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A PRELIMINARY STUDY OF THE USE OF INTERCOOLING AND REHEAT IN CONJUNCTION WITH REGENERATION FOR AIRCRAFT TURBINE ENGINES

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16. Abstract

A study was made to evaluate the effect on fuel consumption of turbofans with intercooled, regenerative cycles and with intercooled, regenerative, reheated cycles. The technology level for both engine and aircraft was that projected for 1985. The simulated mission was a 5556 km (3000 n mi) flight carrying 200 passengers at Mach 0.8 at 11 582 min (38 000 ft). Results indicate that these relatively complex cycles offer little, if any, fuel savings potential relative to a conventional turbofan cycle of comparable advanced technology. The intercooled, regenerative cycle yields about the same fuel economy as a conventional cycle at close to the same overall pressure ratio. Adding reheat to the intercooled regenerative cycle only makes matters worse by yielding still poorer fuel economy.

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SUMMARY

A study was made to evaluate the effect on aircraft fuel consumption of the use of intercooled, regenerative turbofans and intercooled, regenerative turbofans with reheat.

The figure of merit was fuel consumption, although gross weight calculations and some DOC comparisons were made. The level of technology assumed was that projected for 1985. The engines were evaluated in an advanced, 200 passenger, Mach 0.8, four-engined aircraft flying 5556 km (3000 n. mi.) at a cruise altitude of 11 582 m (38 000 ft). The aircraft was also assumed to have the structural and aerodynamic technological level projected for a craft to be flying in 1985.

A range of overall pressure ratios, turbine inlet temperatures and bypass ratios were examined with an assumed heat exchanger effectiveness and with assumed pressure losses in the heat exchangers. An optimum cycle was determined.

The effects of technological level of turbine cooling, heat exchanger effectiveness variation, and variation in pressure losses in the heat exchangers were also examined.

Although the use of both of these cycles resulted in fuel consumption lower than that of current engines (also evaluated on an advanced aircraft), neither of these cycles proved superior to an advanced conventional turbofan with similar 1985 level of technology assumptions.

The optimum intercooled regenerative cycle, that with the lowest fuel consumption, with the assumed 1985 level of turbine cooling, had a 40 overall pressure ratio and a turbine inlet temperature of 1778 K (3200 °R). This cycle with optimistic pressure losses in the heat exchangers, optimistic effectiveness values of the heat exchangers and optimistic engine volume and engine weight penalties reduced fuel consumption by 15% from current engines. However, an advanced conventional turbofan with an overall pressure ratio of 45 and the same 1778 K (3200 °R) turbine inlet temperature also reduced fuel consumption by 15%. The cycle with reheat, intercooling and regeneration saved less fuel than the similar cycle without reheat due to additional cooling requirements of the low pressure turbine.

STAR category 07

INTRODUCTION

The consumption of fuel by civil aircraft in the United States accounts for about 4% of the oil consumed by this country (ref. 1). Further, the FAA predicts that by 1984 the increase in revenue-passenger miles will increase this fuel usage by an additional 50% (ref. 2). Because of this projected increase of civil aircraft activity and because of the world petroleum shortage, there is considerable effort being made to find ways to reduce fuel consumption. In ref. 3 and 4 advanced technologies and reoptimized cycle parameters (higher overall pressure ratios, bypass ratios and turbine inlet temperatures) were applied to otherwise conventional turbofans. It was found that aircraft fuel consumption could be reduced about 15% by such an approach.

Less conventional approaches have also been considered. For example the use of regeneration was studied in references 5, 6, and 7, and also found to offer 15 to 20% reductions in fuel consumption. This was achieved without the need for a very high cycle pressure ratio but with the complication of heat exchangers.

This present study is also an investigation of a possible method for the reduction of fuel in an aircraft engine. Here regeneration is combined either with intercooling alone or with both intercooling and reheat in a turbofan engine. The concept is not a new one. In examining an ideal Brayton cycle it may be shown that theoretically regeneration alone is of considerable help in reducing fuel consumption, and that when it is combined with intercooling or reheat or both, the fuel required for a given power level is reduced even more.

In this study heat in the primary exhaust stream is used to preheat the airflow just prior to its entrance into the combustor. Since the gas entering the combustor has a higher temperature than it would have had without regeneration, less fuel is required to raise the gas temperature to a given turbine inlet temperature. Although the specific thrust is substantially reduced in the core, the reduction in the fuel requirement is such that the specific fuel consumption is still improved. With a high bypass turbofan the engine specific thrust is reduced only slightly since a great portion of the thrust is obtained from the fan and is thus unchanged.

Intercooling is done by using the fan airflow to cool the primary airflow between two high pressure compressors. The compressors now are required to do less work on the cooled, dense air than they did on the uncooled, warmer air of the cycle without intercooling. More energy is available to run the fan which is allowed to do more work. So, the specific work goes up. Since the temperature out of the compressors is low, regeneration takes place at a lower temperature than in the uncooled case. This reduces the core thrust even more than in the uncooled regenerative case. However, the net result for a turbofan is a cycle with lower specific fuel consumption than that of an uncooled regenerative cycle.

When reheat is used the second combustor is located between the high-pressure and low-pressure turbines. This gives the exhaust flow a higher initial temperature. Regeneration then results in a higher air temperature into the combustor. More energy is available to run the fan which is allowed to do more work. The extra thrust thus produced tends to offset the extra fuel required with the overall result of higher specific thrust and a lower SFC than in a non-reheated case. Reference 8 discusses these cycles in detail.

For the sake of simplicity the following general approach was decided upon. For a spectrum of turbine inlet temperatures the bypass ratios and overall pressure ratios resulting in lowest uninstalled SFC's would be used. Initially reasonable but conservative values based upon the literature for effectiveness of and pressure loss in the heat exchangers would be used (refs. 7 and 9). Fuel use of these cycles installed on an aircraft would be compared with the fuel use resulting from utilization of a comparable advanced, but conventional, turbofan. If significant fuel savings resulted a more refined analysis would be made.

Should the improvement in fuel use using conservative parameter values not be significant, more optimistic values of heat exchanger effectiveness and $\Delta P/P$ would be used. In these cases optimistic values of increased weight and drag due to the heat exchangers would be added. Again in this case if significant fuel savings occurred, a more refined analysis would be made. If the gains were not significant the study would end, which is actually what occurred.

These regenerative type cycles are evaluated assuming advanced component technology that might be available after 1985. In order to determine the best cycle a large spectrum of uninstalled cycles is examined with compressor pressure ratios varying from 4 to 56, turbine inlet temperatures varying from 1222 K (2200 °R) to 2222 K (4000 °R), and bypass ratios varying from 6 to 20. The effects of variations in turbine cooling requirements, heat exchanger effectiveness and pressure losses in the heat exchangers are examined.

The potential fuel savings offered by these regenerative cycles is evaluated by assuming them to be installed on an advanced subsonic transport. For every cycle examined both engine and aircraft are sized to maintain the same range and payload. The aircraft carries a 200 passenger payload 5556 km (3000 n. mi.) at Mach 0.8 at an altitude of 11 582 m (38 000 ft). The fuel use is compared with that of advanced non-regenerative turbofan engines and with current engines also installed on the same type of aircraft.

SYMBOLS

B	combustor (burner)
BPR	bypass ratio
C	compressor
C1	first compressor
C2	second compressor
c_p	specific heat, J/kg-K (Btu/(lb-°R))
CPR	compressor pressure ratio
DOC	direct operating cost, cents/seat-km, (cents/seat-statute mile)
ε	heat exchanger effectiveness
F	fan
HT	high pressure turbine
HX	heat exchanger
IHX	intercooler heat exchanger
LT	low pressure turbine
OPR	overall pressure ratio, cycle pressure ratio
Q	heat flow (hot to cold) in heat exchanger
RB	reheat combustor (burner)
RHX	regenerator heat exchanger
SFC	specific fuel consumption kg/(hr-N) (lbm/(hr-lbf))
T	entrance temperature, K (°R), heat exchanger loop
T'	exit temperature, K (°R), heat exchanger loop
TIT	turbine inlet temperature, K (°R)
TOGW	takeoff gross weight kg, (lb)
W_T/WA	weight of engine per unit weight of airflow

$\dot{w}$ rate of mass flow, kg/sec, (lb/sec)

W_{FB} weight of fuel burned, kg, (lb)

Δ difference

$\Delta P_\ell / P_\ell$ fraction of pressure lost in a heat exchanger loop

Subscript:

0 zero bypass ratio

METHOD OF ANALYSIS

Mission

The mission profile is presented in figure 1. The cruise altitude is 11 582 m (38 000 ft). Normal cruise speed is Mach 0.8. The flight to an alternate destination for reserve computation is at Mach 0.65 at an altitude of 6096 m (20 000 ft). The payload is 200 passengers or 18 597 kg (41 000 lb).

Aircraft

Figure 2 presents a sketch of the reference aircraft. Some of the important geometry that is assumed is noted on the figure. Since the aircraft size varies from case to case absolute dimensions are not presented. Table I summarizes these and other aircraft assumptions that remain constant throughout the study.

Engines

Engine configuration. - Figure 3 presents schematic layouts of the various engines. In 3(a) is seen a standard turbofan. Figure 3(b) shows the intercooled-regenerative turbofan. The total high-compression compressor system now consists of two compressors with the intercooling done between them. In figure 3(c) the same cycle is shown with the addition of a second or reheat combustor between the high and low turbines.

Component efficiencies. - The component efficiencies were assumed to be those that might be available in 1985. These component efficiencies and other pertinent engine data are presented in table II.

Turbine cooling. - Two methods of turbine cooling are assumed. One is the convective type cooling used on engines in current transport aircraft. The second is a full coverage film technique which should be available by 1985.

The chief reasons for the use of two turbine cooling criteria in investigating these regenerative cycles were to find the effect on fuel consumption of different cooling techniques and also to find how different an optimum cycle would result from changes in the amount of cooling bleed. The two cooling criteria chosen represent the extremes of the probable techniques that would be available by 1985.

Although the initial parts of the study use both cooling techniques, much of the study is made using only the advanced cooling concept.

Heat Exchangers

No design of heat exchangers was made. A given heat exchanger could be any counter-flow device that transfers heat without mixing the flow streams. A schematic diagram of a turbofan engine with two heat exchangers, an intercooler and a regenerator, is shown in figure 4. As noted on the figure a heat exchanger loop is defined in this study as the path taken by a mass of gas from the engine stream, through the heat exchanger and back to the engine stream. Any pressure losses attributed to the heat exchanger loops is caused by the gas flowing along this path. At no time is the heat exchanger loop referred to as a duct. Only bypass fan flow is referred to as duct flow.

Loop ABCDE is the hot loop of the intercooler. The air out of the first compressor passes through the heat exchanger and, in a cooled state, returns to the core flow. The letters GH refer to the flow of cool fan air through the cold loop of the heat exchanger. Loop JKLM is the cold loop of the regenerator. The air out of the second compressor passes through the heat exchanger where it is heated and returns to the core flow at the combustor entrance. Loop NPQ is the hot loop of the regenerator. Here the hot air out of the low-pressure turbine passes through the heat exchanger and then flows on towards the nozzle.

Note that core air flows through three loops, the hot side of the intercooler and both sides of the regenerator. Fan duct air only flows through the cold side of the intercooler. Whenever the air passes through a heat exchanger loop, the flow suffers a pressure loss.

Although no heat exchanger design is made, a pressure loss for each heat exchanger loop, $\Delta P_{\ell}/P_{\ell}$, and an effectiveness, ε, for each heat exchanger are assumed for the initial cycle study. The effectiveness is assumed to be 0.8 in both heat exchangers and the pressure loss is assumed to be .06% in each loop. The effects of varying $\Delta P_{\ell}/P_{\ell}$ and ε are then examined.

The effectiveness, ε, is defined by the following equation:

$$\varepsilon = \frac{T'_{cold} - T_{cold}}{T_{hot} - T_{cold}} \left(\frac{(\dot{w}\ c_p)_{cold}}{(\dot{w}\ c_p)_{minimum}} \right)$$

where T_{cold} is the entry temperature into the cold loop, T_{hot} is the exit temperature from the cold loop. The product $(\dot{w}\ c_p)_{cold}$ is made up of the weight flow, $\dot{w}$, and the specific heat, c_p, of the cold loop. The product $(\dot{w}\ c_p)_{minimum}$ is the smaller product of $\dot{w}$ and c_p, and thus may be from either the hot or the cold loop.

In the initial calculations for the determination of the best intercooled, regenerative cycle, no increase in engine volume or engine size is taken into account. Thus the only two heat exchanger parameters pertinent to the initial calculations are the effectiveness and the pressure losses. These parameters, included in table II, are for the conservative initial approach. In modifying the computations for comparison with a non-regenerative engine more optimistic values for these parameters are assumed and weight and volume penalties are applied to the regenerative engines. These penalties are merely estimates based on the results presented in reference 7.

Computations

Computational methods. - All engine computations are made by using the NNEP-Navy NASA engine computer program. NNEP allows the simulation of all of the engine cycle concepts that are considered in this study. A discussion of this program is presented in reference 10.

The mission studies were accomplished using AMAC, a non-documented, inhouse, aircraft-performance computer program. This program simulates the required mission and determines the size and weight of the aircraft and engines, and it computes the amount of fuel required. It then computes direct operating cost, DOC.

In the AMAC program base engine weight is determined in accordance with reference 11. The method of DOC computation is that of the 1967 ATA method, reference 12, updated to current prices and modified by replacing the maintenance formuli by those in reference 13.

Engine aerodynamic drag. - In this study the length to diameter ratio of the engine has been held constant at 1.5. All surface areas, including that of the engine pylon are assumed functions of the engine diameter. For the initial portion of the study in which the best intercooled-regenerative cycles are determined, no increases in size of installed engines (and thus drag) due to the volume of the heat exchangers are calculated.

For the final portion of this study, the comparison of these regenerative cycles with non-regenerative cycles, the best regenerative engines have their volumes adjusted to account for the heat exchangers. In order to account for the effects of increased size and thus increased drag of the engines, the assumption has been made that all volume changes result in each dimension of the engine being increased an equal percent. That is the area, and thus the drag, of the engine varies as the 2/3 power of the volume.

From the information given in reference 7 the volume of the engine increased about 70% with a resulting 50% increase in surface area due to the addition of a rotary regenerator. This would yield an exponent of 3/4 which is not too far from the 2/3 exponent assumed.

RESULTS AND DISCUSSION

Intercooler Placement

It was indicated in reference 8 that for an ideal Brayton cycle with one-step intercooling the best cycle efficiency occurs when the intercooler is situated such that the pressure ratio upstream and that downstream of the intercooler are equal. Reference 4 shows that the same is true for a similar cycle even with realistic efficiencies and pressure losses in the engine.

In this study several intercooled regenerative turbofans were examined as shown in figure 5. It is seen that for the turbofan, even though some compression is supplied by the fan, the placement of the intercooler is similar to that of an engine with only one compressor. The intercooler location for minimum specific fuel consumption is such that the high-pressure-compressor pressure ratios upstream and downstream of the intercooler are equal. The intercooler was situated at this point for all cases examined.

Intercooled Regenerative Cycles

Uninstalled cycle SFC minimization - figure 6 basically presents percent change in SFC at cruise as a function of TIT. The datum SFC is 0.051 kg/(hr-N), (0.500 lbm/(hr-lbf)). The SFC is presented for both current and 1985 cooling technology. These results are with the basic conservative values of the parameters for the heat exchangers.

Since each point on both SFC curves represents a minimum SFC point for the given temperature, there is associated with each point a single value for BPR, OPR and (with a fixed FPR) CPR. Each point also has associated with it a value of turbine cooling bleed. The percent cooling bleed and the BPR's are presented by curves.

Other calculations, not presented here, indicated that for any turbine inlet temperature the minimum SFC occurred at essentially the same compressor pressure ratio. Therefore, the CPR is added merely as an additional scale in the abscissa. There is some leeway here. For example a CPR varying from 14 to 16 results in the same SFC value.

Note that at the low bleed end of the figure (near 1440 K (2600 °R) the SFC's are just about the same. Although it is minimum fuel use rather than minimum SFC that is the criterion for an optimum cycle, it is interesting to note that with either technology the minimum SFC is achieved with the same cycle, a 35 CPR combined with a 2000 K (3600 °R) turbine inlet temperature. The actual SFC values, the percent bleed, and the bypass ratios are all different, however. The current level of cooling technology results in about 21% cooling bleed at a bypass ratio of about 14. The advanced level of cooling technology results in about 13% cooling bleed, a BPR of 16, and a 4% lower SFC than current technology cooling.

Mission studies were performed using the cycles represented by this curve to determine the cycle burning the least amount of fuel rather than the minimum SFC cycle as shown here. All of the computations were made using the assumption of 0.8 effectiveness in both heat exchangers and a 6% pressure loss in each loop of each heat exchanger.

Aircraft Performance with Intercooled Regenerative Cycles

Several engines from figure 6 were "installed" on a 200 passenger transport and "flown" along the flight path previously noted. Each engine was the lowest SFC engine for the particular turbine inlet temperature. Since no engines was penalized for the weight and size of the heat exchangers, and since no additional cost was added in computing the DOC, the results as presented in figures 7 and 8 can only be used to compare regenerative intercooled cycles. These values in figures 7 and 8 cannot be used to compare these regenerative cycles with a conventional, nonregenerative cycle.

In figure 7, percent difference in takeoff gross weight and fuel consumed are plotted against turbine inlet temperature at cruise. The dashed curves represent cycles with current cooling technology. The solid curves represent cycles with advanced cooling technology. Note that for either cooling criterion the minimum for both TOGW and consumed fuel occur with the same cycle. The cycle temperature for minimum fuel consumed varies with the cooling criterion, however. The higher cooling bleed case calls for a cycle turbine inlet temperature of 1667 K (3000 °R). The lower cooling bleed case calls for a cycle turbine inlet temperature of 1778 K (3200 °R). Thus, these cycles represent about a 200 to 250 K (360° to 450 °R) increase above current cycles (P&W JT9D, GE CF6 for example). The 1667 K (3000 °R) cycle had an OPR of 35 at a CPR of 22, and the 1778 K (3200 °R) cycle had an OPR of 40 at a CPR of 25. These vary somewhat from the values in figure 6, however no significant difference in SFC could be determined.

In figure 8 relative difference in DOC is plotted against turbine inlet temperature for both the high bleed and low bleed cases. The cycles that resulted in the lowest fuel consumption values in figure 7 are the same ones that result in minimum DOC. Thus there seems to be no economic conflict in choosing the best cycle for fuel consumption.

The two minimum fuel cycles are chosen for comparison with current and advanced turbofan cycles. However, more emphasis is placed on the engines using advanced full-film coverage turbine cooling, the optimistic assumption being made that this advanced cooling will be used in all engines by 1985.

Sensitivity of Intercooled Regenerative Cycle

Most of the comparisons with current and advanced non-regenerative engines are made using the intercooled, regenerative cycles with the advanced full-film coverage turbine cooling technology. Therefore, the sensitivity results for that cycle are discussed and presented. The cycle has a 25 compressor pressure ratio, a 40 overall pressure ratio and a 1778 K (3200 °R) turbine inlet temperature at cruise.

Effect of a change in $\Delta P_\ell/P_\ell$. - Figure 9 presents two relationships. One is the percent difference in SFC as a function of the sum of the pressure losses, $\Delta P_\ell/P_\ell$, resulting from the core flow passing through three heat exchanger loops (see fig. 4), and the percent difference in SFC as a function of the $\Delta P_\ell/P_\ell$ in the cold loop of the intercooler through which fan duct or bypass flow passes.

Note that the curve for the bypass flow is much steeper than the curve for the core flow, an indication that pressure losses in the fan duct flow have a much greater effect on SFC than pressure losses in the core flow. This is a result of two factors. First, the fan pressure ratio is much lower than that of the core and consequently fan duct losses impact SFC much more strongly than core losses. Second, with a higher BPR the greater part of the thrust is supplied by the fan flow. Here the percent change in SFC for a given $\Delta P_\ell/P_\ell$ is 2.3 times greater in the duct flow than in the core flow. It is clear, then, that it is very desirable to reduce the $\Delta P_\ell/P_\ell$ in the fan duct loop.

Effect of a change in SFC on fuel use. - Figure 10 presents a plot of percent change in fuel used as a function of percent change in SFC. The percent changes are exactly the same for usable and consumed fuel. This figure can be used in conjunction with figure 9 to ascertain the effects on fuel use resulting from an improvement in heat exchanger pressure losses.

Effects of changes in propulsion system weight and heat exchanger effectiveness on fuel use. - In the initial calculations to determine the best intercooled, regenerative cycle no weight penalty was included for the heat exchangers. These heat exchangers actually can add a considerable amount to the basic engine weight, which in turn can increase the fuel consumption.

The value for heat exchanger effectiveness in the basic study was simply a reasonable, conservative chosen value. Therefore, it is useful to determine the effect on fuel use of a change in effectiveness.

Sensitivity studies were made for both changes in the weight of the propulsion system and changes in heat-exchanger effectiveness. The results of both studies are combined in figure 11. This figure is used later in modifying the base intercooled-regenerative-turbofan results to the more optimistic heat exchanger case with engine weight and drag penalties added that is used to compare with an advanced, conventional turbofan.

Effect of changes in engine drag on fuel use. - The effect on fuel weight due to the drag associated with changes in engine volume is presented in figure 12. The figure represents the results of a sensitivity study with increased engine drags assumed and the assumption of engine surface area varying as the 2/3 power of the volume (as previously discussed). This figure is also used to modify the base, intercooled, regenerative turbofan that is used for comparison with a conventional, advanced turbofan.

Intercooled Regenerative Cycle with Reheat

Figure 13 presents the percent difference in SFC at the cruise design point as a function of the compressor pressure ratio for the intercooled, regenerative cycle with reheat. The SFC of the base case of the minimum-fuel-use cycle for the intercooled, regenerative cycle is also noted.

The reheat temperature is the same as the main temperature for these cases. All cycle parameter assumptions are the same for this reheated cycle as for the non-reheated cycle.

The most important point to be made from this figure is the fact that the minimum SFC for the reheated cycle is about 3.5 percent higher than that for the non-reheated base case. Entering figure 10 with these values obtained from figure 13, an increase in fuel burned of about 4 percent results. If the compressor pressure ratio is limited to 28, which is probably as high as can be achieved in the 1985-1990 period, the difference in SFC is even a bit greater.

The problem is due chiefly to the additional cooling bleed in the second turbine. Only if engine cooling requirements become very small, due to an advance in materials technology, could this cycle be competitive.

The impact of a 4% increase in engine fuel consumption can be ascertained from figure 11. It is seen that nearly a 70% decrease in engine weight would be required to reduce the fuel use 4%. It is noted in table III that the bypass ratio of the engine with reheat is 17 as compared to 13 for the non-reheated engine. This actually results in a 4 percent decrease in specific thrust requiring a 4% increase in airflow for the same thrust. The engine does not increase 4% in weight, however. According to figure 14 (ref. 11) in going from a bypass ratio of 13 to 17 the relative engine weight per total airflow drops to about 97% of its original value. Thus the resulting weight of the reheated engine for the same thrust as the non-reheated (and disregarding the weight of the second combustor) would be about 1% greater rather than 70% less than the intercooled, regenerative engine. Further, any attempt to increase specific thrust would simply result in worse SFC.

In light of these facts, there is no value in doing flight optimization studies of these cycles.

Advanced Turbofan Engines for Comparison with Advanced Intercooled Regenerative Cycles

It is necessary to compare the intercooled regenerative cycles with turbofan cycles having the same level of technology. Both minimum-fuel-use cycles from figure 7 are compared with a current turbofan and with an advanced turbofan utilizing the same level of cooling technology.

In order to find an advanced, non-regenerative cycle to compare with each regenerative cycle a brief study was made. The details of the examination of the advanced turbofan with advanced cooling is presented in figure 15. Here the uninstalled cycles with the same technology assumptions and the same cruise turbine inlet temperature 1770 K (3200 °R) as the low-bleed intercooled regenerative cycle are presented.

Percent difference in SFC is plotted as a function of bypass ratio for several compressor pressure ratios. The 47 compressor pressure ratio line is dashed merely for the sake of clarity. Note that the minimum uninstalled SFC occurs at a compressor pressure ratio of 50. The overall pressure ratio is 80. This is far higher than appears feasible even by 1985 (see ref. 3). A more attainable value would be an overall pressure ratio of about 45 with the compressor pressure ratio equal to 28. Thus the cycle chosen is that with the 1778 K (3200 °R) turbine inlet temperature, a compressor pressure ratio of 28 and a bypass ratio of 13.

It should be noted here that the BPR's presented here are probably too high since the engines were chosen for minimum uninstalled SFC and the FPR was held constant at 1.6, perhaps a bit low. However, for the purpose of comparing cycles this inflation in optimum BPR is of little consequence since all the cycles were similarly chosen.

A similar study was made for the advanced turbofan using current cooling technology. The resulting cycle had a 1667 K (3000 °R) turbine inlet temperature, a compressor pressure ratio of 28, and a bypass ratio of 10.

These cycles could be chosen without doing a mission study and making a comparison of installed performance between the several compressor pressure ratios below 28. The reason for this can be understood by examining figure 15. The cycles with compressor pressure ratios 28 or less have essentially the same bypass ratio, and they have the same cruise turbine inlet temperature. Therefore, the lapse rate and weight of these engines would be essentially constant. The SFC for these lower CPR cycles rises quite rapidly with reductions in pressure ratio, however. Thus, the only change of any importance in going to lower CPR's is deleterious to fuel consumption.

The comparison between the installed performance of these turbofans and the corresponding regenerative, intercooled turbofans is presented next.

Comparison of Cycle Performance

The performance of eight cycles are presented for comparison. These cycles are presented in table III. The three conventional cycles, one with current technology and two with advanced technology but with different turbine cooling criteria, are each used as a datum cycle against which to evaluate the cycles using heat exchangers.

Three of the cycles using heat exchangers are listed as base cycles. These base cases have many of the penalties associated with them either ignored or roughly approximated. This approach is adequate for choosing the optimum for each cycle and for comparing one heat exchanger cycle with another. However, for the purpose of comparison with an optimum conventional cycle some refinements in penalties must be made. The cycle chosen for such a comparison is listed in table III as having adjusted penalties. The following section of this report is devoted to a discussion of the choice of these adjusted penalties.

Penalty modification of intercooled regenerative cycle with advanced cooling technology. - It was previously noted that the decision had been made that if the initial conservative choice of heat exchanger effectiveness and pressure loss values did not result in improvements in fuel use, a more optimistic choice of these values would be made. When applying these optimistic values, some account was also to be made of engine weight and size penalties. The following presents the rationale for these optimistic choices.

A $\Delta P_\ell/P_\ell$ loss in the cold loop of the intercooler can cause a serious increase in fuel consumption. By keeping the velocity low in this loop, the $\Delta P_\ell/P_\ell$ in the fan duct loop is .03 rather than the .06% initially assumed. No degradation in effectiveness will be assumed (an optimistic view).

The possible effectiveness of heat exchangers has been assumed by many to be 85% or even 90%. For example see reference 9. Therefore, some additional optimism is entered here and the effectiveness now will be assumed at 85%.

In reference 7 a weight of 2311 kg (5095 lb) for the rotary ceramic regenerators in the four engines was presented. The aircraft was essentially the same weight and flying the same mission as that in this report. However, that cycle was at a lower temperature than the cycle of this report, and in the cycle of this report there are two heat exchangers per engine, not one. Nevertheless, the same penalty is used in this report, an additional weight 60% that of the basic engines.

The volume increase of the engine in reference 4 is about 70%. Again, although in this study there is an additional heat exchanger, this 70% volume increase is used.

Using these assumptions and figures 9 through 12, the percent changes presented in table IV are found. The total percent difference in fuel used is about 0.8% more than that of the advanced-cooling-technology base case.

Comparison of fuel use. - Figure 16 presents the percent improvement in fuel use compared to an advanced aircraft with current-type engines. All of the cycles show substantial improvement over current cycles.

Note next the percent difference in fuel saved between the base turbofan and the intercooled, regenerative turbofan both using advanced turbine cooling technology. The intercooled, regenerative cycle shows a fuel savings about 1% greater than the basic turbofan, a very small difference.

Comparing the base and intercooled, regenerative turbofans using current turbine cooling technology the basic turbofan seems better than the regenerative, intercooled engine. This shows that a large increase in cooling bleed requirements not only causes the cycle to vary, but also appears to make the intercooled, regenerative engine less attractive than an advanced turbofan using the same level of cooling technology. However, the percent differences in both cases must be considered small for an analytical study, because minor changes in assumptions could possibly wipe out the differences.

Since the differences are small in either case, and since the low-bleed case seems to offer a small glimmer of hope for the intercooled, regenerative cycle, only one level of cooling technology is examined in greater detail - the advanced cooling cycle.

To more accurately compare the advanced turbofan with intercooling and regeneration to an advanced turbofan that uses no heat exchangers, the changes in pressure loss and effectiveness values and the addition of the various penalties discussed in the preceeding section of the report are made to the low-cooling-bleed, intercooled, regenerative turbofan. When these penalty values are applied (even though they are relatively optimistic), the intercooled, regenerative cycle is just about the same in fuel savings as the advanced 1985 turbofan. The addition of reheat makes the improvement in fuel use less than that of the advanced turbofan.

Because of these results no additional studies to better evaluate penalties associated with heat exchangers were made, and no study to define the cost of engines with heat exchangers was made. It seems that during the time period in which these engines might be built the less-complex, advanced turbofan will be the best of these fuel conservative cycles.

Table III, as noted previously, presents pertinent information about the aircraft performance using each of these cycles. Note that the large gains are from SFC improvement. Weight and drag are not nearly as important.

CONCLUSIONS

In this study two engine cycles that could reduce fuel use in subsonic transport aircraft were examined. The fuel consumption of the intercooled, regenerative turbofan and the intercooled, regenerative turbofan with reheat were compared to a current engine cycle and to an advanced turbofan. The technology for all but current turbofans was assumed to be that that could be incorporated in a flight engine by 1985.

The figure of merit was fuel consumption Takeoff gross weight, and in some cases DOC were also calculated.

The fan pressure ratio was held constant at 1.6. The fuel consumption of all of the engines including the current cycle was evaluated on a four-engine, 200 passenger aircraft with 1985 structural and aerodynamic technology assumed, flying 5556 km (3000 n mi) at Mach 0.8 at 11 582 m (38 000 ft).

The intercooled, regenerative cycle was found to have the lowest fuel consumption at an overall pressure ratio of 40 and a turbine inlet temperature of 1778 K (3200 °R). The advanced turbofan used for comparison was limited to a 45 overall pressure ratio and a turbine inlet temperature of 1778 K (3200 R). The intercooled, regenerative cycle with reheat was also limited to a 45 overall pressure ratio and a 1778 K (3200 °R) turbine inlet temperature.

It was found that all advanced cycles showed an improvement in fuel consumption when compared with current engines. However, the regenerative, intercooled engine was no better in fuel consumption than the projected advanced turbofan. This was true even though the penalties in weight and size that were chosen for the regenerative, intercooled cycle were exceedingly optimistic. When reheat was added, the situation became worse due to the additional cooling bleed requirement. Thus, the regenerative, intercooled cycles remain tantalizing, theoretically the most advantageous, but practically not.

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TABLE I. - BASIC AIRCRAFT DATA

Wing Data	
AR	12
t/c tip	0.164
t/c root	0.080
Leading edge sweep, radians (deg)	0.478 (27.4)
Taper	0.33
Camber	0.07
Wing loading, N/m^2 (lb/ft^2)	5602 (117)
Wing type	Supercritical
$C\ell_0$	0.06
Cd_0	0.022
General Data	
Passenger class	All tourist
Number of passengers	200
Weight of payload, kg (lb)	18 597 (41 000)
Technology level, year	1985
Composite usage Δ weight	-10%
Cruise Mach number	0.8
Cruise altitude m, (feet)	11 582 (38 000)
Takeoff thrust to weight ratio N/kg(g) or lbf/lbm	0.3

TABLE II. - CYCLE INPUTS AT CRUISE FOR ADVANCED ENGINES

Base cases	
Inlet recovery	0.993
Overall pressure ratios examined	6 to 90
Fan pressure ratio	1.6
Cruise turbine inlet temperatures examined, K (°R)	1222 (2200) to 2222 (4000)
Polytropic efficiency of the	
Compressor	0.915
Fan	0.887
Adiabatic efficiency of the	
high pressure turbine	0.91
low pressure turbine	0.90
Efficiency of the combustor	1.00
Turbine cooling technology	1975 and 1985
Cv fan nozzle	0.987
Cv core nozzle	0.9906
Pressure loss, $\Delta P/P$:	
Fan duct	0.017
Combustor	0.045
Heat exchangers each loop	0.06
Engine length/diameter ratio	1.5
Heat exchanger effectiveness - both	0.8
Number of spools	2
Design altitude m, (feet)	10 058 (33 000)
Design Mach number	0.83
Technology level	1985

TABLE III. - PERFORMANCE INFORMATION

	Conventional cycle			Regenerative - intercooled			
				1985 Cooling			Current cooling
Cycle	Current	Advanced 1985 cooling	Advanced current cooling	Base	Adjusted penalties	Base with reheat	Base
SFC actual during cruise	0.0642 kg/hr-N (0.629 hr^{-1})	0.0565 kg/hr-N (0.554 hr^{-1})	0.0576 kg/hr-N (0.565 hr^{-1})	0.0561 kg/hr-N (0.550 hr^{-1})	0.0526 kg/hr-N (0.516 hr^{-1})	0.0581 kg/hr-N (0.570 hr^{-1})	0.0579 kg/hr-n (0.568 hr^{-1})
TIT	1478 K (2660 °R)	1778 K (3200 °R)	1667 K (3000 °R)	1778 K (3200 °R)	1778 K (3200 °R)	1778 K (3200 °R)	1667 K (3000 °R)
OPR	26	45	45	40	40	45	35
BPR	6	13	10	13	13	17	11
TOGW	105 786 kg (233 217 lb)	98 260 kg (216 626 lb)	98 431 kg (217 000 lb)	97 871 kg (215 768 lb)	101 417 kg (223 585 lb)	98 760 kg (217 728 lb)	98 418 kg (216 970 lb)
Weight of propul-sion	8963 kg (19 761 lb)	7722 kg (17 025 lb)	7737 kg (17 056 lb)	7692 kg (16 957 lb)	10 716 kg (23 624 lb)	7761 kg (17 111 lb)	7736 kg (17 054 lb)
Turbine cooling bleed	8%	10%	17%	7%	7%	14%	10%
Percent change in drag due to heat ex-changers	---	---	---	---	42%	---	---
Weight usable fuel	28 654 kg (63 172 lb)	24 279 kg (53 525 lb)	24 744 kg (54 550 lb)	24 020 kg (52 954 lb)	24 219 kg (53 393 lb)	24 970 kg (55 050 lb)	24 857 kg (54 800 lb)
Fuel consumed	23 268 kg (51 296 lb)	19 714 kg (43 462 lb)	20 092 kg (44 295 lb)	19 504 kg (42 999 lb)	19 666 kg (43 355 lb)	20 276 kg (44 701 lb)	20 184 kg (44 498 lb)

TABLE IV. - CHANGES FROM BASE CASE TO CASE WITH IMPROVED COMPUTATION OF PENALTIES

<table>
<tr><th>Parameter</th><th>Base case</th><th>Adjusted case</th><th>Percent change SFC</th><th>Percent change fuel use</th></tr>
<tr><td>ΔP/P cold loop intercooler</td><td>0.06%</td><td>0.03%</td><td>- 4.05</td><td>- 4.53</td></tr>
<tr><td>Effectiveness, all HX loops</td><td>80%</td><td>85%</td><td>- 2.16</td><td rowspan="2">+ 0.90</td></tr>
<tr><td>HX weight penalty as percent bare engine weight</td><td>0</td><td>60%</td><td>---</td></tr>
<tr><td>HX volume penalty as percent basic engine volume</td><td>0</td><td>70%</td><td>---</td><td>+ 4.67</td></tr>
<tr><td>Combination of 4 above</td><td></td><td></td><td></td><td>+ 0.83</td></tr>
</table>

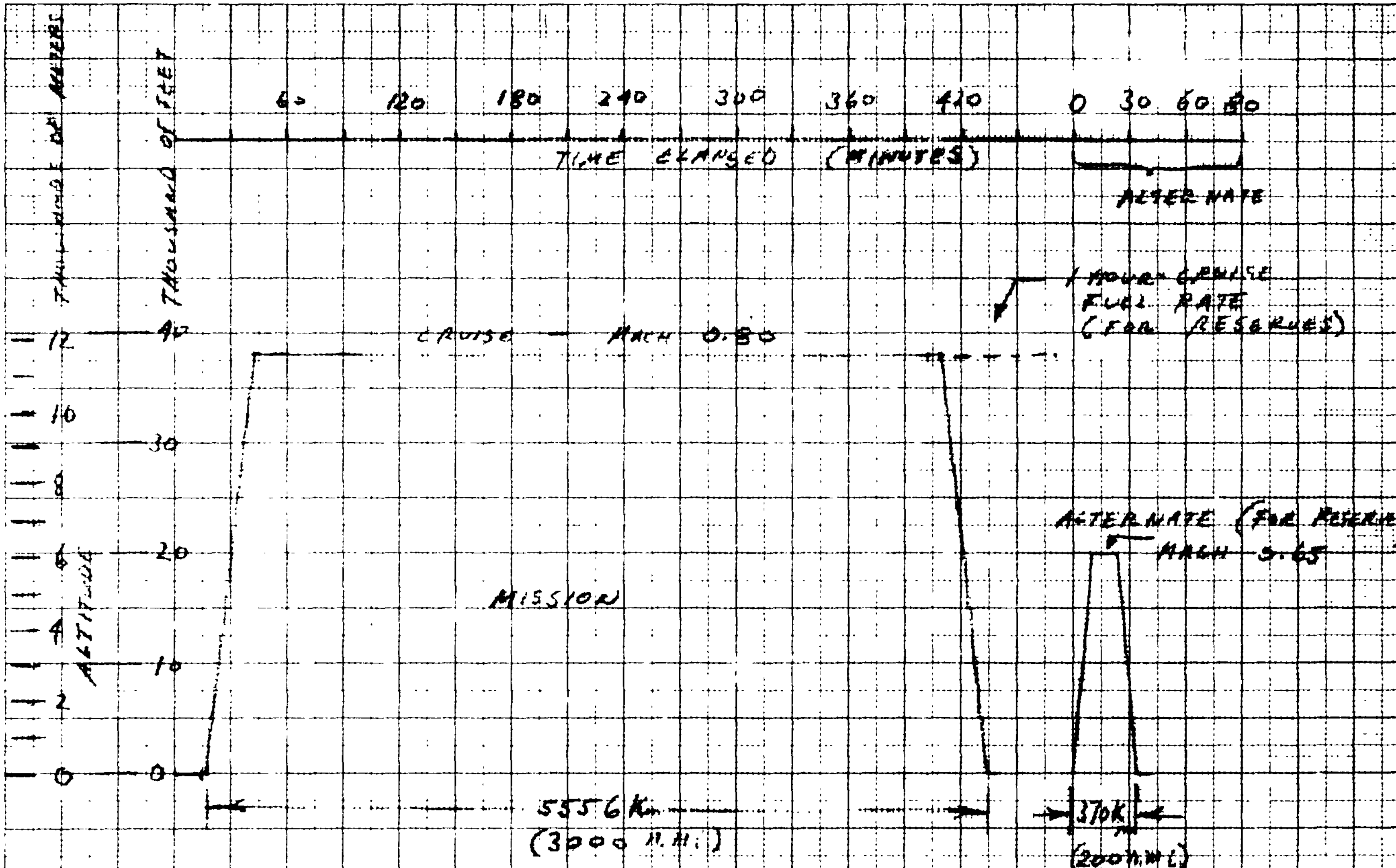


FIGURE 1. MISSION PROFILE AND RESERVE ASSUMPTIONS

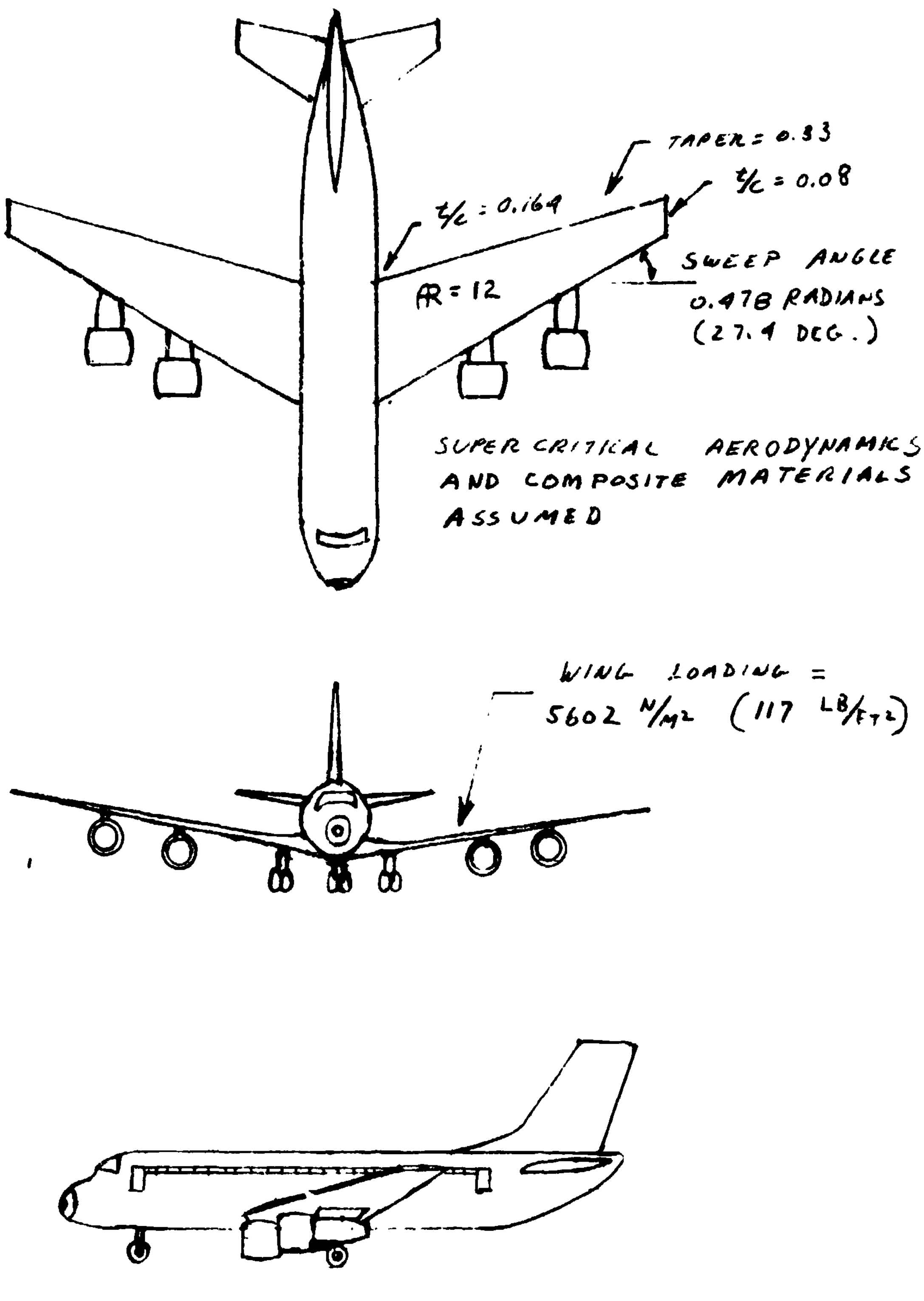
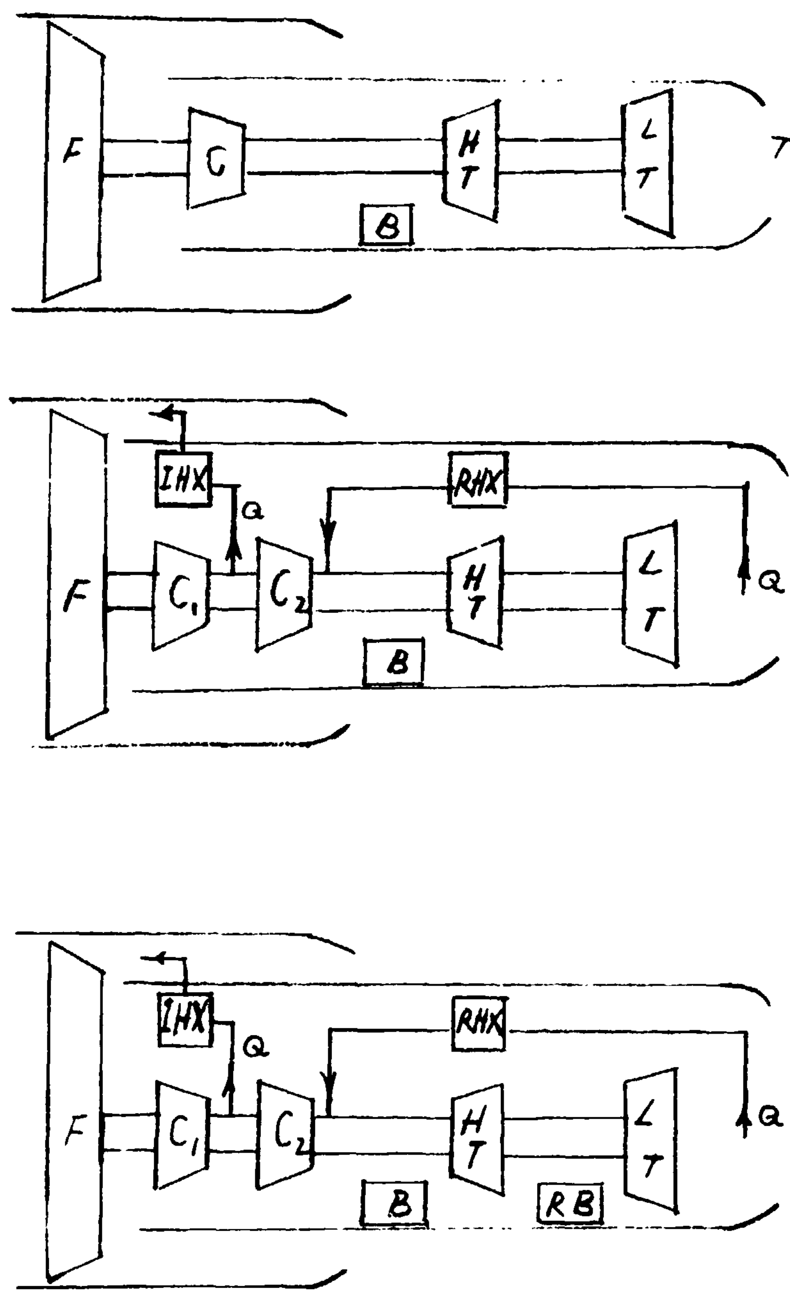


FIGURE 2 - AIRCRAFT CONFIGURATION



3a, TURBOFAN, CONVENTIONAL

3b, TURBOFAN WITH INTERCOOLING AND REGENERATION

3c, TURBOFAN WITH INTERCOOLING REGENERATION AND REHEAT

FIGURE 3 - ENGINE CYCLES CONSIDERED

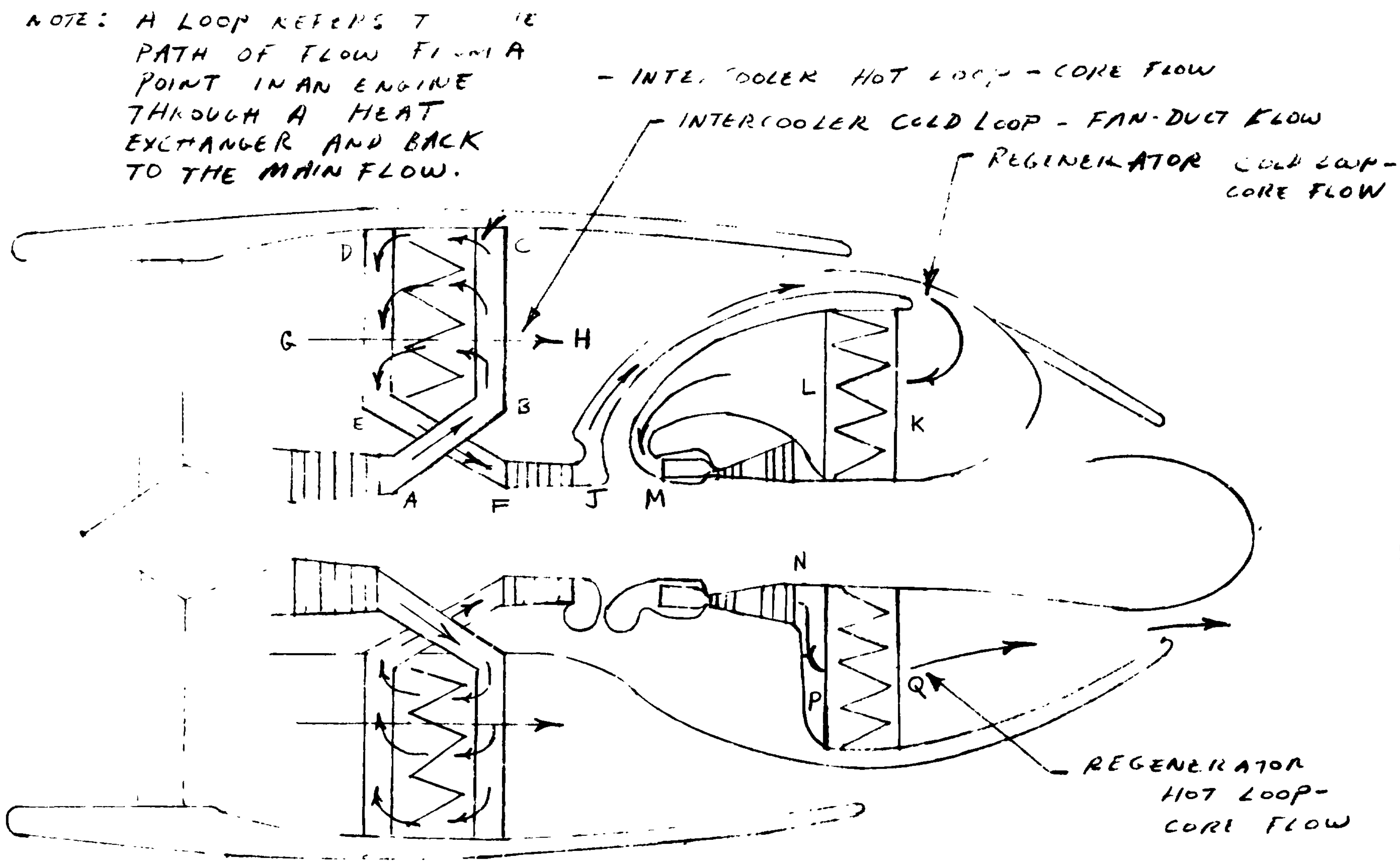


FIGURE 4 SCHEMATIC DIAGRAM SHOWING TURBOFAN ENGINE WITH INTERCOOLER AND REGENERATOR

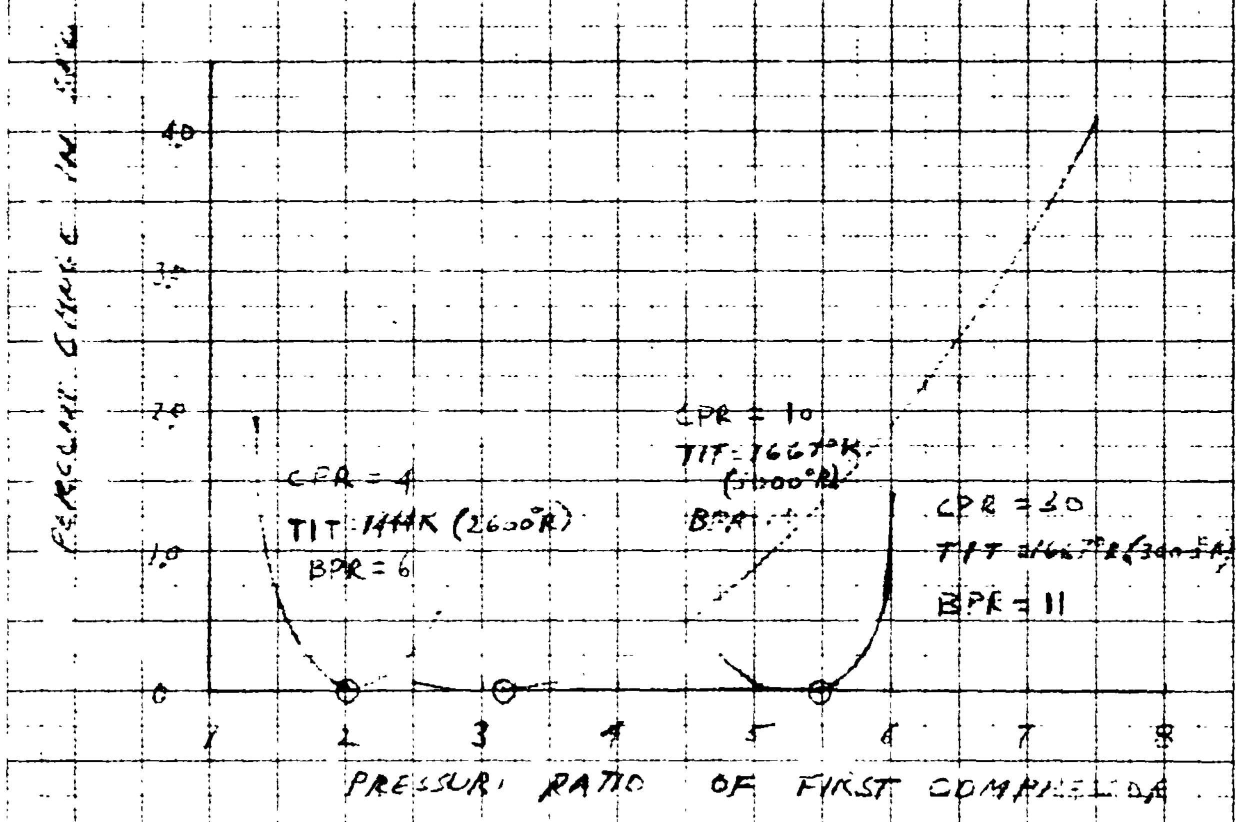


FIGURE 5-EFFECT ON SFC OF INTERCOOLER LOCATION RELATIVE TO COMPRESSOR PRESSURE RISE FOR AN INTERCOOLED REGENERATIVE TURBOFAN. BASE CASE IS LOWEST UNINSTALLED SFC OBTAINED WITH THE GIVEN COMPRESSOR PRESSURE RATIO AND TURBINE INLET TEMPERATURE.

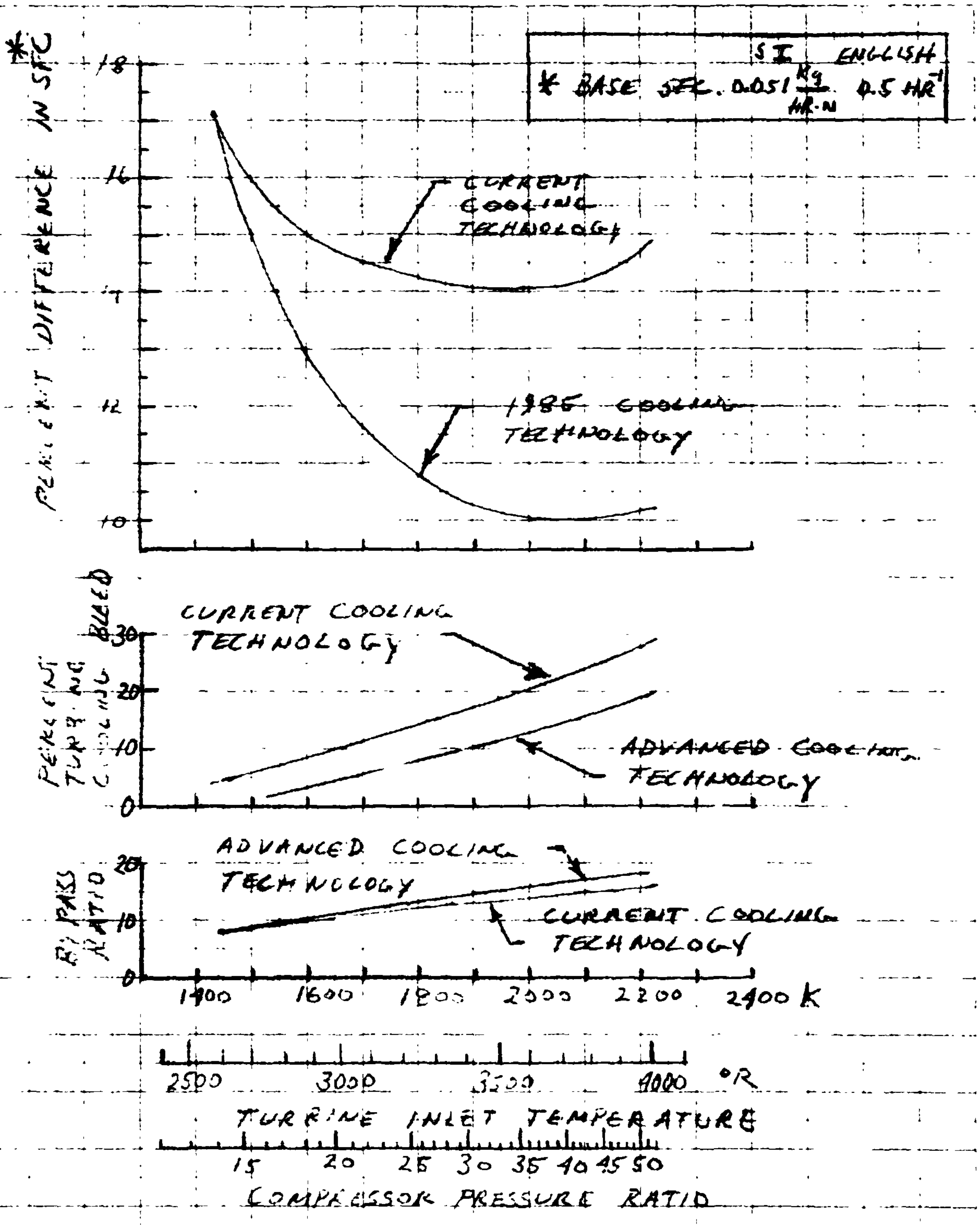


FIGURE 6- DIFFERENCE IN SFC FOR ADVANCED INTERCOOLED REGENERATIVE CYCLES FOR A SPECTRUM OF TURBINE INLET TEMPERATURES AND A BAND OF TURBINE COOLING TECHNOLOGY LEVELS. BPR AND CPR FOR MINIMUM SFC AT EACH POINT. FPR = 1.6

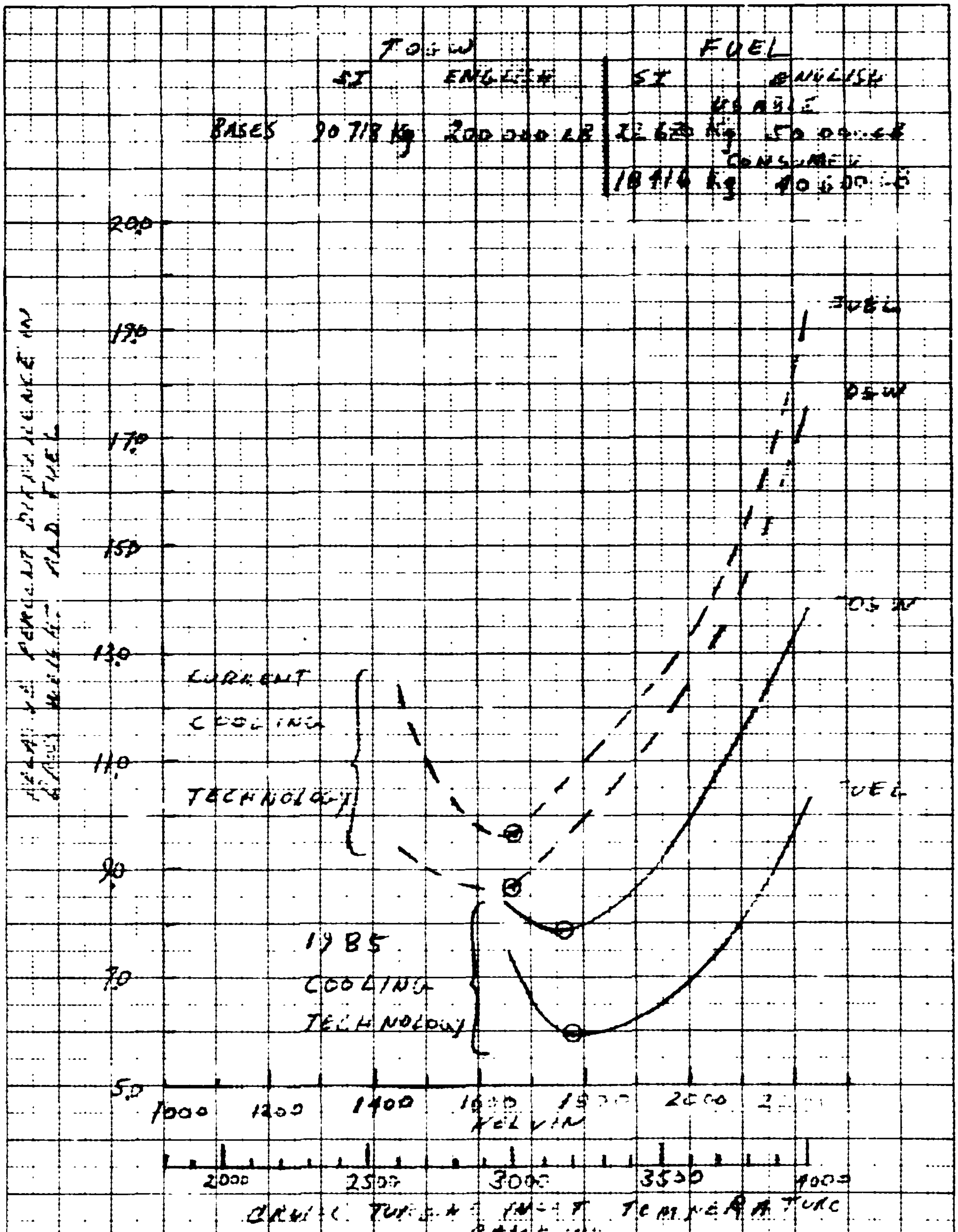


FIGURE 7 - TAKEOFF GROSS WEIGHT AND FUEL CONSUMED AS A FUNCTION OF CRUISE TURBINE INLET TEMPERATURE AND COOLING METHOD, INTER-COOLED REGENERATIVE CYCLES

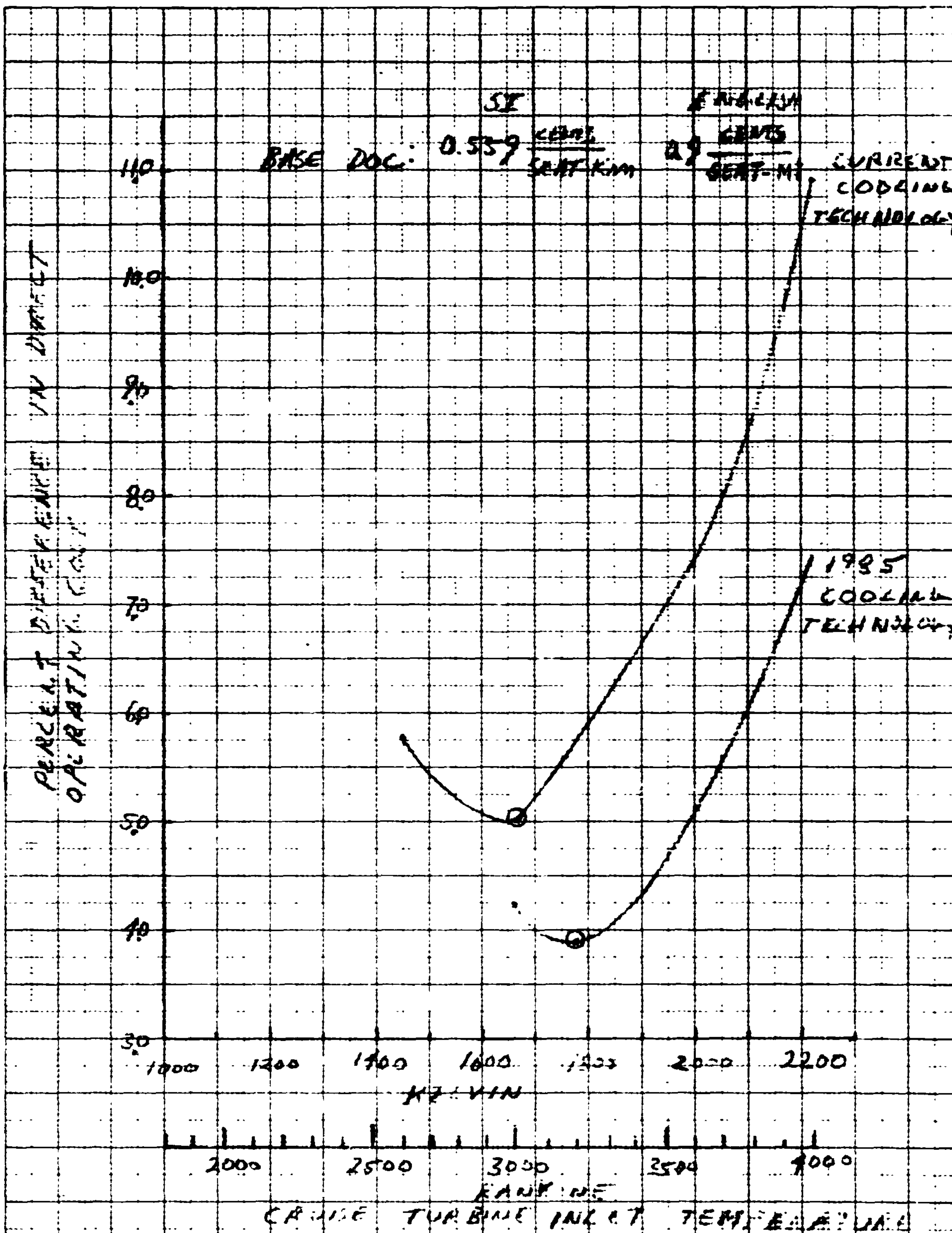


FIGURE 8- DIRECT OPERATING COST AS A FUNCTION OF CRUISE TURBINE INLET TEMPERATURE AND COOLING METHOD, INTERCOOLED REGENERATIVE CYCLE.

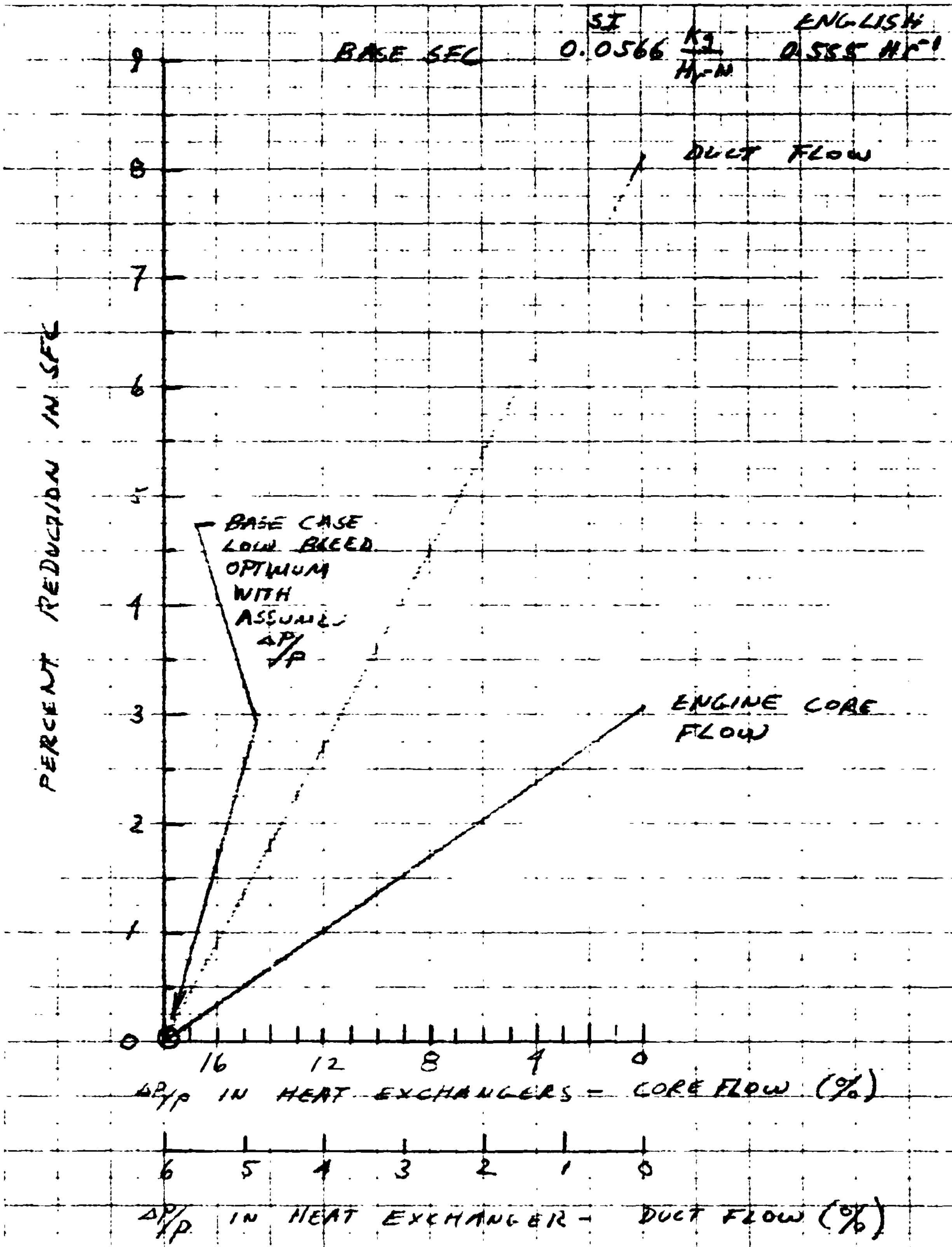


FIGURE 9 - RELATIVE DIFFERENCE IN SFC AS A FUNCTION OF $\Delta P/P$ IN THE HEAT EXCHANGERS

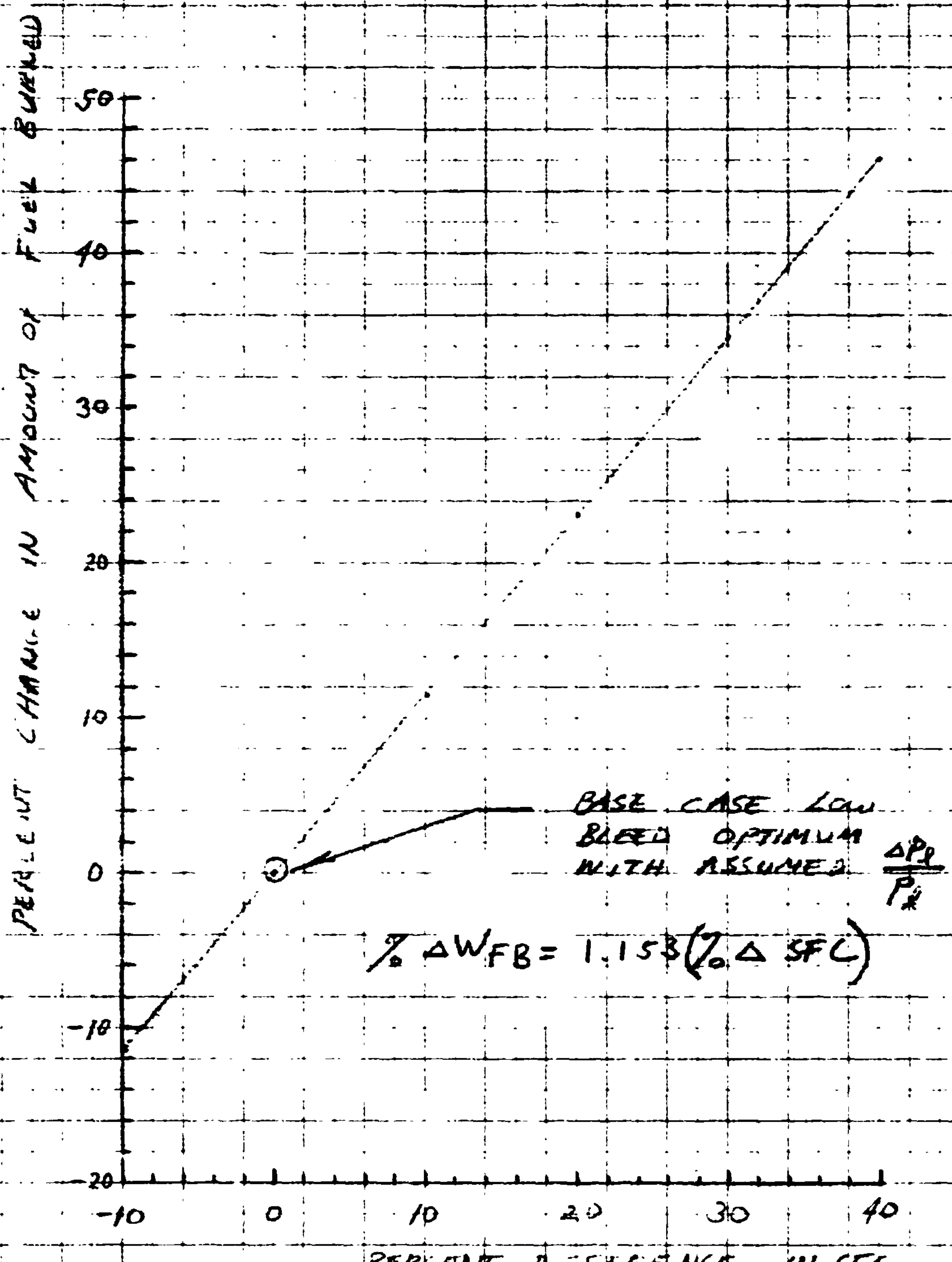


FIGURE 10 - PERCENT CHANGE IN FUEL BURNED DUE TO A PERCENT CHANGE IN TSFC

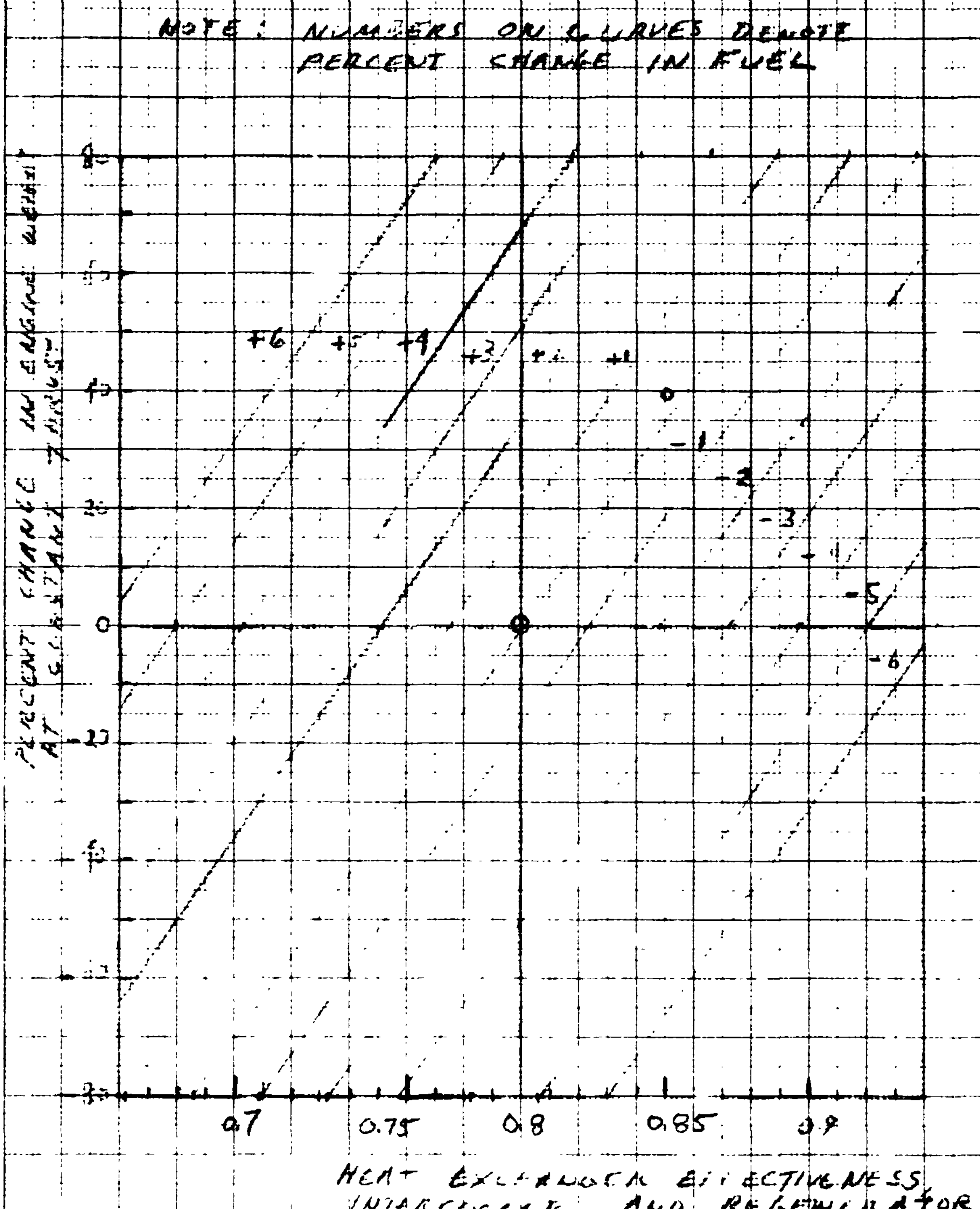


FIGURE 11 EFFECT OF EFFECTIVENESS AND WEIGHT OF HEAT EXCHANGERS ON FUEL USAGE

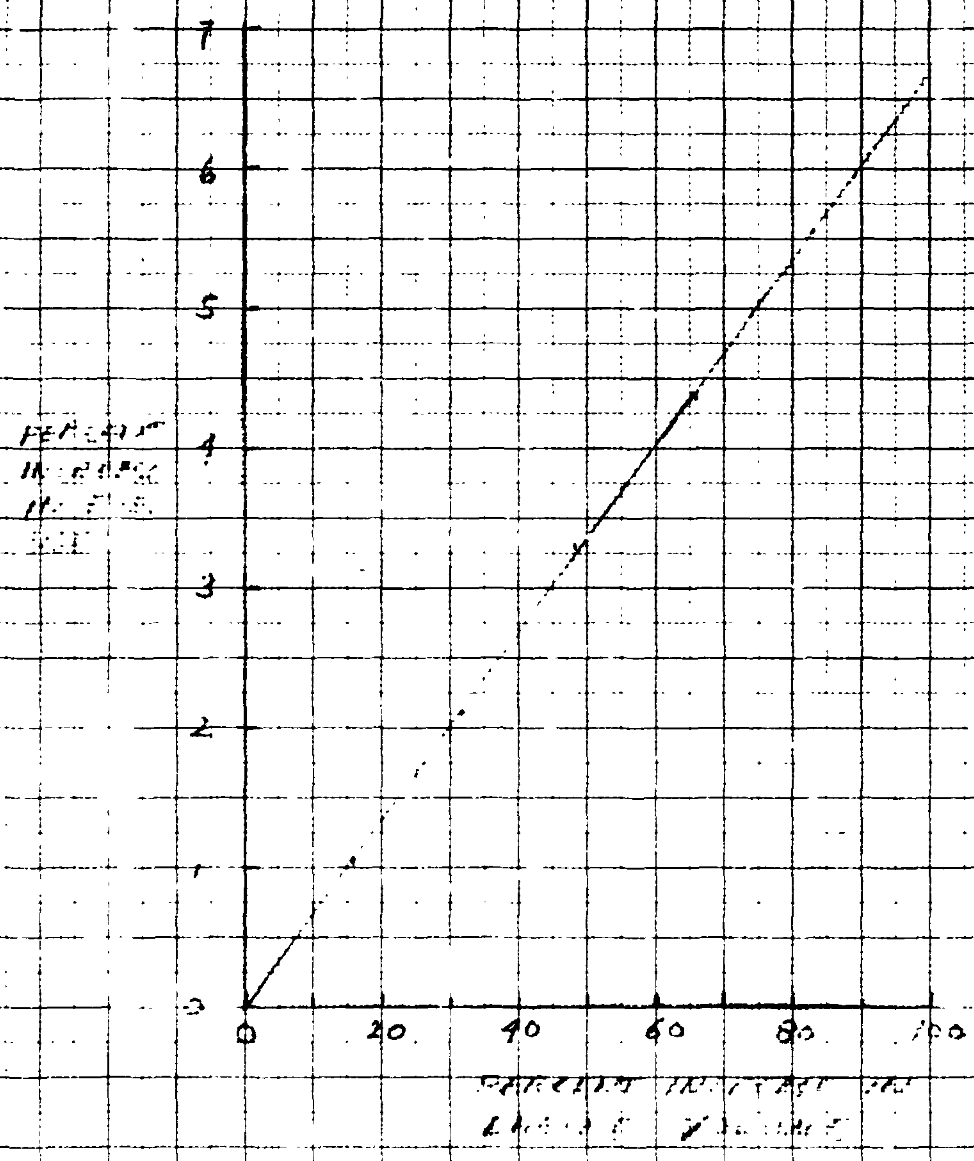


FIGURE 12 — [illegible] INCREASE [illegible]

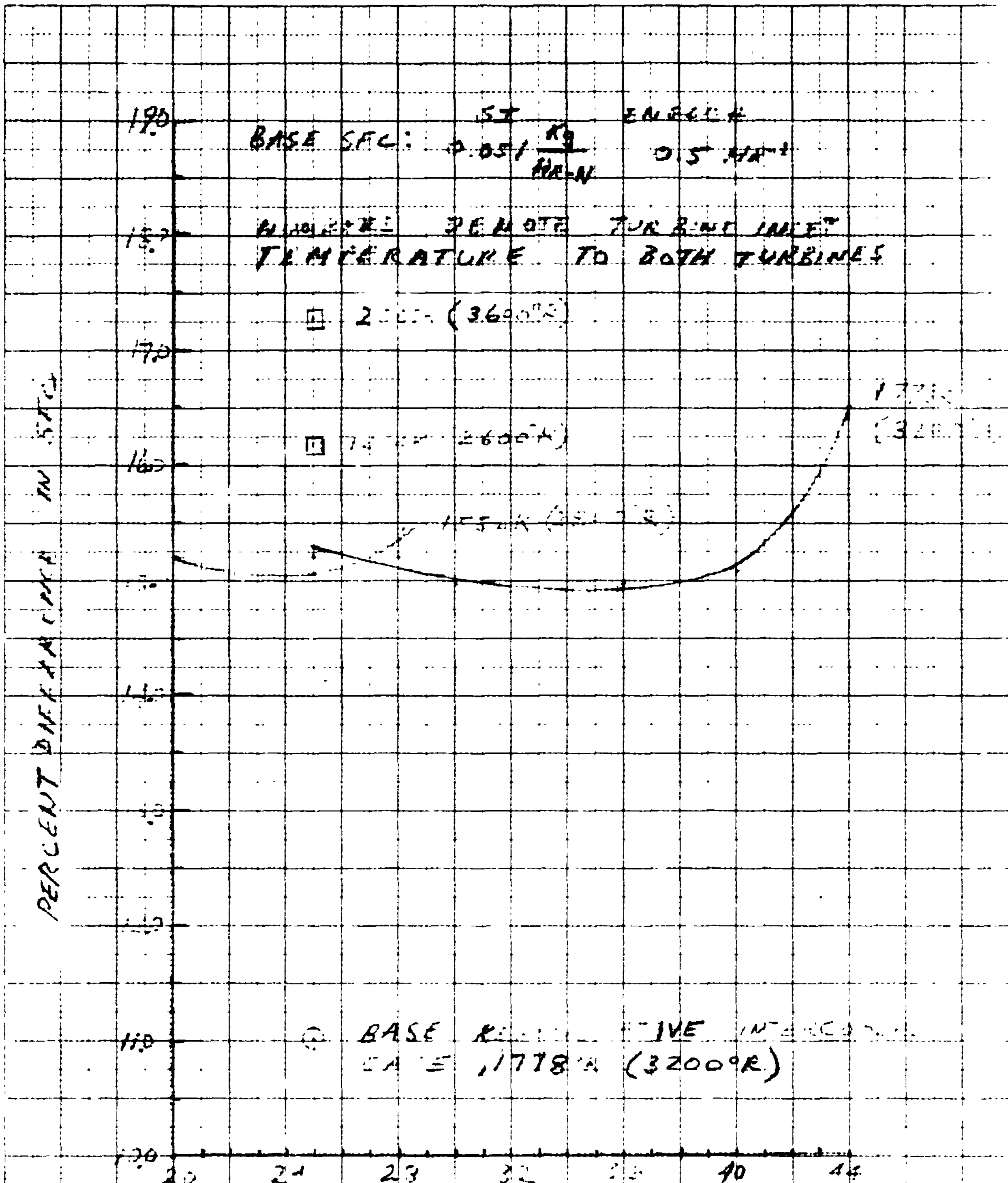


FIGURE 13-SFC ... REGENERATIVE CYCLES WITH REHEAT, AT CRUISE.

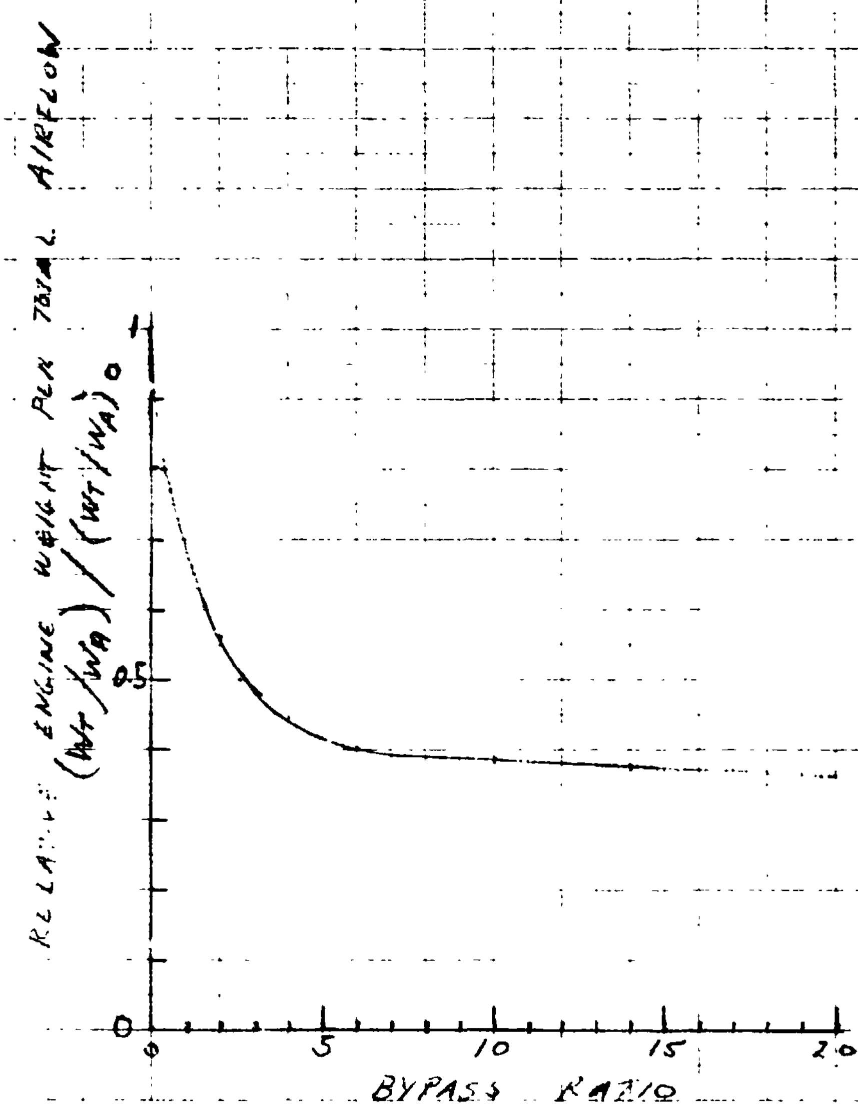


FIGURE 14 - CORRECTION IN ENGINE WEIGHT DUE TO BYPASS RATIO

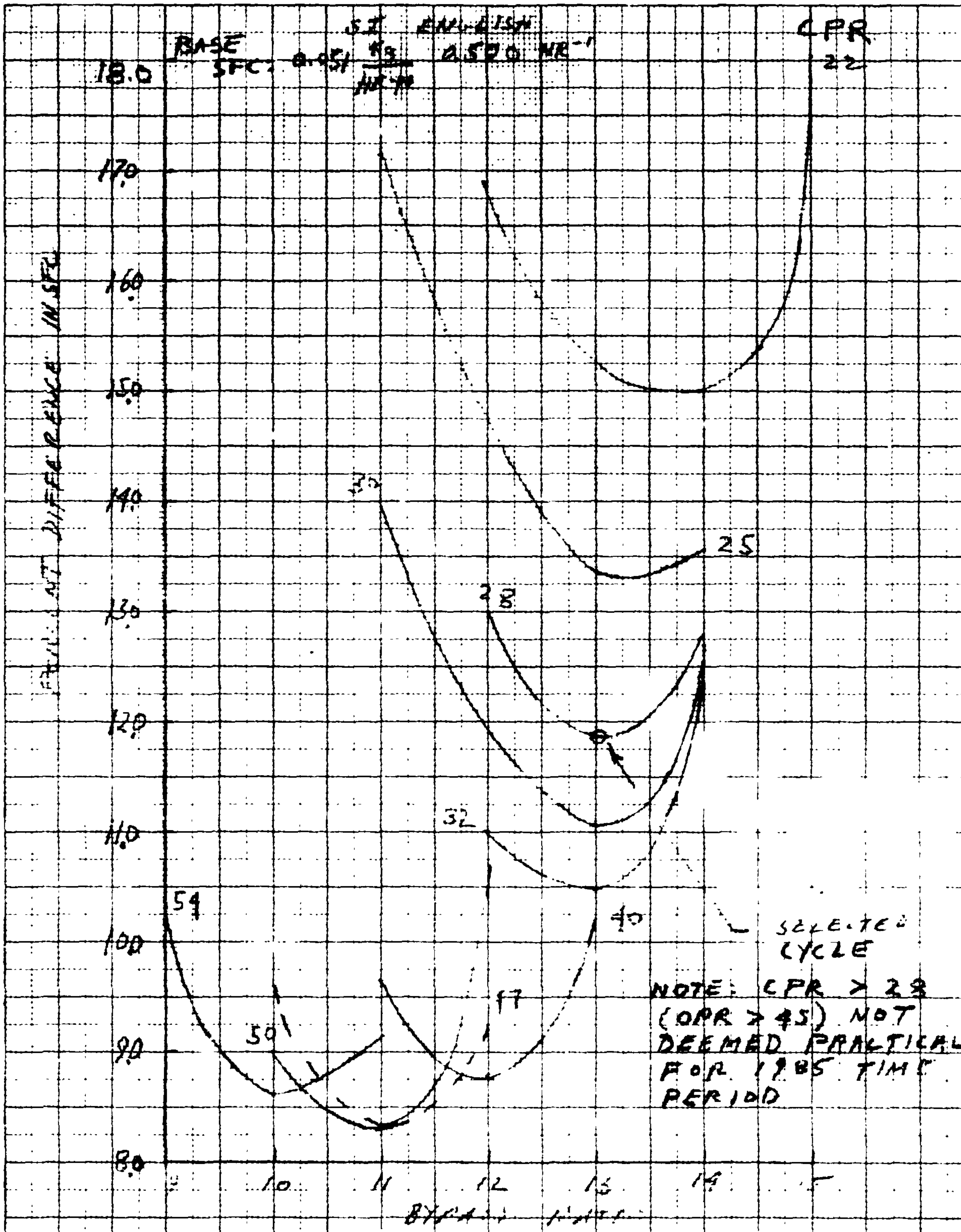


FIGURE 15 - SELECTION OF CONVENTIONAL TURBOFAN BASELINE CYCLE. TIT = 1778 K (3200°R) FPR = 1.6, MACH 0.8, ALTITUDE = 11 582 M (38 000 FT). 1985 TECHNOLOGY

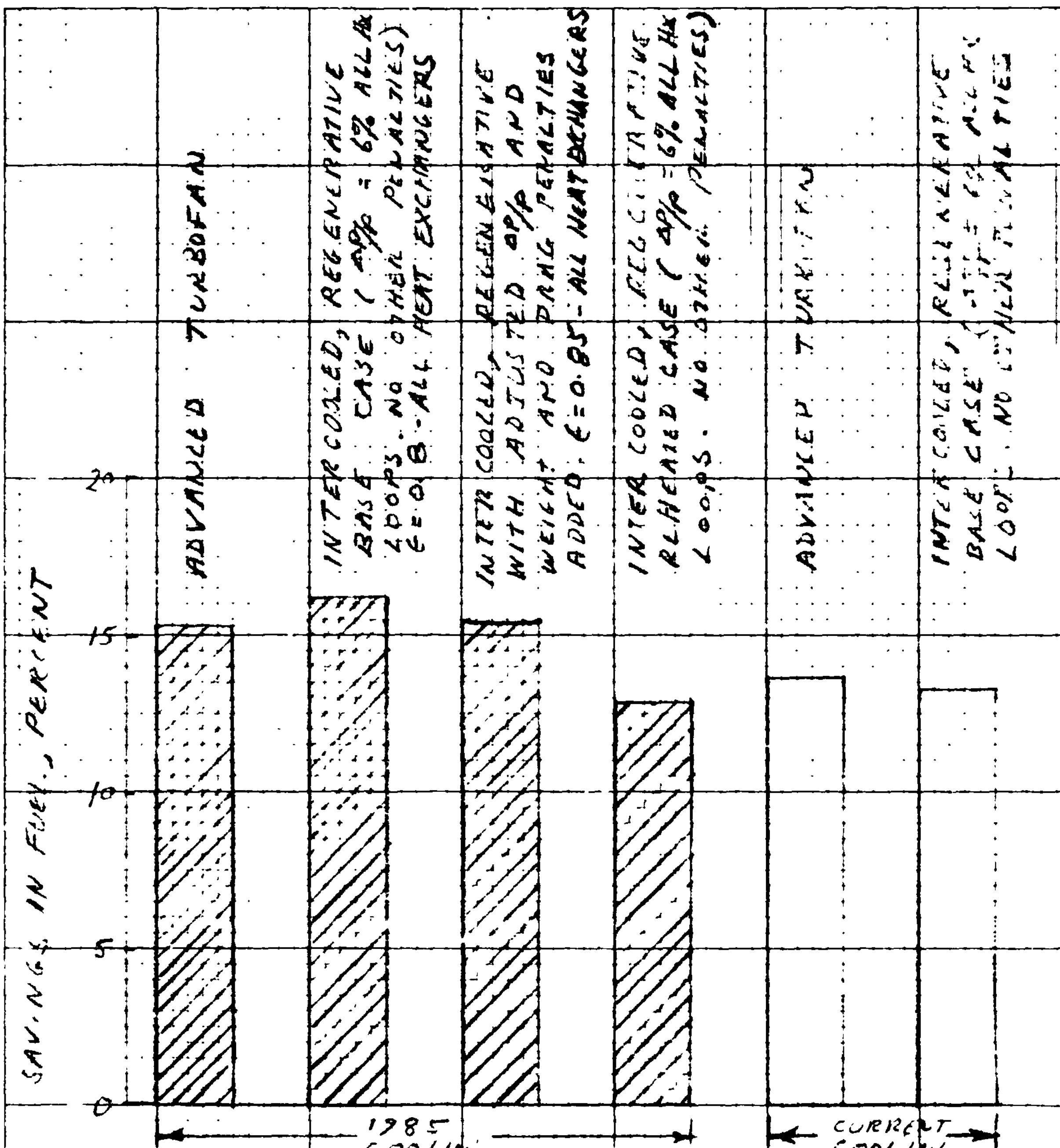


FIGURE 16 - FUEL SAVINGS RELATIVE TO AN AIRCRAFT WITH CURRENT-TECHNOLOGY ENGINES - 230 PASSENGER, 5556 KILOMETER (3000 NAUTICAL MILE), 0.8 MACH NUMBER CRUISE.