assumed to have a failure rate of 500 failures per million of operating hours (MTBF = 2000 operating hours).
Failure rate drops up to 537 if a simple / bootstrap machine is installed.
On the contrary, failure rate estimated for ECS with bootstrap solution is 582.
MTBF's are 1860 and 1718 hours respectively.

6. SYSTEM EVALUATION

At the present stage of the study, both bootstrap and simple / bootstrap cycles achieve target performances. Therefore the subsequent step is to compare the two systems with reference to their masses, power consumption, installability, reliability and maintainability characteristics.

Table II shows mass and electric power data based on **Microtecnica** experience and other qualified sources.

Mass and power consumption for other components than turbomachines and heat exchangers have been assumed the same. The largest difference is due to the presence of the fan with electric motor in the bootstrap configuration which leads to a penalty in terms of electric absorbed power and mass. The heat exchanger mass in the simple/bootstrap is slightly higher than in the bootstrap; this is due to the slightly higher efficiency required and therefore larger core heat transfert area.

From data of Table II, Table III is derived where system performances and reliability / maintainability data are added.

The simple/bootstrap configuration presents, under the same performances, less mass (4.2 kg), less electric power requirements (3 kW), better reliability and maintainability. Another advantage of the three wheel configuration, which emerges from the installation layout is that it is a more compact assembly.
In fact turbine compressor and fan are mounted on the same shaft. In the bootstrap system there are two separate assemblies; the bootstrap-turbine unit on the same shaft and the fan with electric motor.

That, leading to lower overall dimensions and lower installation problems for the three wheel configuration, fits much better than bootstrap configuration the package philosophy.

7. SYSTEM MASS AND POWER PENALTY EVALUATION

Using the data of the previous paragraph, typical mission profile and helicopter data, total fuel penalty for the bootstrap system due the mass excess and the required power for the electric fan can be calculated.
The fuel excess required is depicted versus mission time in Fig. 9.
For a mission of 2 hours the fuel penalty for the bootstrap system is estimated about **3** kg.
This means that, for the same mission time and with the same fuel consumption, the helicopter with three wheel system could carry an additional weight of **31** kg, that represents the **88%** of the total weight of the three wheel air cycle system.

8. CONCLUSIONS

The results of a trade-off study among various ECS solutions performed by **Microtecnica** for a helicopter have been shown. The aircraft here considered as sample case is **Agusta / Westland** EH 101 helicopter. The guidelines of the trade-off and the conclusions were partially defined by the Customer specification which requires definitely an air cycle system. Therefore our comparison has been performed only among the available air cycles philosophies.

Under these assumptions, it has been demonstrated that a simple / bootstrap cycle is the best choice for this application, because it reaches the same level of performance of a bootstrap, but with lower mass, virtually no electric absorption (therefore extremely lower aircraft penalties), higher installability, maintainability and reliability due to the absence of the fan separately driven.

On the other hand, it should be noted that, while such conclusions of the comparison between a bootstrap and a simple / bootstrap can be generally true, the exclusion of the simple cycle system comes from the specific requirements of this application. In fact, the simple cycle could be the right solution in those cases where the engine bleed pressure and flow are sufficiently high in order to allow the requested cooling performance through the complete flight envelope till to idle conditions.

Some criteria of selection have been here shown and discussed. However, the choice of the system best fitting the requirements of the application comes from the designer's experience and it is of course matter of compromise among various needs to be carefully evaluated case by case.

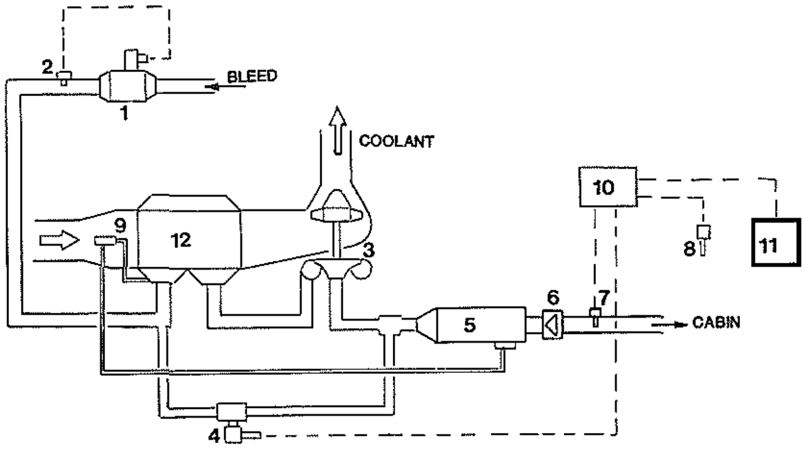

FIG. 1 SIMPLE AIR CYCLE (TURBOFAN)

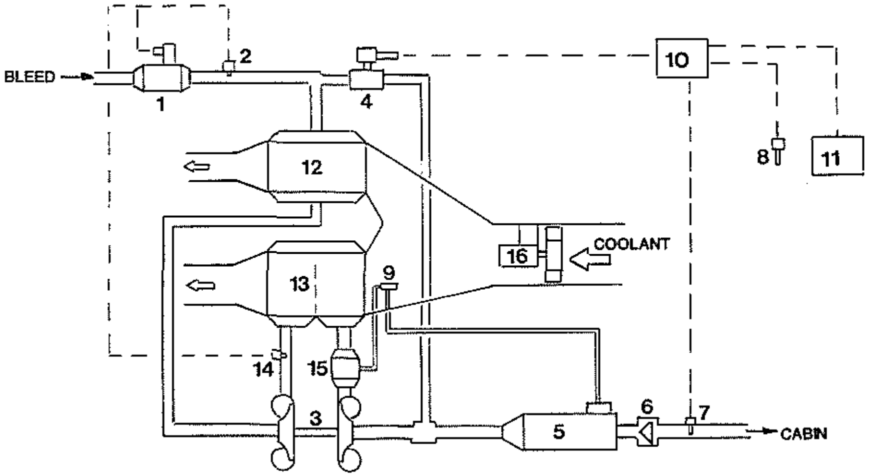

FIG. 2 BOOTSTRAP CYCLE

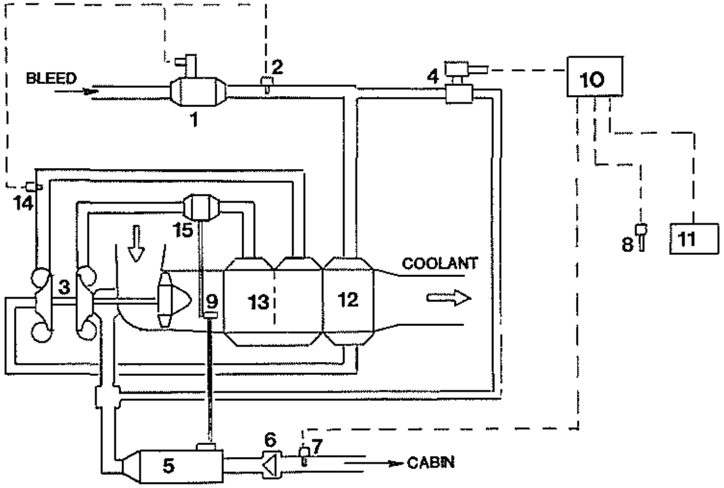

FIG. 3 SIMPLE/BOOTSTRAP CYCLE (THREE WHEEL)

LEGEND

1. Pressure reducing/shutoff valve
2. Overpressure switch
3. Air cycle machine
4. Bypass valve
5. Cabin water separator
6. Non return valve
7. Cabin inlet sensor
8. Cabin outlet sensor
9. Water ejector
10. Temperature controller
11. Temperature selector
12. Heat exchanger (primary)
13. Heat exchanger (secondary)
14. Compressor outlet overtemperature switch
15. Water collector
16. Electric motor and fan

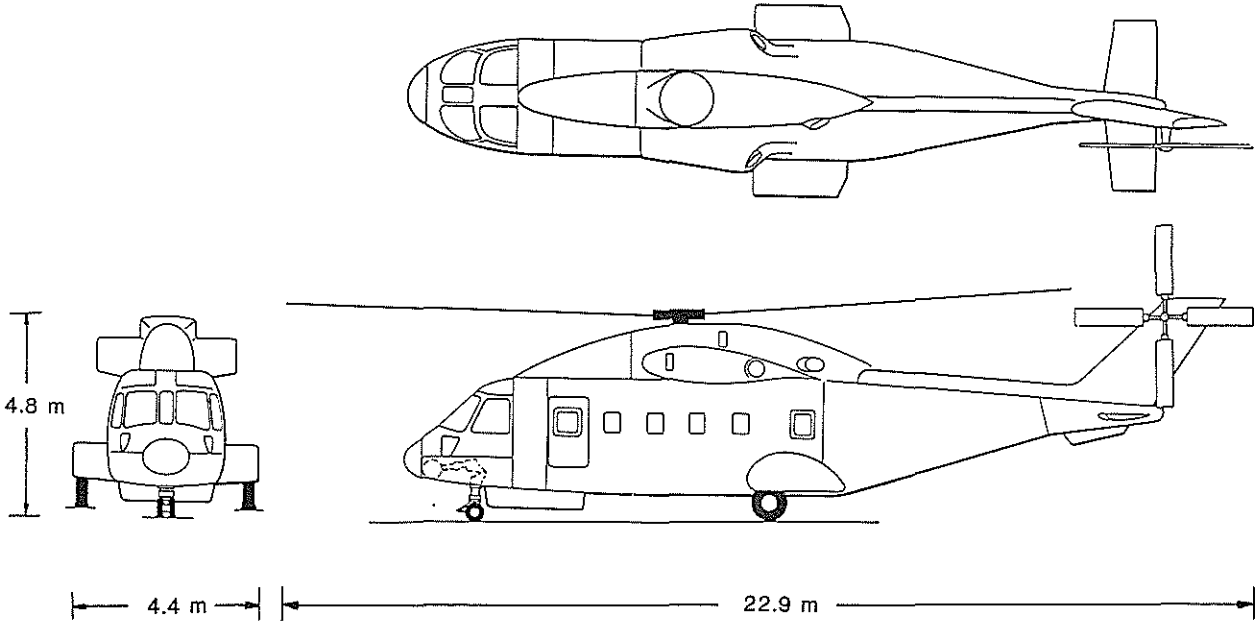

FIG. 4 AGUSTA/WESTLAND EH101 HELICOPTER

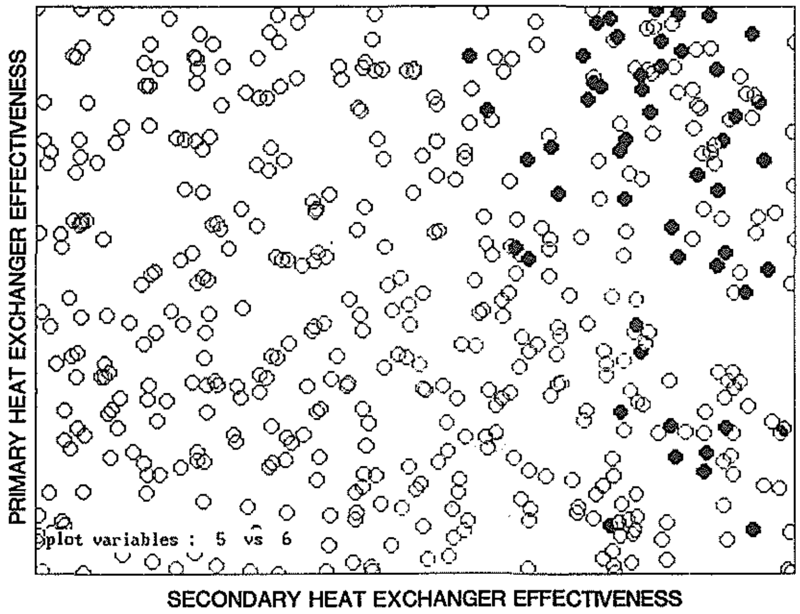

FIG. 5 A TIPICAL "CLUSTER ANALYSIS" RESULT SHOWING THE HIGHER IMPORTANCE OF THE PARAMETER IN ABSCISSA

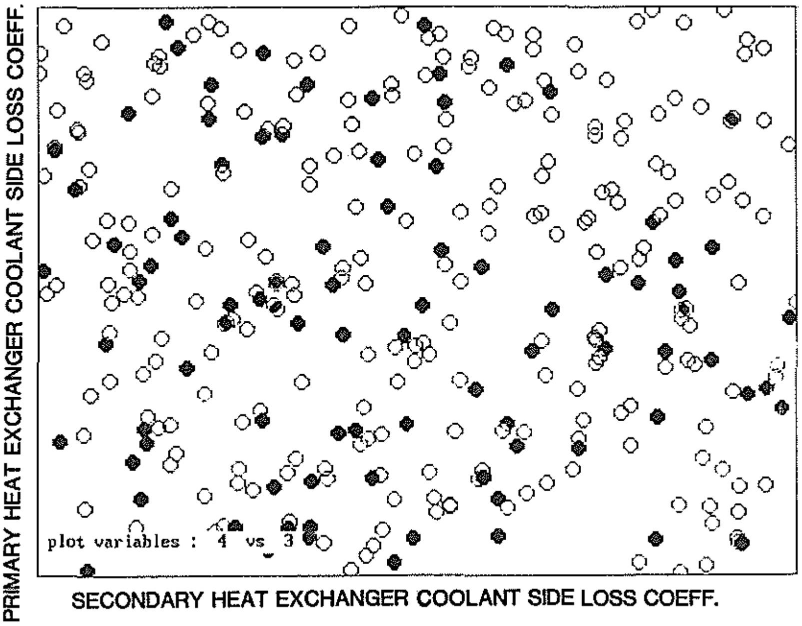

FIG. 6 A TIPICAL "CLUSTER ANALYSIS" SHOWING THAT THE FINAL RESULT IS NOT MAINLY AFFECTED BY JUST ONE PARAMETER

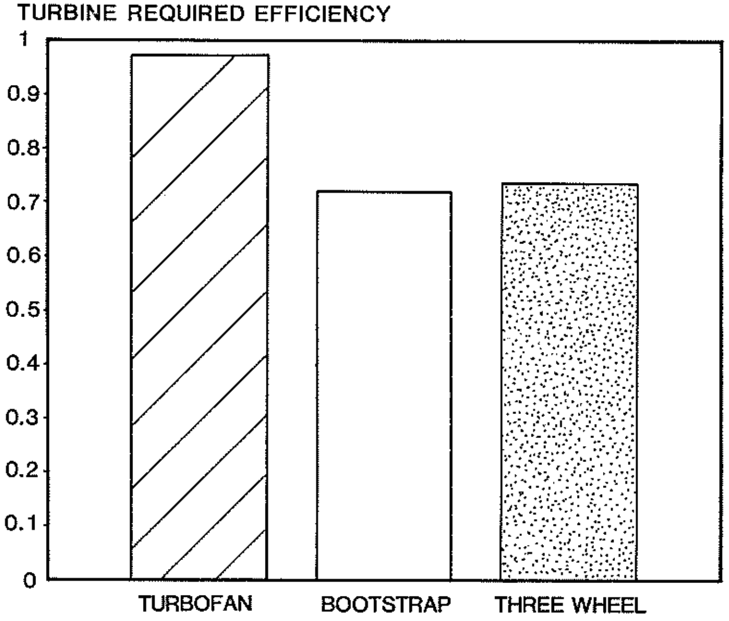

FIG. 7 TURBINE EFFICIENCIES FOR 3 SYSTEM PHILOSOPHIES HAVING THE SAME SYSTEM PERFORMANCES

CONFIGURATION PARAMETERS	BOOTSTRAP SYSTEM	SIMPLE/ BOOTSTRAP SYSTEM
COMPRESSOR EFFICIENCY	0.73	0.75
TURBINE EFFICIENCY	0.79	0.83
FAN EFFICIENCY	0.5	0.5
PRIMARY HEAT EXCHANGER EFFECTIVENESS	0.81	0.83
SECONDARY HEAT EXCHANGER EFFECTIVENESS	0.94	0.95
PRIMARY HEAT EXCHANGER COOLANT SIDE LOSS COEFF.	0.66	0.67
SECONDARY HEAT EXCHANGER COOLANT SIDE LOSS COEFF.	0.49	0.50
ABSORBED ELECTRIC POWER	YES	NO

TABLE I
COMPONENTS EFFICIENCIES LEADING TO THE SAME SYSTEM PERFORMANCES

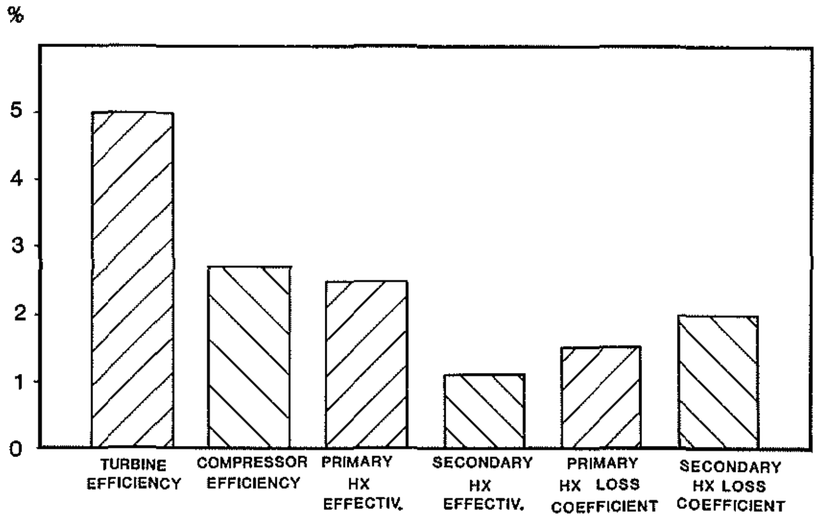

FIG. 8 PERCENTAGE DIFFERENCES BETWEEN COMPONENTS EFFICIENCIES OF 3 WHEEL AND BOOTSTRAP CYCLES HAVING THE SAME SYSTEM PERFORMANCES

CONFIGURATION / PARAMETERS	BOOTSTRAP SYSTEM	SIMPLE/ BOOTSTRAP SYSTEM
AIR CYCLE MACHINE MASS (kg)	7.5	11.1
HEAT EXCHANGERS MASS (kg)	8.5	8.7
WATER SEPARATORS MASS (kg)	3.2	3.2
ELECTRIC MOTOR AND FAN MASS (kg)	8.0	-
OTHER COMPONENTS MASS (kg)	12.3	12.3
ELECTRIC MOTOR AND FAN ABSORBED POWER (kW)	3.0	-
OTHER COMPONENTS ABSORBED POWER (kW)	0.15	0.15

TABLE II
MASS AND POWER EVALUATION

CONFIGURATION PARAMETERS	BOOTSTRAP SYSTEM	SIMPLE/ BOOTSTRAP SYSTEM
SYSTEM COOLING CAPACITY (sensible heat load) (kW)	7.5	
BLEED AIR CONSUMPTION (kg/s)	0.2	
SYSTEM MASS (kg)	39.5	35.3
ELECTRIC POWER CONSUMPTION (kW)	3.15	0.15
MTBF (operating hours)	1718	1860

TABLE III
SYSTEM FIGURES EVALUATION

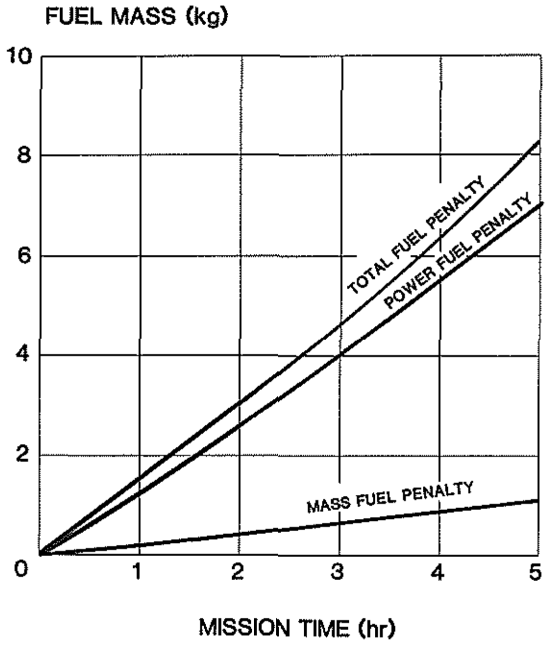

FIG. 9 FUEL PENALTY AS FUNCTION OF MISSION TIME