SAFE, RELIABLE AND ECONOMICAL SUPPLY OF SECONDARY POWER FOR PASSENGERS AND SYSTEMS OF FUTURE COMMERCIAL AIRCRAFT

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Abstract

Secondary power - the term means all required power on board an a/c, which does not serve the immediate purpose of propulsion - is an indispensable value, which must be paid for in terms of fuel consumption. Traditionally the main engines have supplied secondary power in flight.

Recently, ideas have arisen that with increasing bypass ratio the main engines would be more sensitive to bleed air extraction or would not be capable of supplying secondary power any more. It was therefore suggested that the "clean engine" or the "full duty APU" concept would have to be applied or would show advantages.

At Deutsche Aerospace Airbus, a study has been conducted, considering secondary power supply by the full duty APU, by dedicated compressors (for bleed air), or by the main engines.

The findings were:

The main engines are the safest, most reliable, most efficient and most economical source; showing lowest costs, lowest weight, lowest complexity and lowest additional maintenance effort. They are capable of supplying secondary power regardless of the bypass ratio - if designed appropriately.

A recommendation is given not to spend further efforts on the full duty APU, but to optimize the engines for the tasks of supplying both thrust and secondary power.

1. Secondary Power

The term "secondary power" designates that part of the required power, which is provided, transformed and distributed in order to meet the needs of the passengers and aircraft systems. One might call it that very part of power, which does not immediately serve the purpose of propulsion.

The main consumers of secondary power are the passengers (environmental control, cabin pressurization, galleys), the anti-ice system, flight controls and landing gear (hydraulic system), fuel pumps, lights, avionics and main engine start.

The main suppliers of secondary power, on the other hand, are the main engines, the auxiliary power unit (APU) and the ground support, leaving the ram air turbine, the batteries and the pilot's muscles out of consideration as the less important suppliers regarding the power balance.

Secondary power is required in different forms, especially as mechanical power, pneumatic power, and electrical power.

In order to meet the requirements with regard to the different forms of secondary power and to enhance the safety and reliability of the secondary power supply even in cases of failure and to avoid conversion losses as far as practicable - secondary power is distributed in different forms as well, i.e. as mechanical power, pneumatic power, hydraulic power and electrical power.

Secondary power can be transformed into the different modes required by means of generators and motors, pumps, compressors, fans, actuators and turbines.

Finally, however, the supply of secondary power can be traced back to its roots, i.e. the supply of pneumatic power by means of bleed air and the supply of mechanical power in the form of shaft power.

1.1 Different Means of Secondary Power Supply

The traditional way of supplying secondary power is to extract it from the main engines during flight by bleeding the compressor at different tapping ports and taking the shaft power from the high pressure spool. On the ground, with the main engines not running, the APU has been introduced to take over this task in order to be independent of ground support, which is not reliably available at every airport. (1)

The extraction of secondary power from the main engines naturally causes an increase in fuel consumption and/or sacrifices thrust. Since the provision of thrust is the principal task of the main engines, people often are tempted to regard the supply of secondary power as something "disturbing" this principal task, as something in a certain respect "parasitic".

This attitude, however, is not the right approach to the needs of secondary power supply. We need secondary power since the task of our aircraft consists not only of passenger transport, but also of keeping those passengers alive while doing so. That is why secondary power represents an indispensable value in itself and therefore the appropriate price must be paid for it. (2) (There is no such thing as a free lunch). The currency to be paid for secondary power is fuel. This remains true whatever special means for the supply of secondary power might be conceived.

For these reasons the task can only be to provide secondary power in a way, which is safe, reliable and economical simultaneously. Economical means in this respect causing low losses (resulting in low fuel consumption) and going along with low cost of ownership, which, on the other hand, calls for low provisioning effort, low weight and good maintainability for the system.

1.2 New Ideas for Secondary Power Supply

Recently there heve been more and more voices heard stating the concern that with increasing bypass ratio the main engines would be more sensitive to bleed air extraction or even might be unable to fulfil the secondary power requirements at all. That is why ideas arise to relieve the main engines from this task, leading to the "clean engine" concept. (3)

A further impetus for this idea is the fact that the APU is on board all the time, but working on the ground only. So why should such a device be carried constituting dead weight only during flight and doing no job? (4) (5)

Another impetus might be the vague feeling that there should be a clear distinction between different tasks, as there is propulsion on one hand and secondary power generation on the other hand.

2. Study of Optimal Secondary Power Supply

In order not to be dependent of such vague feelings but to find out the most suitable means for safe, reliable and economical supply of secondary power an in-depth study of this topic has been conducted at Deutsche Aerospace Airbus, taking into account three different methods:

1. Provide the secondary power during all flight phases by auxiliary power units (APU) only - the concept of the "full duty APU".

2. Supply the bleed air separately by dedicated compressors driven by shaft power from the main engines.

3. Extract the secondary power from the main engines - the conventional way.

The analysis concerning fuel consumption and losses is based upon flight test data for the A320 with V2500 engines as well as guaranteed performance data received from engine and APU manufacturers. Calculations have been done for a typical mission profile of the A320 with an 800 nautical miles stage length taking into account all flight phases.

The findings of the above mentioned study revealed a very clear favourite out of these three solutions under consideration:

The winner was no. 3, the conventional solution - to extract the secondary power from the main engines. This solution turned out to represent not only the safest and most reliable way but to be most economical as well.

2.1 Aspects of the Full Duty APU

The APU has been introduced to fulfil one (and only one) requirement: To ensure the supply of secondary power on the ground at airports, where the appropriate ground service is not available. That is what today's APUs are designed for and that is how they are mainly used. If - in special cases - they have been used beyond that for minor tasks in flight as for example to relieve the main engines during take off, for main engine relight assistance, for electrical supply in case of generator failure or to supply a limited amount of bleed air during climb in low altitudes while in icing conditions - this has always been a side effect, which by no means influences the APU design.

If, however, we wanted to assign the task of secondary power supply during the whole flight envelope to the APU, we would have to create a totally new and different scenario, which would establish different design criteria and therefore require a completely new APU design.

2.1.1 Design to Requirements

There is one (and only one) advantage for the full duty APU, that is, the APU can be designed in this case exactly to meet the requirements, especially to supply bleed air with just the pressure which is needed. This is an advantage in comparison to the main engines, where the bleed pressure is often too high due to the limited number of tapping ports (causing losses when throttled down).

On the other hand, the whole flight envelope as the mission profile for the full duty APU sets up a very difficult environment with which to cope. The performance capability of any air breathing machine is approximately proportional to the air density. The air density in the A320 ceiling altitude of 39.000 ft, however, runs up to not more than 25% of the density at sea level - or 33%, if including the ram recovery into consideration (see Fig. 1). The required secondary power output, however, is almost independent of the altitude (Fig. 2). Therefore the full duty APU would have to be designed to meet the requirements at ceiling altitude, which would result in oversizing on the ground by a factor of approximately 3 (Fig. 3).

The main engines, by the way, do not have this problem, since they are exposed to different requirements: There is no power requirement (or thrust requirement respectively), which would remain constant with varying altitude. The thrust requirement quite on the contrary is proportional to the air density (since the drag to be overcome by the thrust shows this behaviour), that is why the main engines are very well adapted to their task.

The full duty APU, when you come to think of it, has got even more problems. The bleed air pressure at compressor outlet has to remain approximately constant with variation in altitude. But the inlet static pressure within ceiling altitude amounts to only 19% of the sea level pressure (about 28% taking into account the ram recovery). That means, the bleed air compressor has to cope with a variation in pressure ratio of at least 1:3.5. No compressor at all would be able to do so without varying the compressor shaft speed (resulting in loss of efficiency) and/or variable geometry (adding costs, weight, complexity, failure probability and maintenance effort).

Along with the necessary oversize of the power section as well as the load compressor of the full duty APU, there would be a corresponding weight increase of the APU. Furthermore, with this weight increase there would be a snowball effect, since weight taken from the engine (at the wing) would be put in the fuselage, which means structural weight would increase due to the fact that the weight carried on the wing relieves the structure.

2.1.2 Efficiency

Taking into account fuel consumption, today's APUs by far do not reach the efficiency of main engines, not on the ground (Fig. 4), but more than ever not in flight (Fig. 5), and there is no reason to assume that the full duty APU would perform in a better way. This bad fuel efficiency can be derived from two facts:

1. Small engines usually work less efficiently than large ones do, because the component efficiency as well as the overall efficiency increase with increasing size of the engine (equal level of technology provided).
2. Every engine has a minimum operation idle fuel burn, just to "keep the engine running" (Fig.6).

As a consequence, a number of small engines cannot be more efficient than one large engine doing the same job, or, to put it the other way round, the sizing effect means that an engine designed to provide thrust **and** secondary power works more efficiently than the same engine designed to provide thrust only and more efficiently than an engine that provides secondary power only as well.

Along with the lower fuel efficiency of the full duty APU, there would be an increase in pollutant emissions like CO and NOx.

A further point resulting in even worse efficiency is that APUs traditionally have a very bad intake characteristic, due to the boundary layer of the fuselage.

Another point, which must not be forgotten in this case (though usually disregarded in trade-off studies) is the impulse loss of the power section air as well as the load compressor air. This impulse loss results in an additional parasitic drag, which would have to be coped with by the required thrust accordingly and contributes to additional fuel burn. While doing this job, the engines cause an impulse loss as well, but to begin with, this impulse loss is lower since they require less air to produce the same power due to their better efficiency. Secondly this impulse loss is already allowed for with the thrust balance done by the engine manufacturer.

2.1.3 Safety

With bleed air supplied by an APU (installed in the tailcone) there would be a need for the bleed air ducts to be routed through the pressurized fuselage. In case of duct burst, there would be a sudden gush of hot compressed air (up to 250 °C) into the cabin, which unduely affects safety. This concern does not exist with bleed air tapped from the main engines (wing mounted), since their bleed air ducts are not routed through the pressurized fuselage.

A further point of concern is that due to the unfavourable position of the APU intake, the APU might be prone to the ingestion of drained fluids, which might result in bleed air contamination.

2.1.4 Reliability

Any secondary power system has to maintain at least today's reliability. This means there would be a need for **three** systems redundancy for electrical power generation, **two** systems redundancy for bleed air generation at high altitude (environmental control) and **three** systems redundancy for bleed air generation at low altitudes (anti-ice) as well as **three** systems redundancy for hydraulic power generation. For the bleed air generation for environmental control at high altitudes a triple system would be more convenient as well, since in failure cases the certification rules call for 66% of the normal airflow, which one remaining out of two systems would hardly be able to comply with.

Summing up, it may be said that to fulfil the reliability requirement a **three** systems redundancy would be necessary, i.e. **three** APUs would have to be installed! This on the other hand would mean, not only the APU would have to change its design, the aircraft itself would look different as well (Fig.7).

Notwithstanding that, each APU would have to show at least the reliability of a main engine, which would result in high effort (and high costs eventually) for certification and maintenance. Today's APUs by far do not show this reliability and it is hard to see that this aim might be reached without an extraordinary effort.

But even if this aim were reached, the dispatch reliability of the aircraft would nevertheless decrease considerably, since the failure probability increases with the number of independent units which might be subject to failure. Each of the three full duty APUs would become an essential unit, which means, dispatch would become impossible with only one of these units inoperative.

2.1.5 Maintenance

Each full duty APU would have to be treated and maintained like a main engine. Thus maintenance effort would increase. Furthermore, the maintenance effort would increase once more due to the increase of the hours of operation. Nevertheless, for the same reason, the failure probability would increase, affecting maintenance as well as reliability. The APU would furthermore need earlier replacement. All the above points are cost drivers.

2.1.6 Installation

A set of three APUs would have to be installed somewhere on board the aircraft. Installing them in the tailcone would affect the centre of gravity disadvantageously. Good accessibility would have to be secured, a tailcone installation requiring working platforms to access the APU. Mutual influence would have to be minimized by separate compartments, all these factors driving installation weight.

The bleed air ducts in the wings could not be removed (in order to save weight), but have to remain for engine starting. The APU bleed air lines would have at least to be duplicated for redundancy reasons. The ram air turbine could not be omitted, since the APUs as well as the main engines depend upon fuel supply and therefore might become inoperative due to a common cause. A full duty APU would have to drive hydraulic pumps. Therefore additional (three) hydraulic lines would have to be installed. All these factors are further weight drivers.

2.2 Dedicated Compressors

These compressors - especially designed to fulfil the task of generating bleed air - do not generate shaft power of their own as the full duty APU does, but have to be driven by some external means. It would be conceivable to drive these compressors

1. by electric motors,
2. by hydraulic motors or
3. directly by a shaft driven by the engine gearbox.

(A fourth possibility, to drive these compressors by a turbine, which on the other hand is driven by bleed air from the main engine, need not be considered further, since this procedure obviously causes huge losses and has no advantages. It has been used in the past - with B707 - for other reasons: To keep the bleed air free from oil smell).

The power to drive these compressors therefore has finally to be extracted from the main engines. The only justification to employ such dedicated compressors is consequently the idea of the main engine being able to supply shaft power rather than bleed air. In any case, however, with the transmission of the power from the main engine to the dedicated compressor a transmission loss has to be accepted.

The solutions 1 and 2 - driving these dedicated compressors by electric or hydraulic motors - , however, would cause huge losses due to the two transformations involved (from mechanical power to electrical power - or hydraulic power respectively - by generator or pump and vice versa by motor). Furthermore they would require equipment (motors and generators or pumps respectively), which in this power class is not readily available for use within aircraft. Additionally these solutions would require a totally new design for the electrical power generation and distribution system or the hydraulic system respectively. That is why solutions 1 and 2 have to be rejected.

Solution 3 - driving the dedicated compressors directly by shaft from the engine gearbox - would require an installation close to the engines, i.e. within the engine nacelle for wing mounted engines. This would mean, however, the nacelle drag would increase considerably.

Concerning the operating environment and the resulting oversize, the affected efficiency, impulse loss, reliability and maintenance problems, the above mentioned statements for the full duty APU (para 2.1.1 through 2.1.5) apply accordingly.

Since the main engines are running with speeds which cannot allow for the dedicated compressor needs, there would be a necessity to install a variable gear drive between the engine gearbox and the drive shaft, thus adding weight, costs and complexity, causing additional maintenance effort and decreasing reliability. Additionally a speed up gear would be required to convert the low engine speed to the high compressor speed. Such a gear would add once more a considerable amount of surplus weight.

Summing up, it can be said that dedicated compressors offer almost only disadvantages compared with bleeding the main engines directly.

2.3 Secondary Power from Main Engines

The main engines are the **most reliable** secondary power source. They are the best maintained units on board the aircraft and offer superior reliability. If for any reason during flight the main engines were no longer operative, there would be no need for secondary power generation during glide by the main engines either (the remaining time until landing can be bridged by the ram air turbine and the batteries).

Furthermore the main engines are the **most efficient** source of secondary power and they are the **most economical** bleed air source.

The main engines additionally show the **lowest complexity** with respect to secondary power generation, resulting in **lowest costs, weight** and **maintenance effort**.

Modern high bypass engines have the accessory gearbox mounted on the core, therefore, omitting generator and hydraulic pump would have no effect upon the nacelle size and consequently no effect on the nacelle drag. The engine core might be slightly smaller, if it did not need to produce secondary power, whereas this slightly smaller engine would show an increased specific fuel consumption (sizing effect). The corresponding effect on the fan diameter, however, would be almost negligible. As a result, nacelle drag could not be reduced significantly.

But what about the above mentioned (para 1.2) concern that with increasing bypass ratio the main engines would be more sensitive to bleed air extraction? It is true that with increasing bypass ratio the main engines become more sensitive. This is due to the fact that with increasing bypass ratio the propulsion efficiency increases as well, thus allowing the core mass flow to be reduced accordingly. That, on the other hand, means that a constant amount of bleed air mass flow would total to a higher percentage of core mass flow (Fig. 8).

However, this increased sensitivity will be experienced only if the engine has been designed without making the appropriate allowances for the expected bleed air requirement. This would result in being surprised to see the effect of bleed air offtakes (seen as a disturbing effect then).

A simple chain of reasoning will prove this. The core of the high bypass engine is mainly a shaft power generator. A part of this shaft power could be used to drive a dedicated (engine driven) separate compressor (para 2.2). If we integrated the dedicated compressor into the main engine compressor, however, (Fig. 9), which would mean just to enlarge the compressor diameter by that amount required for bleed air, the effect would be the same..

After all, there is no reason why a high bypass engine designed from the drawing board should not be capable of providing secondary power. Even with high bypass engines air supply can be definitely provided by bleeding the engines, if the appropriate allowances are made during engine design.

The message is, therefore, the engine manufacturers need to be urged to design their engines having in mind the secondary power requirements. Supplying secondary power is one of the tasks of the main engine. Secondary power is one of the required outputs of the main engine (and must not be counted as loss or parasitic when calculating the installed engine efficiency).

There is still a potential for improvement of the main engine bleed system. The bleed air system efficiency can be enhanced by using a multiple tapping system (trading system complexity against efficiency). Furthermore the tapping port losses can be reduced by using a more careful design of the individual port (trying to recover the total pressure instead of the static pressure and avoiding pressure losses caused by flow diversion).

Conclusion

From the three candidates under investigation, capable of supplying secondary power, - the full duty APU, the dedicated compressor and the main engine - one of them, the main engine, was found to be the clear favourite. The main engines offer the safest, the most reliable, most efficient and most economical source. They show the lowest complexity, lowest costs, lowest weight and lowest (additional) maintenance effort.

The recommendation therefore is:

- We should cease to dream of clean engines showing any advantage over the present situation. We should not raise hopes any more to the engine manufacturers that their task might be simplified. We should quite on the contrary urge them to design engines while having in mind the secondary power requirements and optimizing these engines for both tasks: To supply thrust **and** secondary power.

- We should, furthermore, cease to dream of upgrading the APU. We should rather convince the airport people to provide the appropriate ground support in order to abandon those disliked troublemakers.

Acknowledgement

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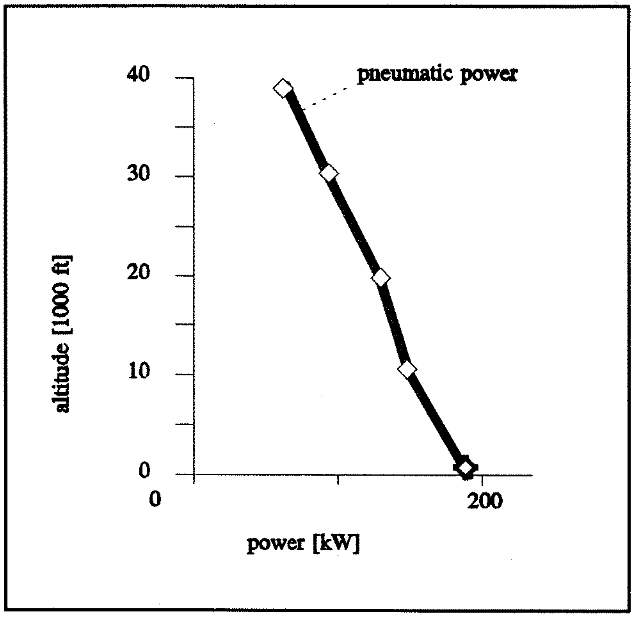

Fig. 1: Performance capability of the A 320 APU as function of altitude

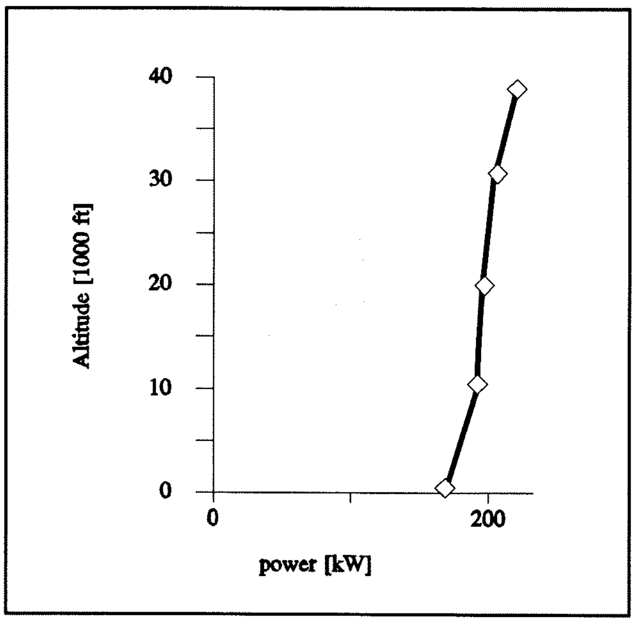

Fig. 2: Power required for A 320 ECS

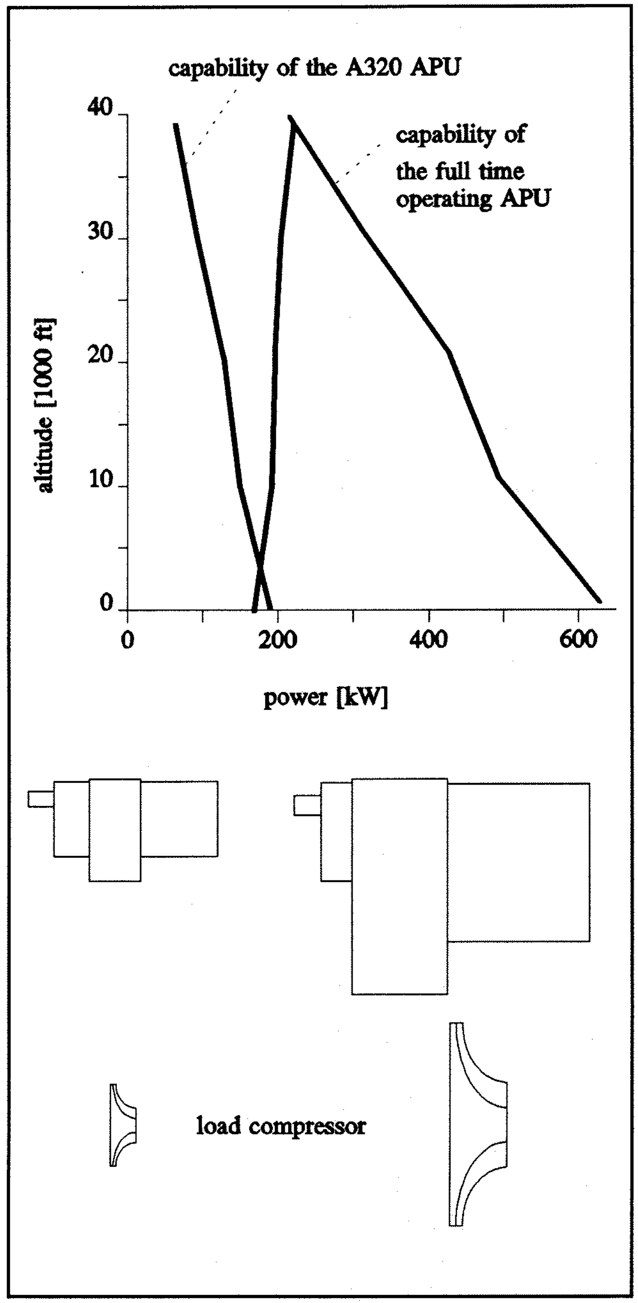

Fig. 3: Oversize of the full duty APU

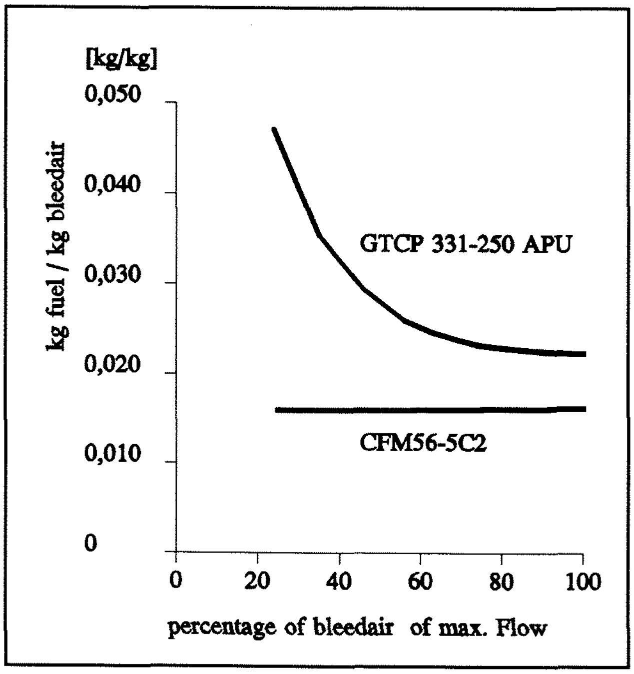

Fig. 4: Fuel consumption for bleed air on the ground (SL)

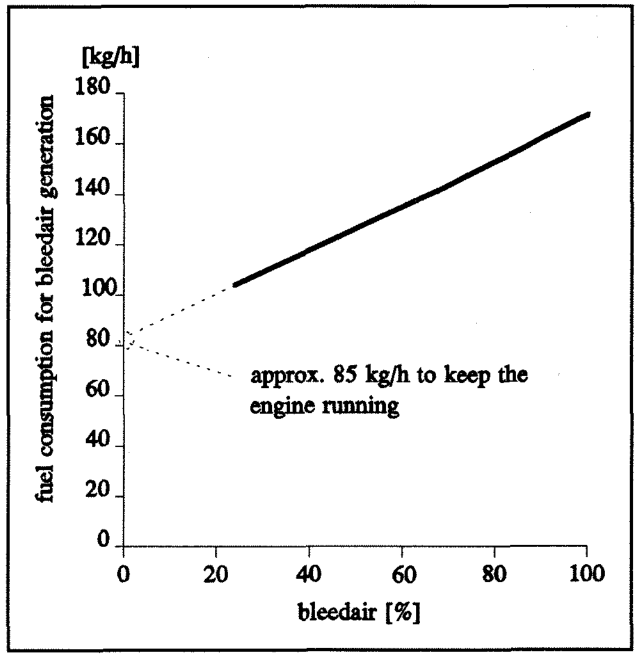

Fig. 6: Fuel consumption for bleed air, SL, A 310 APU

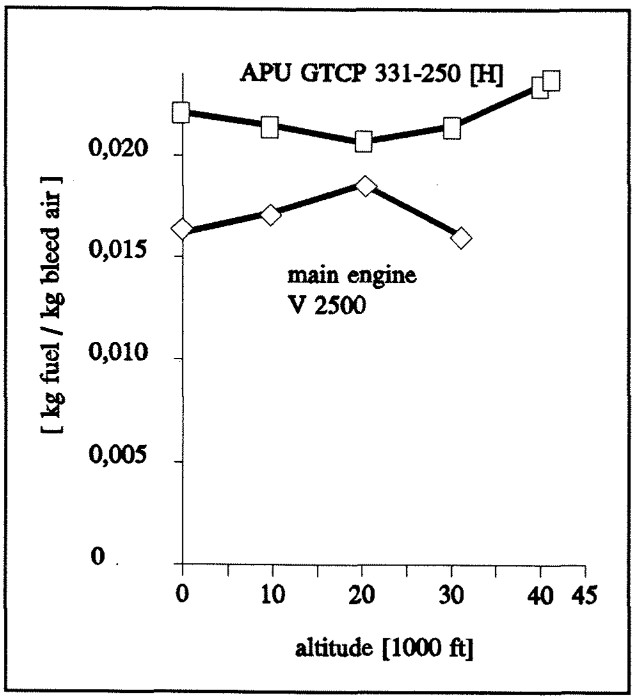

Fig. 5: Fuel consumption for bleed air

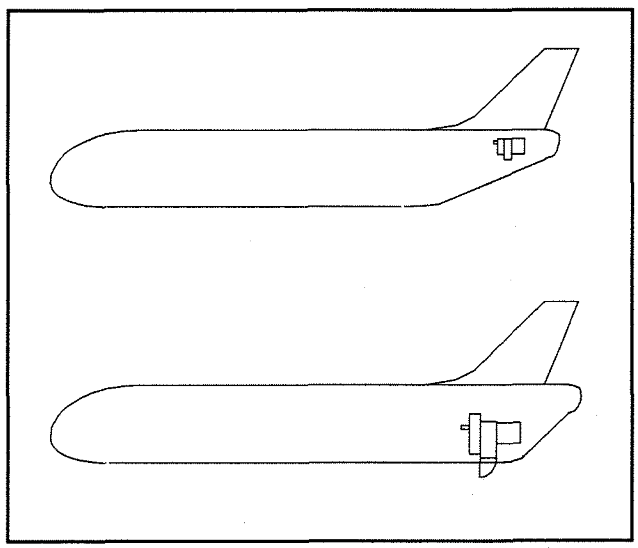

Fig. 7: An aircraft with full time operating APU would look different from today's aircraft

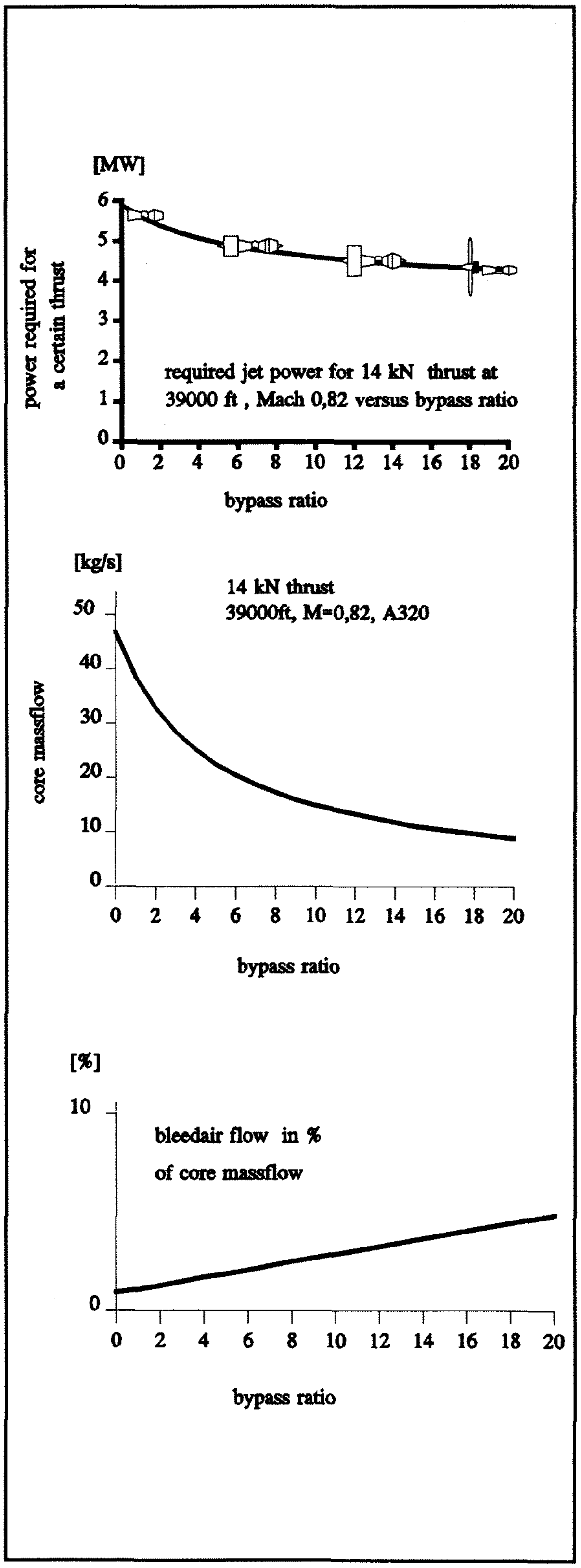

Fig. 8: Bleed air share of core mass flow as function of bypass ratio

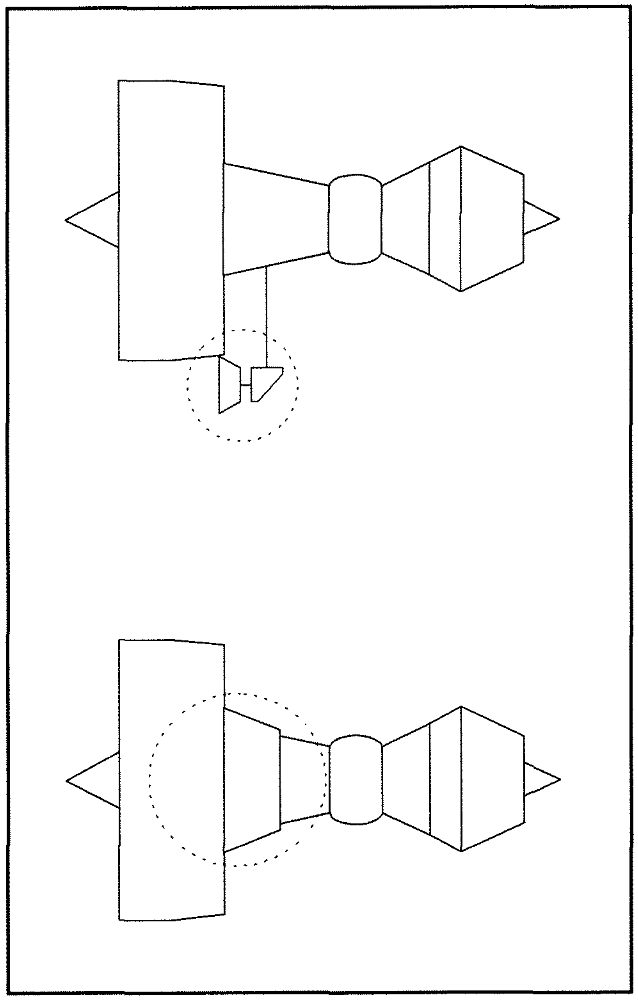

Fig. 9: Integrating the dedicated compressor into the core compressor