SECONDARY ELECTRIC POWER GENERATION
WITH MINIMUM ENGINE BLEED

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In studies conducted throughout the last 20 years, trade-offs in terms of engine power extraction have been common. What then is different about this study

Probably the most important difference is that today economics is a greater factor than ever before. Also, because of the large cost of development the form and characteristics of the benefits are important. Is less fuel burned Is cost lower Is weight lower Do these things counteract each other An erroneous comparison impacts thousands and millions of dollars, and so the purpose of this study is an overall, comprehensive analysis that answers two questions:

(1) If you had to build a system today, what would be the nature of that system?

(2) What would be the cost, performance, and weight?

The engine probably has the most significant effect on the selection of a secondary power system. Most of the electrical system development in the last few years has been an attempt to make the system better. Another approach is to question the trend to eliminate the use of bleed systems.

New energy-efficient engines will have

(1) Higher turbine inlet temperatures

(2) Higher bypass ratios

(3) Higher pressure ratios

(4) Lower core airflows

(5) Less available bleed air

The main effects of engines, apart from their technical characteristics, are that there is less core flow and less bleed air available. Thus, from a pragmatic standpoint, whether or not you want to change the secondary power system, you may be forced to change it.

Figure 1 shows a comparison of two typical engines and airplane systems. A typical engine for the Boeing 767, with a 12-percent nominal limit provides, for an idle descent condition at 22 000 ft and Mach 0.55, which is also typical of a holding condition, a bleed flow of about 3.6 lb/sec. This is sufficient to provide air for refrigeration and pressurization. If air is also required for cowl and wing anti-icing, the amount of air required would exceed what the engine supplies within its nominal limits. This problem was solved operationally by increasing the thrust during these conditions to provide the necessary pressure and flow. This is basically the current status.

The type of energy-efficient engine that would be used on a 1988 airplane, for a typical 150-passenger baseline, would have a nominal limit of around 9 percent. Because of the small core airflow it would provide much less bleed flow than required for refrigeration, pressurization, and cowl and wing anti-icing. On that particular airplane Boeing has already chosen an alternative for hot-air anti-icing of the wing. For pressurization and cooling and cowl anti-icing there is a wider gap to fill in terms of increasing engine thrust. With an even more advanced energy-efficient engine, to be used on a 150-passenger airplane in 1995, there may even be problems in meeting the

requirement for environmental control alone. Therefore apart from an electrical system development advantage, from a pragmatic standpoint, we may be forced to abandon bleed systems, either in whole or in part.

This then was the motivation for a study (fig. 2) to address the engine, which is the basic source of power, both primary and secondary. First, the three engine manufacturers were asked to what extent they could rematch the engine, that is, make it smaller and more efficient, with no engine bleed at all. Next, an airplane configuration and a secondary power system were selected as a total system that could be built with current technology and would meet not only the basic requirements, but all of the failure conditions. Also, in selecting a two-engine airplane, the problems of system redundancy, failure conditions, and all of the operational requirements were addressed as well. We then put together a study that would provide an initial estimate of weight, performance, and cost, within the scope of secondary power generation. The study will address these issues and concerns:

    (1) Engine starting
    (2) Electric power generation
    (3) Power controllers
    (4) Power distribution
    (5) Ground power
    (6) Auxiliary power unit (APU)
    (7) Airconditioning
    (8) Cowl and wing anti-icing

In this study, the role of the APU had to be evaluated very carefully. The APU, of course, originally was a flying piece of ground support equipment used to provide independent capability for starting and ground cooling as well as some ground electric power. Later the APU was used to provide in-flight power. So in any cost-performance trade, it was necessary to sort out the role of the APU in terms of its ground functions and its in-flight functions. Throughout this study all of the penalties and benefits related to the APU are based on its in-flight function only.

The purpose of this study was not only to get technical results, but also to indicate direction - where we should be putting our money and where the next logical step for equipment development would be. Those who know the Boeing approach know that we are not only interested in what the right analysis numbers are. For any piece of equipment to be put into inventory, either commercial or military, we need to test the systems on an airplane. Therefore we rely on hardware development, "ironbird" testing, and flight testing on at least a component and subsystem basis. For this we need direction as to where to put our emphasis.

The study involved putting together a task team. We not only had systems experts, but we brought in configuration, system installation, aerodynamics, weight, product assurance, and finance specialists. This study was a model of a very comprehensive analysis not only to identify systems but to evaluate them.

One of the major problems in a customer-client relationship is that the client, in this case the engine manufacturers, will try to satisfy what they perceive as the customer's requirements. Thus it was very important, in our study, to point out that we wanted to know the best answer in terms of power extraction - whether or not to bleed the engine. We also wanted to get a good data base on which to evaluate an advanced-bleed system. That was the purpose of these particular simulations - to get a good engine performance deck that would allow us to bleed air from any port from an optimum standpoint and therefore provide the best possible bleed system and compare it with a good minimum-bleed system.

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The next step was to select a go representative airplane. Of course, it makes quite a difference whether it : a two-, three-, or four-engine airplane and whether it is a short or a long-range airplane. With the preponderance of short and intermediate-range airplanes today, we selected a two-engine, short-haul airplane as representative for the present and near future. The last objective was to meet all of the dispatch and operational requirements, both from a FAA and a customer standpoint.

Figure 3 shows the general arrangement of the airplane that was used in the study.

Any study that will be accepted by management has to have a very credible data base. The data base used in this study was a two-port bleed baseline (the 767 airplane). Because of the detailed weights and good definition available for that system, the task team used this particular configuration as the data base. This was not necessarily our configuration baseline, but it was our data base. Table I shows the systems that were varied in the study. As a secondary trade-off minimum bleed was figured with and without an APU, but the basic overall study did include an APU.

One of the criticisms of most studies is that an old airplane is used for a particular set of conditions and compared with another airplane under a new set of conditions. In this particular study we took the data base and then put together an advanced bleed system so that in comparing it with the minimum-bleed system we were comparing comparable technology. We did not include in the study advantages that would be applied in one set of conditions and not in the other.

As shown in table I the advanced-bleed system had a conventional constant-speed drive (CSD) and 75-kVA generators. The minimum-bleed system with an APU had one 160-kVA system per engine; without an APU two generators were used on each engine to meet the failure and power-out conditions. The minimum-bleed systems also had an electric starter-generator system. Two factors were held constant in the study: (1) hot-air cowl anti-icing and (2) the hydraulic and flight control system. At present, we do not have confidence in an alternative to cowl anti-icing other than hot air. There are a lot of developments going on and we would be glad to change our position in the near future. But for the sake of this study, we stayed with the hot-air cowl anti-icing system.

Details of the secondary electric power generation system with and without an APU are given in figures 4 and 5. The system with an APU (fig. 4) had one generator on each engine and another generator on the APU. Two electric-driven compressors provided the air for environmental control. The APU was the third air source in case of failure. Power controllers controlled both the starter-generator function and the power of the environmental control system (ECS). Without the APU (fig. 5) another way must be provided to get the third power source. Two generators were used on each engine and a third electric-driven compressor was provided in lieu of the air provided by the APU. This arrangement required an extra set of power controllers.

The system with no APU involved a great many switches. If it were not for the failure conditions, all of those switches could be eliminated. What distinguishes this study from simple weight or energy trade-offs is that it addresses all of the failure conditions.

The advanced-bleed system is compared with the minimum-bleed system in table II. The weight of the starting system decreased from 180 lb for the advanced system to about 10 lb for the minimum-bleed system, and the weight of the pneumatic system, which involves the precooler, the bleed valves, and providing for switchover during engine-out, decreased from 640 lb to 70 lb.

Eliminating the pneumatic engine start and bleed system led to weight savings but adding the starter-generators, of course, increased the weight again. The difference in APU weight had to do with the increased size of the generator for the APU. The net result was a 700-lb weight increase for the minimum-bleed system over the advanced-bleed system.

Table III shows the effect on performance without resizing the airplane. For a basic engine selection the change in the lift-drag ratio is small, but there is a significant reduction in specific fuel consumption for the minimum-bleed systems.

Our environmental control studies kept track of the air required to supply the engine-driven compressors and compared it with the effect of not bleeding the engines. The diagram on the left of figure 6 shows the results of this study as compared with the baseline. The diagram on the right shows the relative effect between the advanced-bleed system and the minimum-bleed system. Both, of course, have extremely low drag; it can hardly be measured. But, for the purists, there is a slight advantage to the advanced-bleed system. Both have less drag than current baseline systems.

An overall performance comparison on a resized airplane is shown in table IV. There is a significant increase percentage-wise in block fuel saving, even though the total numbers do not vary much. The main advantage is that less fuel is burned with the minimum-bleed system than with the advanced-bleed system.

One of the factors that bears on the subject is what a typical block time or block range is. From our 737 experience, the typical block range is a little less than 300 nautical miles. A 727, which is nominally a 2000-nautical-mile-range airplane, has an average block range of less than 400 nautical miles. Between 300 and 500 nautical miles is a typical block range for this size of airplane.

Cost is the most difficult parameter to evaluate from a supplier's, an engine manufacturer's, an airframe contractor's, and an airline's standpoints. The parameters may all be the same, but the significance of the parameters differs. Therefore we chose to evaluate the cost of ownership relative to an airline customer. We have through the years developed a cost model that may not be precise but is fairly accurate in terms of relative comparison. This basically is the model that we used.

The model is based on
(1) Airline fleet service period of 15 yr, 1986 to 2000
(2) Thirty-airplane-fleet nonrecurring cost, prorated to 300-airplane minimum production
(3) 3000 Flight-hours per year, per aircraft
(4) Depreciation schedule, 10 yr
(5) Investment tax credit, 10 percent
(6) Corporate income tax, 48 percent
(7) Annual inflation rate, 7 percent for labor and materials
(8) Current dollars, after taxes
(9) Spares level, 6 percent for equipment, 30 percent for APU

This model (fig. 7) shows that the total cost of ownership consists of investment costs, operating costs, flight operation, and tax adjustments. For this study we included all of the factors that are indicated with solid bullets. The factors indicated with open bullets are in the model but were not included in the study.

Figure 8 shows the difference in cost of ownership between a minimum-bleed system and an advanced-bleed system as compared with the current baseline, namely the 767 two-port bleed system. For the 300- to 500-nautical-mile

range the difference is $3 million to $4 million per year. This is approximately half the saving achieved by the recent decision to go from a three to a two-man crew. The comparison with and without an APU shows benefits that are even larger. The relative comparisons for a 1500-nautical-mile range are much less. However, this particular airplane is not designed to operate at that range most of the time.

Another factor in a cost comparison is increasing fuel price. How do you evaluate the change in fuel price and what effect does it have on the relative comparison between the systems   From 1972 to 1982 the increase in fuel price was dramatic; in the last two years the price was more stable. Figure 9 compares an advanced-bleed system with two minimum-bleed systems, both with and without an APU. The left line represents the stable fuel price period of 1980 to 1982; the right line represents the unstable period of 1972 to 1982. Even though the absolute numbers change between the lines, the relative difference between the systems is about the same.

In summary, we took an in-depth conservative approach to the technical data. In all of our weight comparisons and in all of our equipment selections, we did not guess what the potential would be 5 or 10 years from now. We took existing technology and weighed the systems and costed the systems as they exist so as not to inflate the study in favor of the minimum-bleed system. The other technical results are as we have just gone over. Operating weight increased, but block fuel and cost of ownership decreased.

Table V takes these comparisons and addresses our current system in terms of a future developed system. In spite of the 700-lb weight increase, we believe comparable weight between an advanced-bleed system and a minimum-bleed system can be achieved for this type of airplane. The block fuel was less and, as the weight came down, the fuel burned would, of course, be further reduced. From a relative standpoint, we still kept it in the same general category as being less. The significant parameter, however, would be cost. The cost of ownership currently is less, but it would be much less for the developed system, especially the cost of new equipment as well as the fuel and operating costs.

In terms of direction, the switching in the secondary electric power generation system (fig. 5) can be significantly simplified. Subsystem trade-offs, especially in the environmental control system, be it air-cycle or vapor-cycle, can be significantly improved. The role of the APU is always an interesting one. Although it is a high-cost item, airlines need self-sufficiency. So we are going to conduct some studies relative to APU uses and the better way of integrating the APU into an all-electric system.

Engine selection and optimization turned out to be a very critical factor in our study. Eliminating wing anti-icing resulted in a 7-percent reduction in engine size. Therefore a key factor, both from an airframe and engine standpoint, is that there probably is a greater penalty for mismatching the engine with the airplane than was apparent in the past. And that disparity is even more pertinent today.

In terms of activities, there already has been a fair amount of work done with starter-generators. A program just being completed at the General Electric Co. in Lynn, Mass., has been very successful. We have got quite a bit of development work in power controllers and in electric-driven compressors, and the work being done with alternatives to hot-air anti-icing for both wing and cowl is especially pertinent to Lewis.

Going back to the integration with other systems, needless to say, this study was of limited scope. It only addressed one part of secondary power; a study needs to be done from an overall systems standpoint. We need to include

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the power distribution system and all of the synergistic benefits that can be achieved by pulling these systems together. One of the main advantages, over and above the technical results of the study, was that we developed expertise. Our task team arrangement, our ability to put all of the parameters in model form and evaluate different airplane, engine, and system combinations, was successful. We feel that we are in a good position to take the next step.

TABLE I. STUDY CONFIGURATIONS

SYSTEM	2-PORT BLEED BASELINE	ADVANCED BLEED	MINIMUM BLEED WITH APU	MINIMUM BLEED WITHOUT APU
ENGINE GENERATORS	1-75 kVA GENERATOR/ ENGINE	SAME AS BASELINE	1-160 kVA GENERATOR/ ENGINE	2-120 kVA GENERATOR/ ENGINE
CSD's	1-CSD/ENGINE		–	–
APU GENERATOR	1-75 kVA GENERATOR/APU		1-160 kVA GENERATOR/APU	–
ELECTRIC DISTRIBUTION	400 Hz		HYBRID (400 Hz + WILD FREQUENCY)	HYBRID
AIR SOURCE	2-PORT BLEED	3-PORT BLEED	2 ELECTRIC-DRIVEN COMPRESSORS	3 ELECTRIC DRIVEN COMPRESSORS
COWL ANTI-ICING	HOT AIR	HOT AIR	HOT AIR	HOT AIR
WING ANTI-ICING	HOT AIR	FLUID	FLUID	FLUID
ENGINE STARTING	PNEUMATIC	SAME AS BASELINE	ELECTRIC START	ELECTRIC START
APU	YES WITH AIR SOURCE	SAME AS BASELINE	YES WITH AIR SOURCE	DELETED
HYDRAULICS	STANDARD	SAME AS BASELINE	SAME AS BASELINE	SAME AS BASELINE

TABLE II. - FUNCTIONAL GROUP WEIGHT SUMMARY

Affected functional groups	Baseline bleed (lb)	Advanced bleed (lb)	Minimum bleed with APU (lb)	Minimum bleed without APU (lb)
Vertical tail	850	770	770	770
Body	17,650	17,650	17,650	17,450
Nacelle and strut	2,810	2,660	2,600	2,630
Engine	9,790	9,400	9,400	9,400
Starting system	180	180	10	10
Pneumatics	670	640	70	70
Electrical	1,910	1,910	2,790	3,510
Air-conditioning	1,710	1,710	2,110	2,290
Anti-icing	240	320	320	320
APU	1,150	1,150	1,370	–
OEW (reference)	84,930	84,360	85,060	84,420
Δ OEW	Base	-570	+130	-510
		Base	+700	+60

TABLE III. - RELATIVE PERFORMANCE-DEPENDENT CHARACTERISTICS

| | Δ OEW | Average cruise | | Climb |
		Δ (L/D)	Δ SFC	Δ (T/W)
Baseline bleed	Base	Base	Base	Base
Advanced bleed	-0.79%	+0.18%	-0.17%	-1.91%
Minimum bleed with APU	+0.34%	-0.02%	-0.68%	0%
Minimum bleed without APU	-0.41%	-0.10%	-0.68%	+0.55%

TABLE IV. - PERFORMANCE SUMMARY COMPARISON
[Range, 0530 n mi; altitude, 35 000 to 39 000 ft;
step cruise at Mach 0.75; payload, 30 800 lb.]

| | Baseline bleed | Advanced bleed | Minimum bleed | |
			With APU	Without APU
Taxi weight, lb	142,086	141,242	142,160	141,330
TOGW, lb	141,900	141,056	141,920	141,144
OEW, lb	84,930	84,260	85,220	84,580
Fuel load, lb	26,352	26,182	26,086	25,950
TSLS, lb	24,300	23,300	23,300	23,300
T/W	0.34	0.33	0.33	0.33
Block time (1530 nmi), hr	4.046	4.049	4.042	4.042
Block fuel (1530 nmi), lb	18,673	18,608	18,525	18,420
Block fuel (500 nmi), lb	6,986	6,922	6,857	6,829
Block fuel (300 nmi), lb	4,875	4,821	4,763	4,745
% change block fuel (1530 nmi)	Base	-0.35	-0.79	-1.35
% change block fuel (500 nmi)	Base	-0.92	-1.85	-2.25
% change block fuel (300 nmi)	Base	-1.11	-2.30	-2.67

TABLE V. - CONCLUSIONS AND RECOMMENDATIONS

Results Comparison

	CURRENT	DEVELOPED
WEIGHT	HIGHER	EQUAL
BLOCK FUEL	LESS	LESS
COST OF OWNERSHIP	LESS	MUCH LESS

Direction

STUDIES	ACTIVITIES
● SYSTEM IMPROVEMENTS 　● SIMPLIFICATION 　● SUBSYSTEM TRADES ● APU USE AND ALTERNATIVES ● INTEGRATION WITH OTHER SYSTEMS ● ENGINE SELECTION AND OPTIMIZATION	● STARTER/GENERATORS ● POWER CONTROLLERS ● ELECTRIC DRIVEN ECS ● COWL AND WING ANTI-ICING

Figure 1. - Bleed availability versus environmental control system and anti-icing requirements.
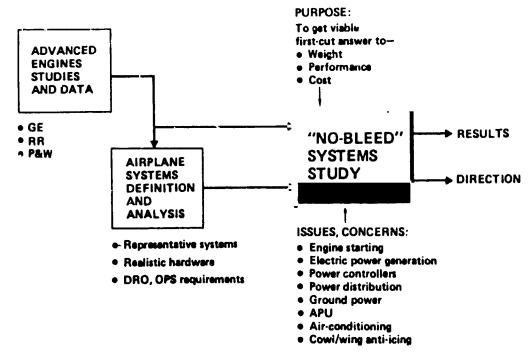

Figure 2. - Study plan.

Wing area = 1,500 ft^2
Wing AR = 8.56
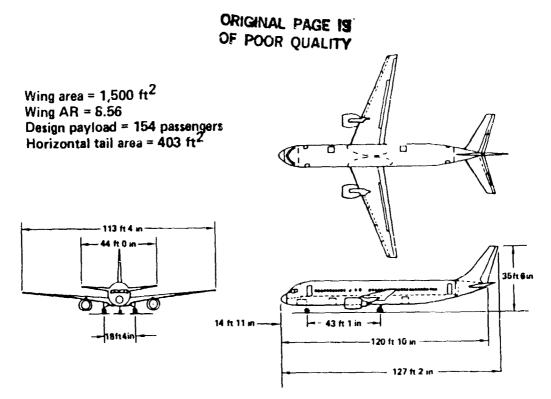Design payload = 154 passengers
Horizontal tail area = 403 ft^2

Figure 3. - General arrangement of airplane used in study.
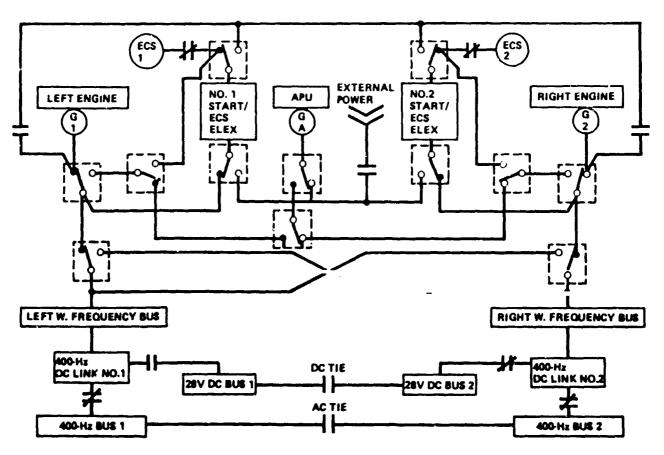

Figure 4. - Electric power system - with APU.

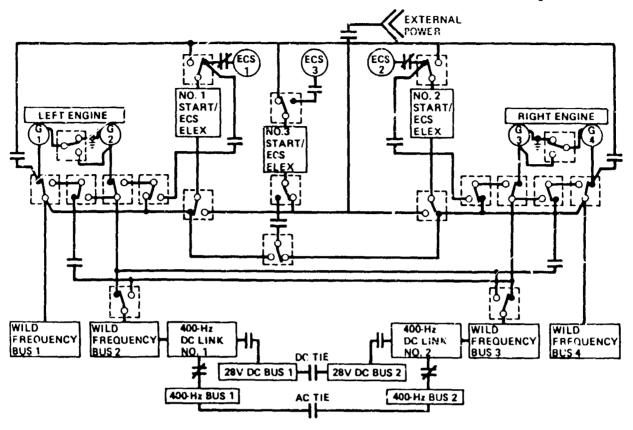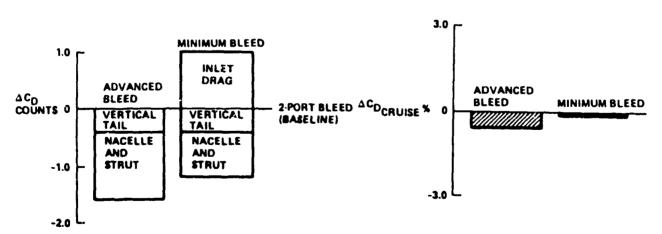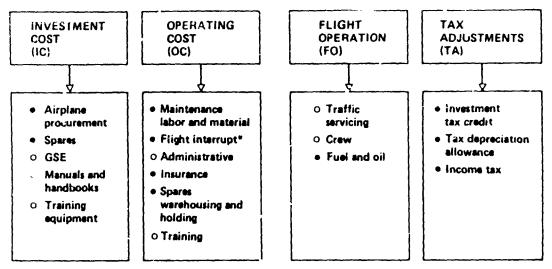Figure 5. - Electric power system - without APU.

1 COUNT = 0.0001

Figure 6. - Drag summary.

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INVESTMENT COST (IC)	OPERATING COST (OC)	FLIGHT OPERATION (FO)	TAX ADJUSTMENTS (TA)
• Airplane procurement • Spares ○ GSE 、Manuals and handbooks ○ Training equipment	• Maintenance labor and material • Flight interrupt* ○ Administrative • Insurance • Spares warehousing and holding ○ Training	○ Traffic servicing ○ Crew • Fuel and oil	• Investment tax credit • Tax depreciation allowance • Income tax

*Partial for delay and cancellation.
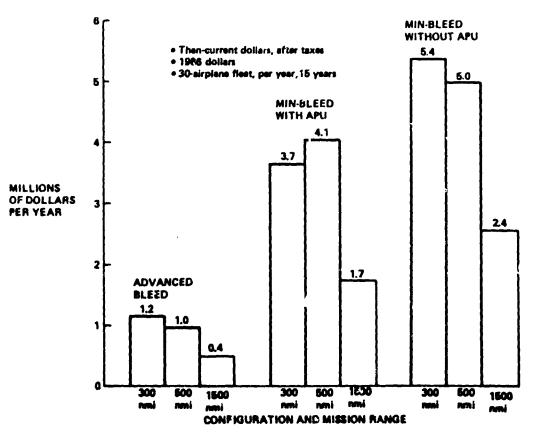
Figure 7. - Total cost of ownership.

Figure 8. - Difference in cost of ownership between a minimum-bleed system, an advanced-bleed system, and the current baseline.
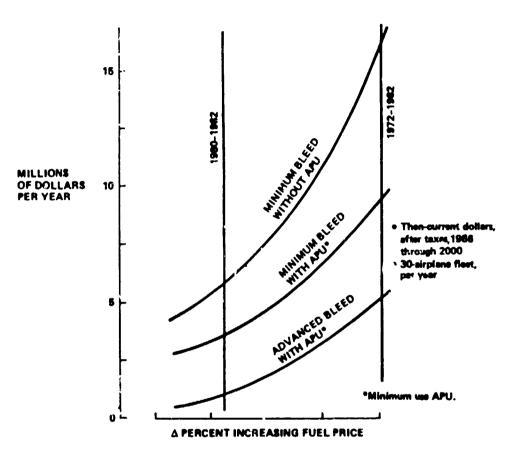
Figure 9. - Cost of ownership for the three systems as a function of fuel
price.