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INCREASING THE EMERGENCY POWER RESERVE OF TURBOSHAFT ENGINES

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Summary

Six engines of the same technology and 1080-kW take-off rating at a turbine entry temperature of $T_{4.1}$ = 1500 K are compared with regard to their emergency power reserve. The engines have three basically different compressor designs and two levels of turbine cooling airflow. The engine with the lowest compressor aerodynamic overspeed capability and with turbine cooling designed for take-off rating is considered the basic engine. The emergency power reserve of all engines for sea level and 2000 m altitude is shown for all other engines in comparison to this basic engine.

Emergency power reserve is very much dependent on compressor inlet temperature and several engine limitations, such as corrected speed, mechanical speed, gas generator and power turbine entry temperature. The engine with the lowest fuel consumption, lowest price and weight will be superior with regard to the emergency power reserve at low compressor inlet temperature and worse at high inlet temperature as compared to the basic engine. A design with some penalties in fuel consumption, price, weight and complexity will give a significant increase in emergency power reserve.

Such an engine may be superior to an engine which is merely oversized in order to meet stringent emergency power requirements.

Notations

H	m, km	pressure altitude
M_o	-	flight mach number
N_{GG}	rpm	mechanical gas generator speed
$N/\sqrt{\theta_2}$	rpm	corrected standard day compressor speed
O.P.R.	-	compressor pressure ratio
P	kW	engine output
$P_{T.O.}$	kW	take-off rating (30 min)
$P_{30''}$	kW	emergency rating (30 sec)
SFC	$\frac{g}{kWh}$	specific fuel consumption
T_2	K	compressor inlet temperature
T_3	K	compressor outlet temperature
$T_{4.4}$	K	power turbine entry temperature
$T_{4.1}$	K	HP turbine rotor entry temperature
W_{A2}	$\frac{kg}{s}$	compressor inlet flow
W_{CLHP}	%	cooling air (centrifugal-flow compressor outlet)
W_{CLLP}	%	cooling air (axial-flow compressor outlet)
$W_{4.1\ cor}$	$\frac{kg \cdot \sqrt{K}}{s \cdot bar}$	corrected HP turbine mass flow
θ_2	-	$T_2/288.15$ K

1. Introduction

The size of engine to use in two-engine helicopters is generally ruled by the safety reserve required in the event of a single engine failure. More often than not, therefore, these engines are oversize. In normal service with both engines intact, therefore, they necessarily operate at outputs lower than would be commensurate with optimum mission consumptions.

Harmonisation of engine size with helicopter power requirements can be much improved if the engines mounted on two-engine helicopters are tolerant of brief overloads in the one engine out condition. The amount of power needed for the purpose much exceeds that for the take-off requirement; it is known as emergency power reserve which normally is allowed for single-engine flight of uninterrupted durations not exceeding 20 seconds.

Essential methods to sustain intermittent power boosts for turboshaft engines are listed in ref. 1, which obviates the need for repeating them at this point.

Nor does the present study investigate the measures that in ref. 1 are termed "exotic".

The emergency power available from an engine varies largely with the compressor inlet temperature prevailing at the time the emergency power is needed. In the present paper, therefore, the respective available emergency power is investigated as a function of compressor inlet temperature T_2.

The prime objective of this study is to generate supporting material enabling the helicopter industry to realistically weigh the pros and cons of augmented emergency power reserve for various helicopter designs and mission requirements.

Strictly speaking, the evidence here obtained applies to emergency power augmentation of no engines other than with the 1080-kW take-off rating and its various design variants investigated in this report. It will be appreciated, however, that the evidence can be transferred to some degree also to airframe project applications of other take-off powers.

2. Description of Reference Engines

For indication of the relative merits of various measures to boost the emergency power reserve of turboshaft engines, six engines were compared. They are here termed reference engines 1 through 6.

The air flows of the reference engines investigated were selected to give all engines the same take-off power (1080 kW) at the same turbine entry temperature (1500 K).

The compressor pressure ratios of the engines range from 13:1 to 14:1.

Also the same for all engines was the mechanical design-point speed of the gas generator. Fig. 1 gives the reference engine data for ISA, H = 0 and take-off rating.

The design of the six reference engines is much the same, with engines 1 to 5 reflecting the layout shown in Fig. 2.

The engine shown in Fig. 2 has a combined axial-/centrifugal-flow compressor of three axial-flow stages and one centrifugal-flow stage. The compressor is driven by a single-stage axial-flow gas generator turbine. As a combustion chamber, use was made of a reverse-flow annular type. The shaft horse-power is generated by a two-stage power turbine.

It is only engine 6 which has an additional axial-flow stage in the compressor.

Fig. 1 is a condensed representation of the various engine designs. Ref. 2 gives a closer description of the engine designs.

The reference engines 1 to 6 here compared are all characterised by a relatively simple and economical design. For use on helicopters, they are viewed as a suitable trade-off regarding fuel consumption and complexity of design.

The engine designs were selected to suit various measures taken to boost the emergency power reserve, with the following differences existing among them.

Reference Engine 1

The compressor is designed such that it will run at a high corrected speed $n/\sqrt{\Theta_2}$ already at standard day conditions. The pressure ratio is 14:1 at a relatively low compressor efficiency, which improves accordingly in the part-load range and so makes for a shallow consumption vs. output curve. The remaining reserve, relative to the design point, of corrected speed is a mere 1.5%, owing to the design selected. The maximum allowable turbine entry temperature $T_{4.1}$ is 1597 K emergency power and occurs at a compressor inlet temperature of T_2 = 20°C.

Reference Engine 2

The basic design corresponds to that of the reference engine 1. To raise the temperature margin $T_{4.1}$, the cooling air flow available to cool the high-pressure turbine blades is raised from 3.4% to 4.9% of the compressor flow. The raise in cooling air flow lowers the HP turbine efficiency by 1%. Cooling is provided also for the stage 1 inlet guide vanes of the power turbine, and 1.5% of the compressor air flow are diverted for this purpose at a point upstream of the centrifugal flow compressor. As a result of improved cooling the maximum turbine entry temperature $T_{4.1}$ at emergency power can be raised to 1623 K. This figure occurs at a compressor inlet temperature of T_2 = 25°C.

<u>Reference Engine 3</u>

This engine uses a compressor of the same technological background as reference engines 1 and 2. But it is designed for a lower corrected speed, at the design point, than are reference engines 1 and 2. This widens the speed margin from 1,5% to 5%, while the compressor pressure ratio falls from 14:1 to 13:1 and the compressor efficiency improves at the design point.

The maximum part-load efficiency of the compressor is the same for all engines under study.

Engine 3 reflects a typical conventional design. The maximum turbine entry temperature at emergency power is $T_{4.1}$ = 1585 K and is limited by the maximum allowable entry temperature ($T_{4.4}$) of the uncooled power turbine.

<u>Reference Engine 4</u>

The design of this engine corresponds to that of engine 3, except that the stage 1 inlet guide vanes of the power turbine are cooled, where similarly to reference engine 2, 1.5% of the compressor air flow are bled from a point upstream of the centrifugal-flow compressor. The maximum turbine entry temperature at emergency power increases to 1629 K at a compressor inlet temperature of T_2 = 5°C.

<u>Reference Engine 5</u>

The compressor design of this engine is the same as that of engines 3 and 4, and it has the same overspeed margin of 5%.

It differs from engine 4 by more intensive cooling of the high-pressure turbine blades, where similarly to engine 2, 4.9% of the compressor air flow are diverted.

While more intensive cooling causes the turbine efficiency to drop, the maximum temperature at emergency power can safely be raised. It is 1662 K at $T_2 = 15°C$.

Reference Engine 6

The design of engine 6 incorporates all features considered helpful in the interest of improved emergency power reserve. At the design point the compressor operates at a still lower corrected speed than do engines 3, 4 and 5, with an axial-flow compressor stage being added to raise the pressure ratio at the design point to 14:1 as for engines 1 and 2. This design permits the maximum corrected speed to be raised to 107%, which adds two percentage points to the margin of engines 3, 4 and 5. The turbine cooling arrangement is the same design as that for engines 2 and 5. This design permits the engine 6, at practically the same low specific fuel consumption as for engine 3, to use a maximum turbine entry temperature at emergency power of 1685 K versus 1585 K for engine 3. This high-level temperature is achieved at a compressor inlet temperature of a mere -5°C.

3. Rating Structure of Reference Engines

The six reference engines are using the same concept for the turbine entry temperature vs. compressor inlet temperature profile for all ratings except emergency.

Starting from the design point (designated ADP in Fig. 3), the turbine entry temperature vs. T_2 profile is selected such that the helicopter will have a constant excess power until the compressor inlet temperature T_2 equals 25°C. At temperatures above that the turbine entry temperature is lowered such that the material temperature of the HP turbine blades remains constant. At the design point $T_{4.1}$ equals 1500 K.

For max. continuous power, the temperature $T_{4.1}$ is lowered by 50 K in all compressor inlet temperature ranges T_2 for which it is intended to certify the engine. This deduction results from the service life requirements imposed on helicopter engines.

For max. contingency power (2.5 min. power) the temperature $T_{4.1}$ can be raised a mere 35 K above T_2 = 25°C. The profile is selected such that, again, the material temperature of HP turbine blades remains constant. For all compressor inlet temperatures below 25°C the turbine entry temperature is assumed to be a constant $T_{4.1}$ = 1550 K.

On days of temperatures below 25°C, additional power becomes available for added safety in the event of single-engine failure.

At low temperatures the profile of the above-mentioned rating temperatures are limited when the maximum corrected speed is reached.

For emergency power (30 sec max. duration), the maximum value varies with the engine design and, accordingly, is not the same for all six reference engines. The maximum corrected speed, too, is reached at higher temperatures T_2 for engines 1 and 2 than for engines 3, 4 and 5, which admit of higher corrected speeds. Engine 6, finally, reaches this limit at a T_2 that is still lower than that for engines 3, 4 and 5. Plotted in Fig. 3 as an example of the rating temperatures selected are those of reference engine 3.

The altitude range studied was, again, 0 to 3 km at compressor inlet temperatures ranging from about -45°C to +45°C as in Fig. 5.

The number of limitations applicable to engine 1 is here raised by another three. At H = 0 this primarily involves the maximum fuel flow. From the design aspect this limitation can readily be shifted, although this will involve additional costs for the fuel system in that the ratio of the maximum to the minimum fuel flow to be selected will increase.

Further limitations are imposed by the maximum mechanical speed N_{GG} of the gas generator, and by the entry temperature $T_{4.4}$ of the power turbine.

The latter limitation can be influenced by cooling the stage 1 inlet guide vanes of the power turbine.

The increase in maximum gas generator speed has a tremendous impact on the engine design, where the strength reserve of the rotor discs needs investigating as much as do issues regarding the critical speed margin.

The rise in turbine entry temperature $T_{4.1}$ with rising engine output varies with the engine design and so also with the degree to which the compressor and the gas generator turbine are attuned one to the other. Plotted in Fig. 7 is the turbine entry temperature vs. engine power profile for the six reference engines. As it will readily become apparent the temperature of engines having a considerable reserve relative to $N/\sqrt{\Theta_2}$ will grow less steeply than that of engines having a more moderate aerodynamic overspeed reserve. The rise of $T_{4.1}$ above take-off power will therefore be steepest with engines 1 and 2, while with engine 6 the profile is the most shallow.

At emergency power conditions, however, control of the turbine entry temperature is not made dependent solely upon a constant material temperature of the high-pressure turbine.

With all six reference engines the compressor exit temperature T_3 is maintained at a constant level. This prevents the centrifugal-flow compressor and HP turbine disc from being overloaded.

The rating temperatures shown in Fig. 3 produce the H = 0 and Mo = 0 ratings shown in Fig. 4 for reference engine 3.

As it will also become apparent from Fig. 4, the emergency power is restricted by various limits. These limits vary among the six reference engines under study and make themselves felt also at varying compressor inlet temperatures T_2.

4. Emergency Power Reserve of Reference Engines

4.1 Limitation of available Emergency Power Reserve

The emergency power reserve available from any one engine is subject to various limitations. In the most simple instance these are the maximum corrected speed $N/\sqrt{\theta_2}$ and the maximum turbine entry temperature $T_{4.1}$.

Fig. 5 illustrates the emergency power performance of reference engine 1. For all 0 to 3 km altitudes studied the power has no limitations other than the two just mentioned.

If these limitations are shifted towards higher values, however, as when increasing the speed margin and raising the maximum overtemperature, these limitations will not have been reached before other limitations arise to restrict the emergency power reserve. This is exemplified in Fig. 6 by way of reference engine 3.

The inconsistencies in the profiles are attributable to the different temperatures at which the various limits restrict the output of the engines under study.

Plotted in Fig. 8b similarly to the representation in Fig. 8a are the corresponding values for H = 2000 m. The shapes of the curves are comparable in character. At low temperatures the maximum attainable value of corrected speed again imposes the major limitation on the power output.

Compressor inlet temperatures equal to or exceeding T_2 = 30°C are rare occurrences at an altitude of 2000 m. This is why the power relationships at temperatures about T_2 = 0°C are of special interest at this altitude.

5. Consequences of Emergency Power Reserve for Reference Engines

5.1 Impact on Reference Engine Fuel Consumption

Once the emergency power reserves of the six reference engines are known, it remains to be seen what other properties of the engines, as perhaps specific consumption, weight and cost, may be affected by the various measures taken to raise the emergency power.

Differences in specific consumption are viewed first. They are shown in Fig. 9, where all values are referred to the consumption of engine 1 at take-off rating (1080 kW) and H = 0, ISA.

Considering that all engines base on the same technology, the differences becoming apparent from Fig. 9 are attributable to differences in the cycle and to the respective effect of attuning components one with the other. For engines 1 and 2, the specific fuel consumption vs. output profile is relatively shallow, which is explained by the fact that the compressor, at 100% power, operates at a

4.2 Comparison of Reference Engine Emergency Power Reserves

The emergency power reserve available from a single engine is subject to various limitations described in the chapter above. Inasmuch as these limitations may in turn be a function of the compressor inlet temperature, the emergency power available will vary largely with the compressor inlet temperature T_2.

Fig. 8a shows the emergency powers available from all 6 reference engines referred to that of engine 1, which will become apparent from Fig. 5.

There are two typical regions: at low temperatures (T_2 = 0°C) it is the maximum possible corrected speed which determines the level of the emergency power available from each engine (without fuel flow limit).

The engines 3, 4 and 5 show a 15% to 16% gain in emergency power below T_2 = 0°C and engine 6 gains fully 30% over engines 1 and 2.

In the second characteristic regime in which limitations other than corrected speed will determine the level of emergency power available, the various engines have rather different emergency power profiles. If emergency power at T_2 = 28°C is taken as a point for comparison, engines 1, 3 and 4 will reach the same value at this temperature, while engine 2 reaches an additional 4.5%, engine 5 additionally about 8.5% over engine 1, and engine 6 a whopping 17% boost in emergency power. When comparing the reference engines with one another, engine 2 is notably the single engine of rising emergency power profile at $T_2 \geqq$ 20°C.

The emergency power is here limited by the turbine entry temperature $T_{4.1}$. This is the range in which the compressor efficiency will improve.

little more; reference engine 2 weighing an extra 2.5 kg. The extra weight of engine 6 is in that vicinity, at 2.3 kg. At a basic weight of 155 kg for engine 1, these changes amount to 1 or 2 percentage points.

Fig. 11 illustrates the differences in the cost of the 6 reference engines. The tendencies here are somewhat like those for weights, but a point to remember is that the cooling provisions for the stage 1 of the power turbine add to the complexity of construction and, therefore, to the price.

The same holds true, e.g. with engine 6, for the addition of an axial-flow compressor stage.

Compared with the other engines, engine 3 is the lowest in weight and cost alike. Referred to engine 1, the cost of engine 6 is up 3,5%, but on hot days it will provide maximally 18% more emergency power than engine 3 (which costs 0.7% less than engine 1).

It is only an assessment of all criteria, including output, consumption, weight and cost, which will enable the respective optimum engine concept to be selected for a given mission.

relatively high corrected speed and no longer achieves any notably good efficiency. In the part-load range, e.g. at 60% of take-off rating, the curve of engine 1 again approaches those of engines 3 and 4. The differences in consumption between engine 1 and engine 2 and that between engine 4 and 5, is attributed to the raised cooling air demand and the lower efficiency of the high-pressure turbine. The cooling air of the stage 1 inlet guide vanes of the power turbine raises the fuel consumption by a modest 0.35% (cf. difference between engine 3 and engine 4).

Worth noting here is that engine 6 reaches practically the same consumption as engine 3, which is best in this respect. Whereas the emergency power it can provide on hot days is superior to that of engine 3 by fully 18%.

It will be up to the helicopter makers to determine whether or not the different emergency power reserves of the reference engines 1 to 6 will permit the use of engines of reduced take-off power for an envisioned application. Fig. 9, therefore, will not permit any inferences to be made regarding the mission consumptions of the various engines.

In applications in which a great amount of emergency power enables the rated output of the engine to be reduced, an engine like reference engine 6 would afford advantages in mission consumption.

5.2 Impact on Weight and Cost of Reference Engines

For an assessment of the various emergency power reserves of the reference engines, the attendant changes in weight and cost will necessarily need exploring.

Fig. 10 is a survey of the differences in weight of the reference engines 1 to 6 under study. The differences all refer to the basic weight of engine 1. While engine 3 weighs less than any of the others, engine 4 and 5 weigh

Data of Reference Engines

T.O.-Power, ISA, $H = 0$, $M_0 = 0$

Reference Engine	1	2	3	4	5	6
Design	3A + 1R + 1A + 2A					4A + 1R +1A + 2A
W_{CLHP} (% W_{A2})	3,4	4,9	3,4	3,4	4,9	4,9
W_{CLLP} (% W_{A2})	0	1,5	0	1,5	1,5	1,5
max. % $N/\sqrt{\Theta_2}$	101,5	101,5	105,0	105,0	105,0	107,0
O.P.R.	14	14	13	13	13	14
$W_{4.1\,Cor.}$ $\frac{kg \cdot \sqrt{K}}{s \cdot bar}$	10,6	11,0	10,8	10,9	11,2	10,2
SFC $\left[\frac{g}{kWh}\right]$	287	299	281	282	290	282
W_{A2} $\left[\frac{kg}{s}\right]$	3,81	4,09	3,61	3,68	3,84	3,79
max. $T_{4.1}$ [K] at Emergency Rating	1597 (20°C)	1623 (25°C)	1585 (10°C)	1629 (5°C)	1662 (15°C)	1685 (−5°C)

For all Engines at T.O.-Power, ISA, $H = 0$, $M_0 = 0$: $P_{min\,T.O.} = 1080$ kW, $T_{4.1} = 1500$ K, $N_{GG} = 100$ %

Fig. 1

Design of Reference Engine 3 and Station Identification

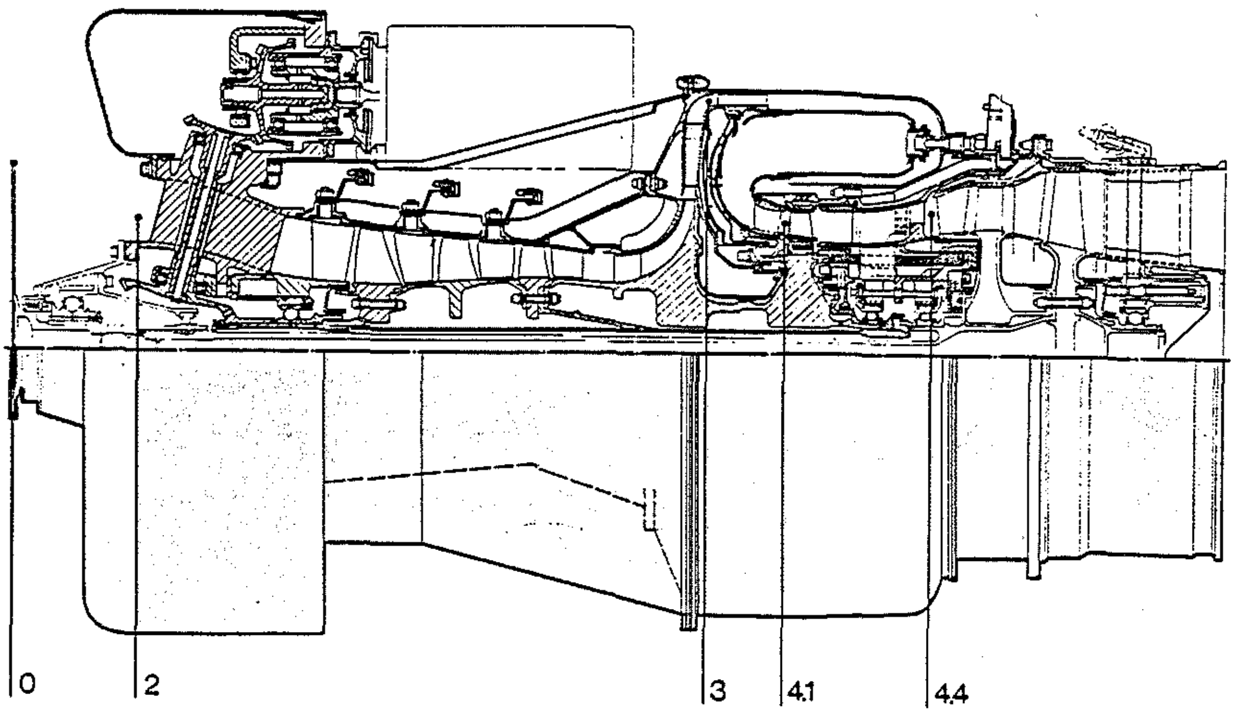

Fig. 2

References

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2) K. Trappmann: New Technology in an All New Heilicopter Engine - The Engine Designer's Answer to the Requirements of Today.
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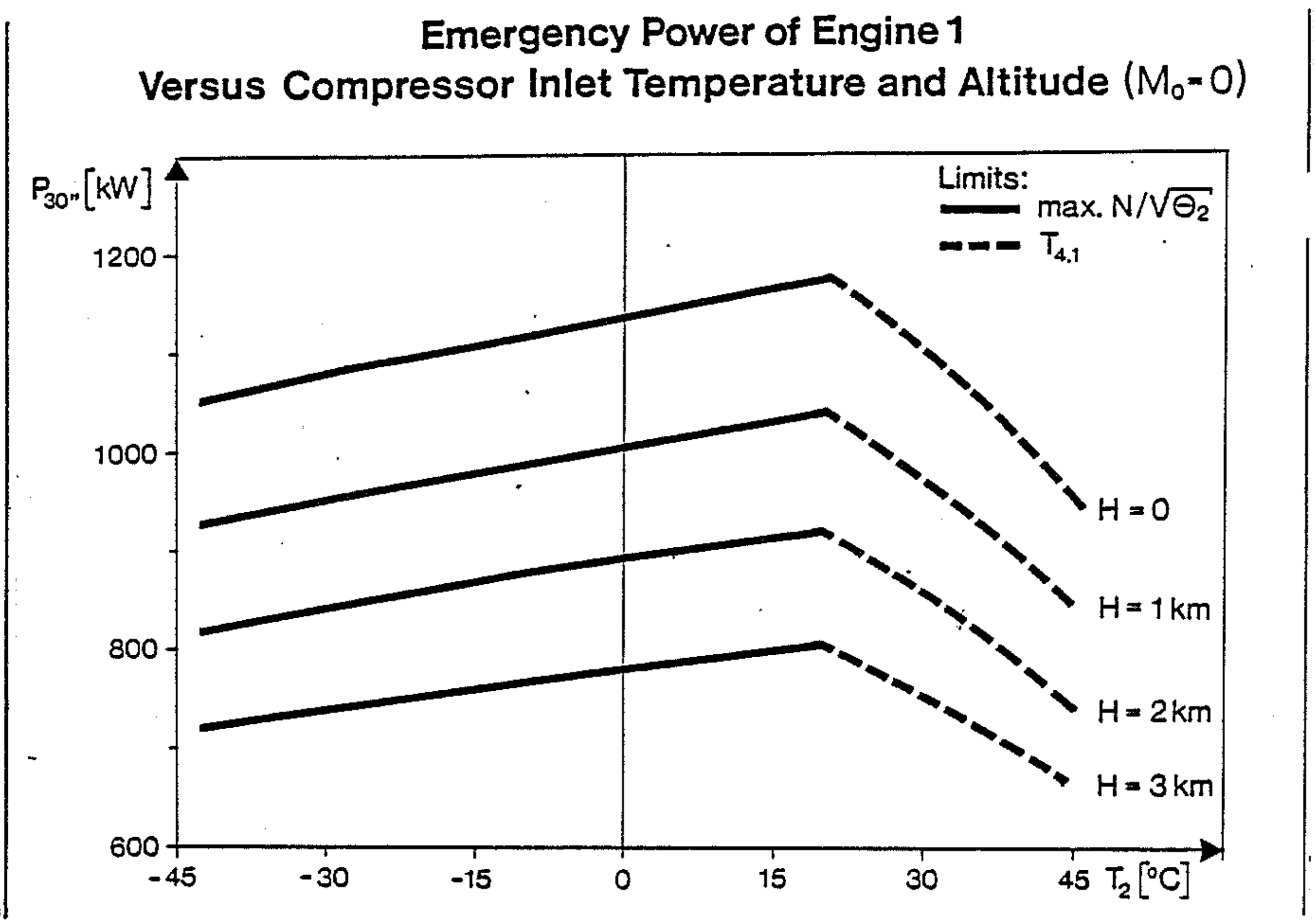
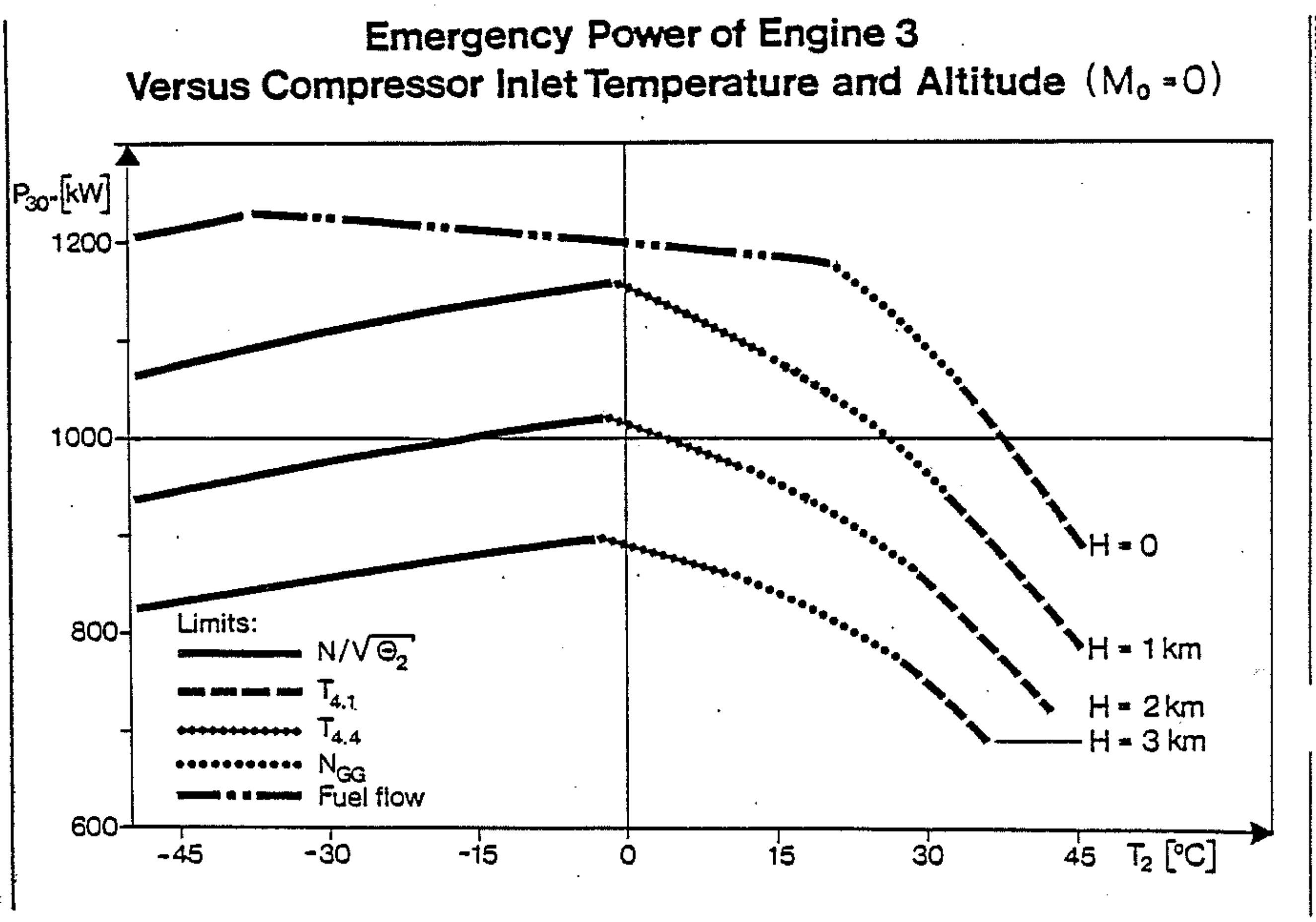

Emergency Power of Engine 1
Versus Compressor Inlet Temperature and Altitude (M₀=0)
P30" [kW]
1200
1000
800
600
-45
-30
-15
0
15
30
45
T2 [°C]
Limits:
max. N/√Θ2
T4.1
H = 0
H = 1 km
H = 2 km
H = 3 km


Emergency Power of Engine 3
Versus Compressor Inlet Temperature and Altitude (M₀ = 0)
P30" [kW]
1200
1000
800
600
-45
-30
-15
0
15
30
45
T2 [°C]
Limits:
N/√Θ2
T4.1
T4.4
NGG
Fuel flow
H = 0
H = 1 km
H = 2 km
H = 3 km

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Rated Temperatures of Reference Engine 3 VS Compressor Inlet Temperature T_2

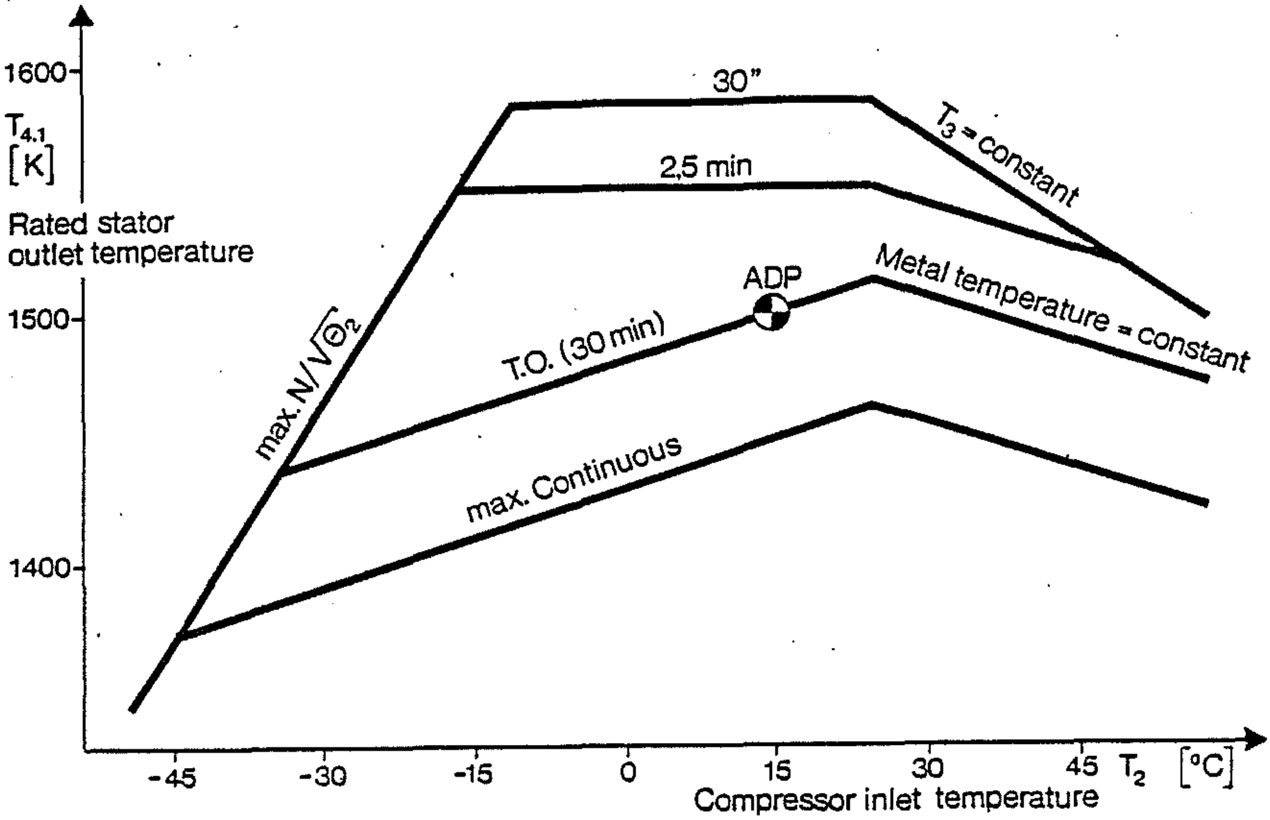

Fig.3

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Ratings of Engine 3 Versus Compressor Inlet Temperature (H = 0, M_0 = 0)

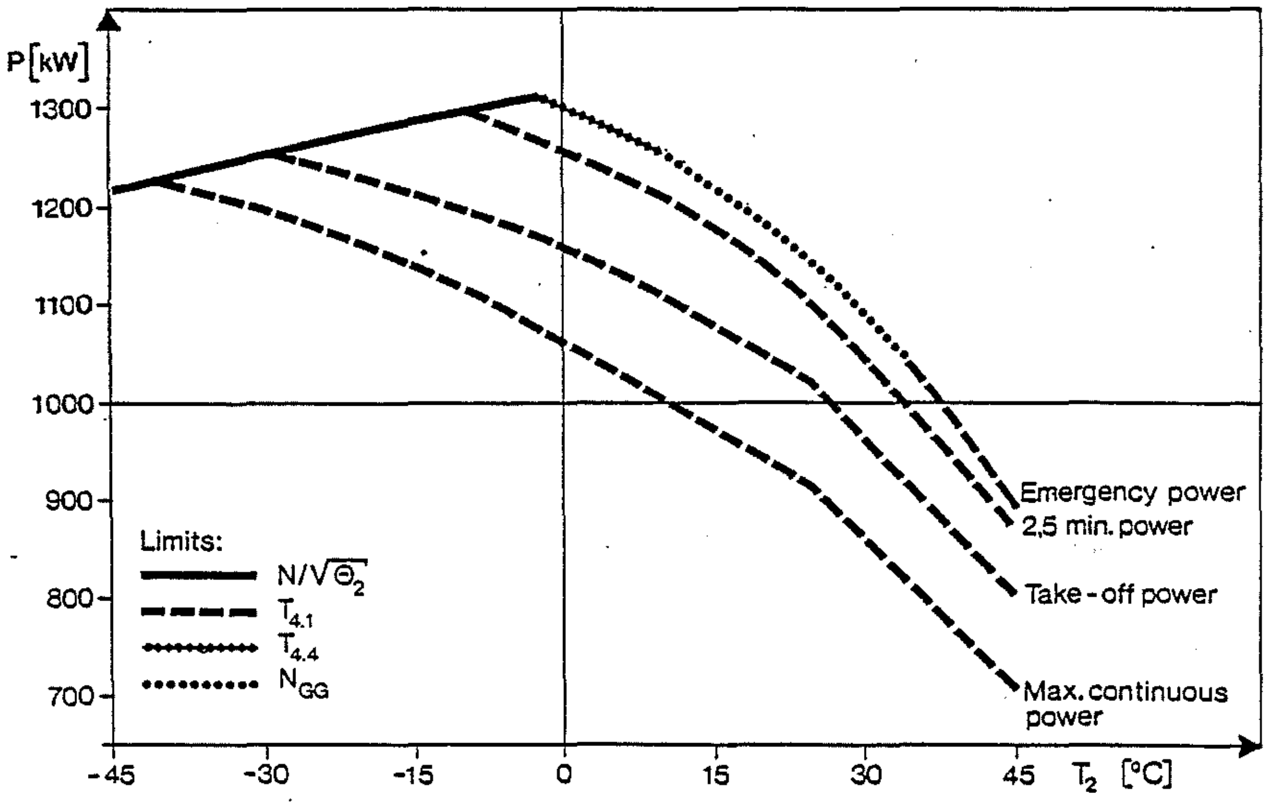

Fig. 4

Relative Emergency Power Versus Compressor Inlet Temperature
(H=0, M_0 = 0)

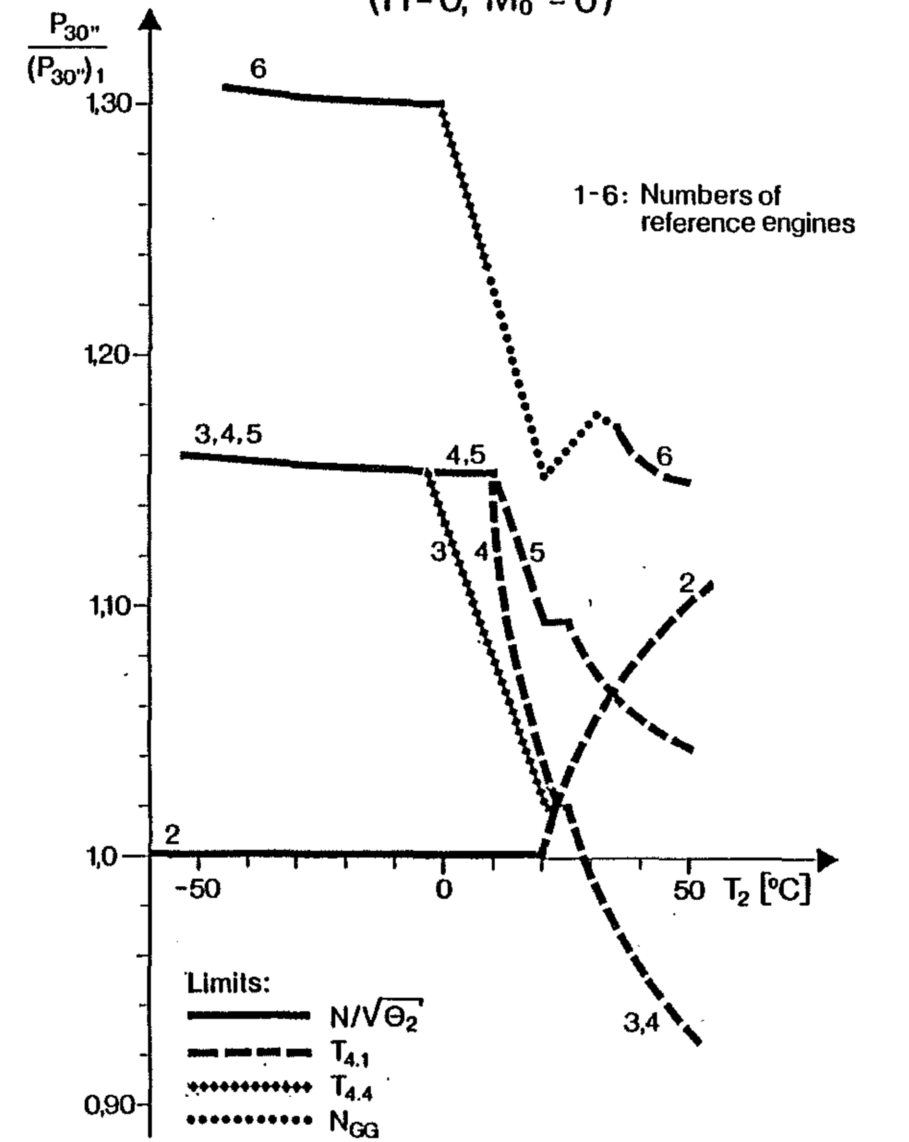

Fig. 8a

Relative Emergency Power Versus Compressor Inlet Temperature
(H=2000m, M_0 = 0)

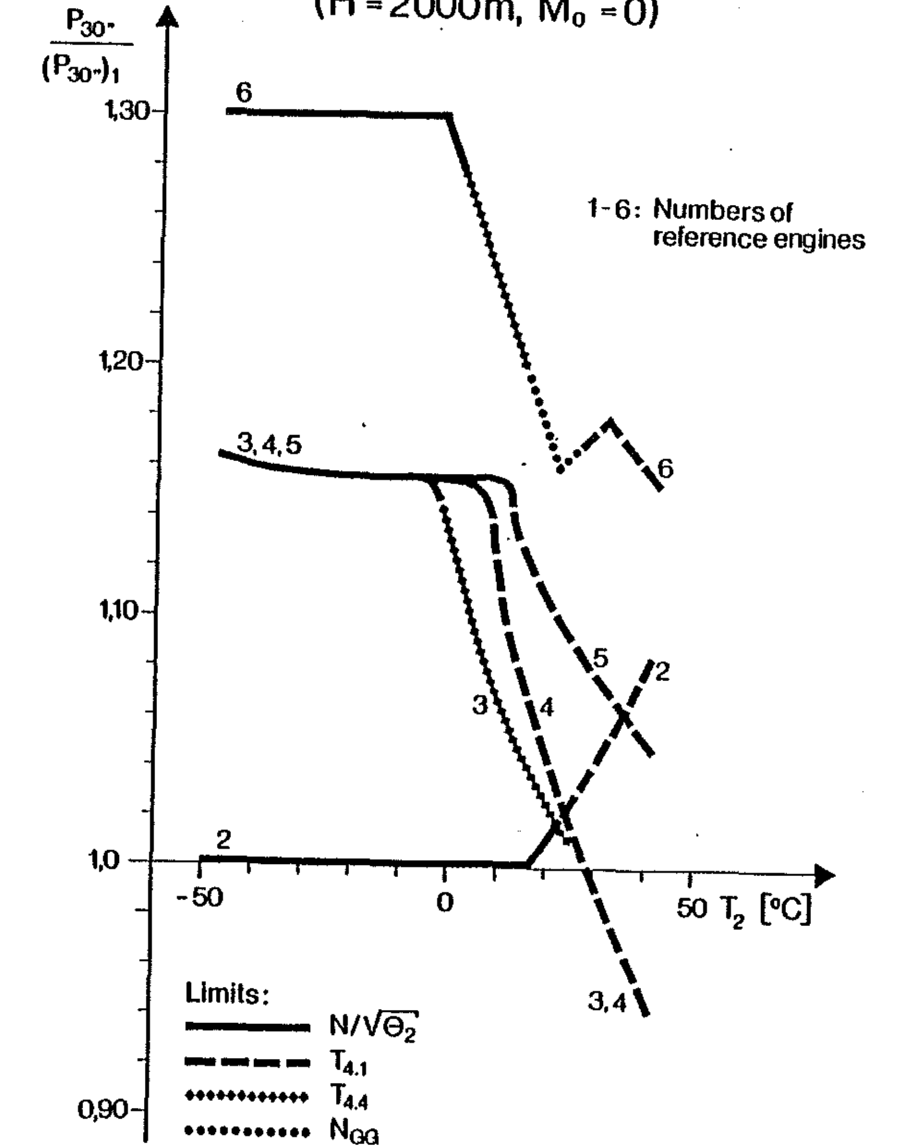

Fig. 8b

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Turbine Inlet Temperature Versus Shaft Power

H=0, ISA, M_0 = 0

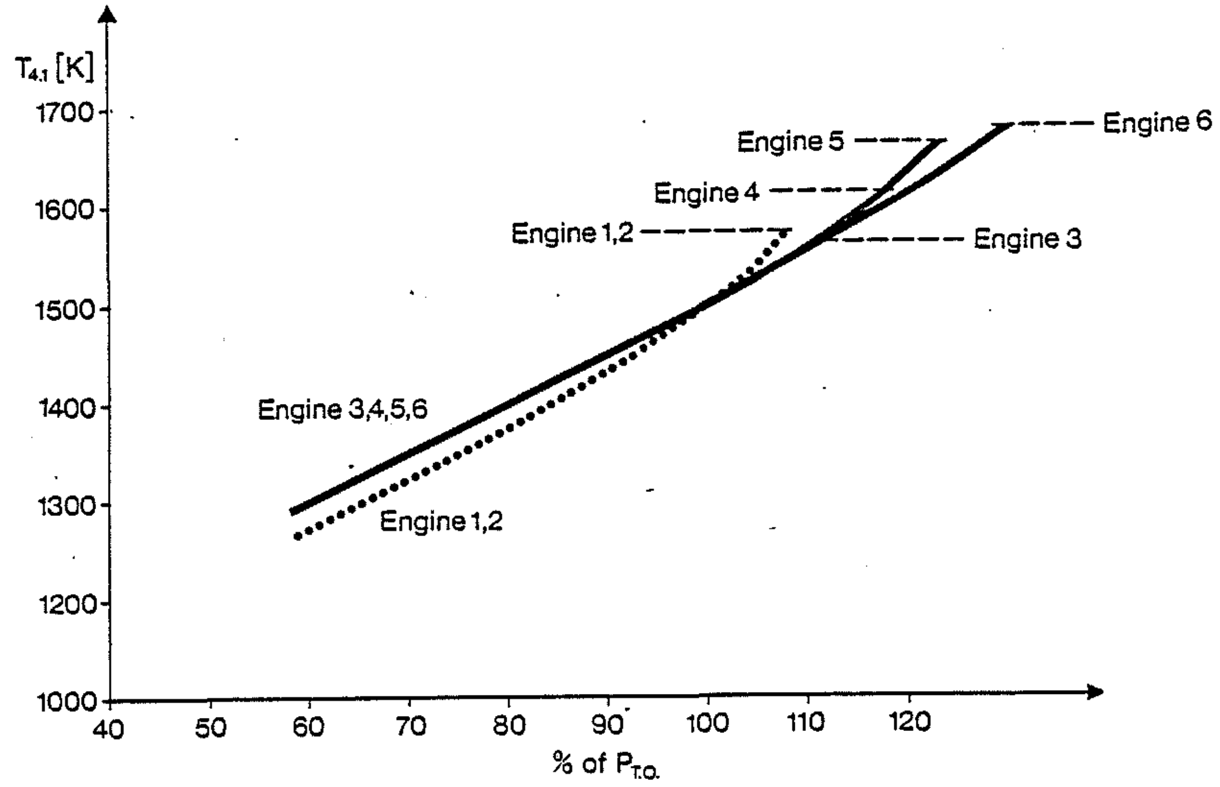

Fig.7

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Relative Specific Fuel Consumption of Reference Engines

(H = 0, ISA, M_0 = 0)

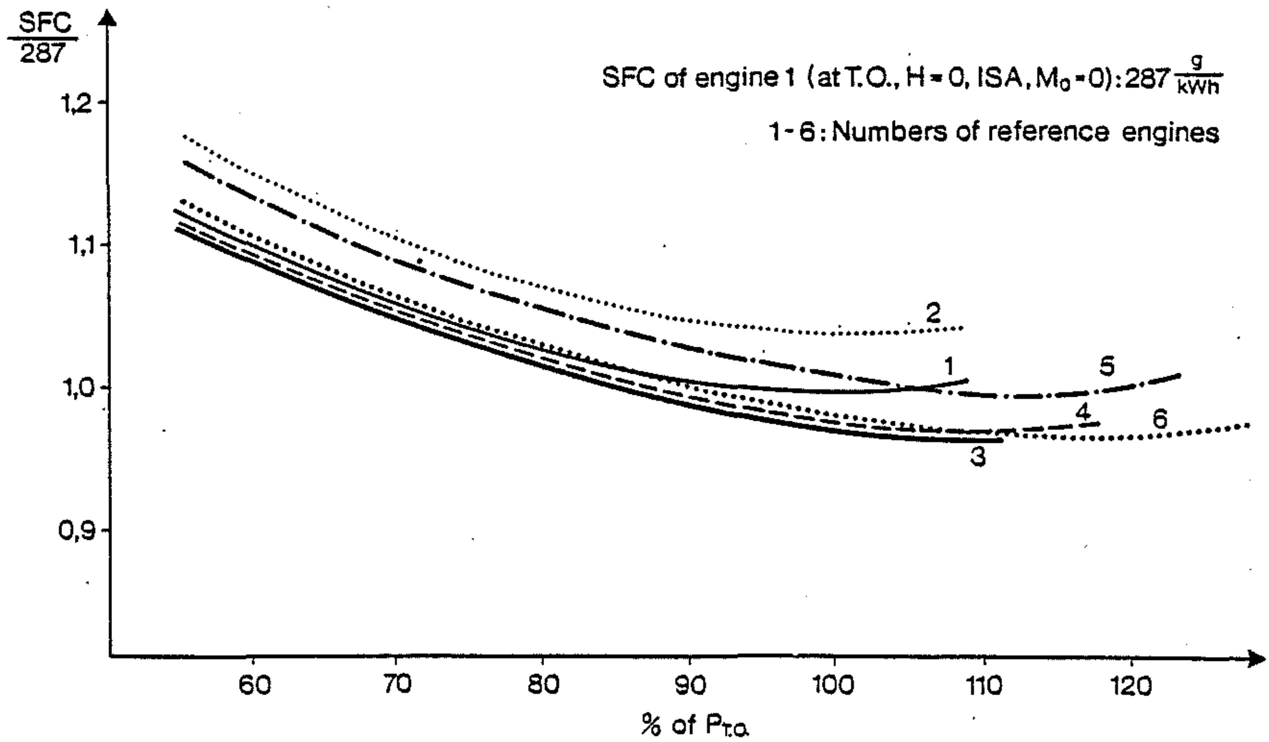

Figure 9

Weight Difference of Reference Engines

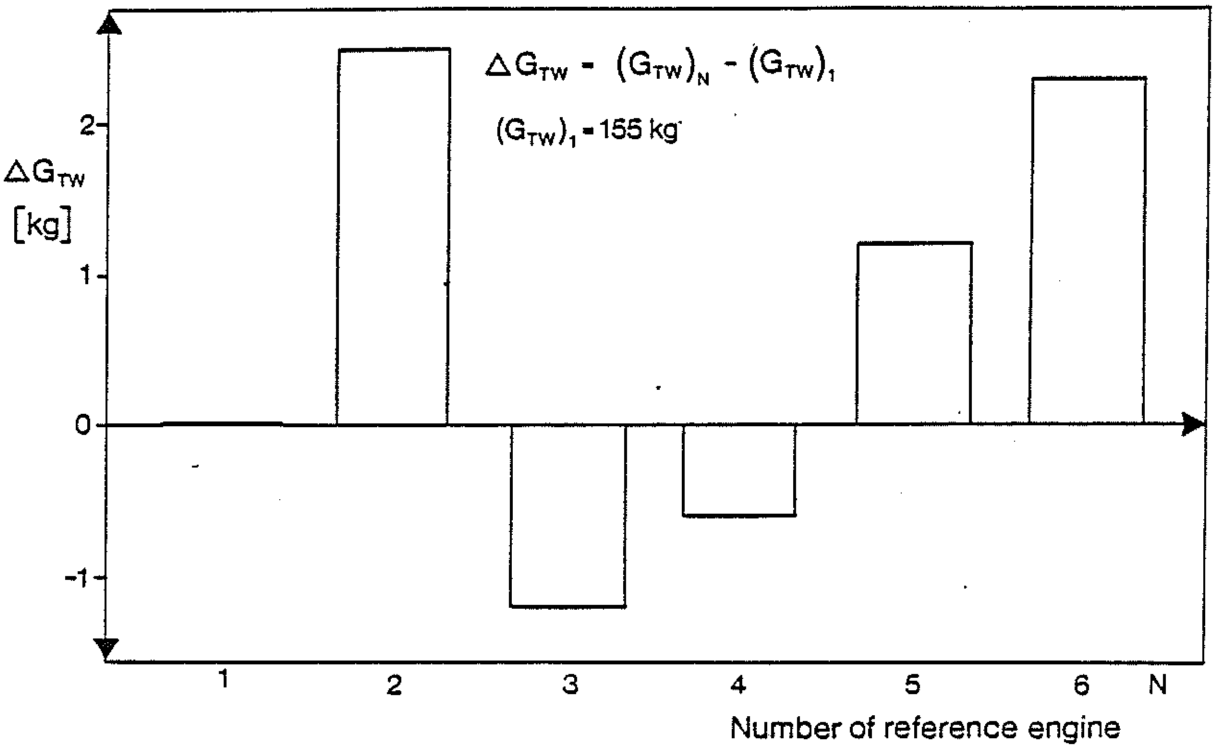

Fig. 10

Cost Difference of Reference Engines
Δc = % Cost Difference Relative to Reference Engine 1

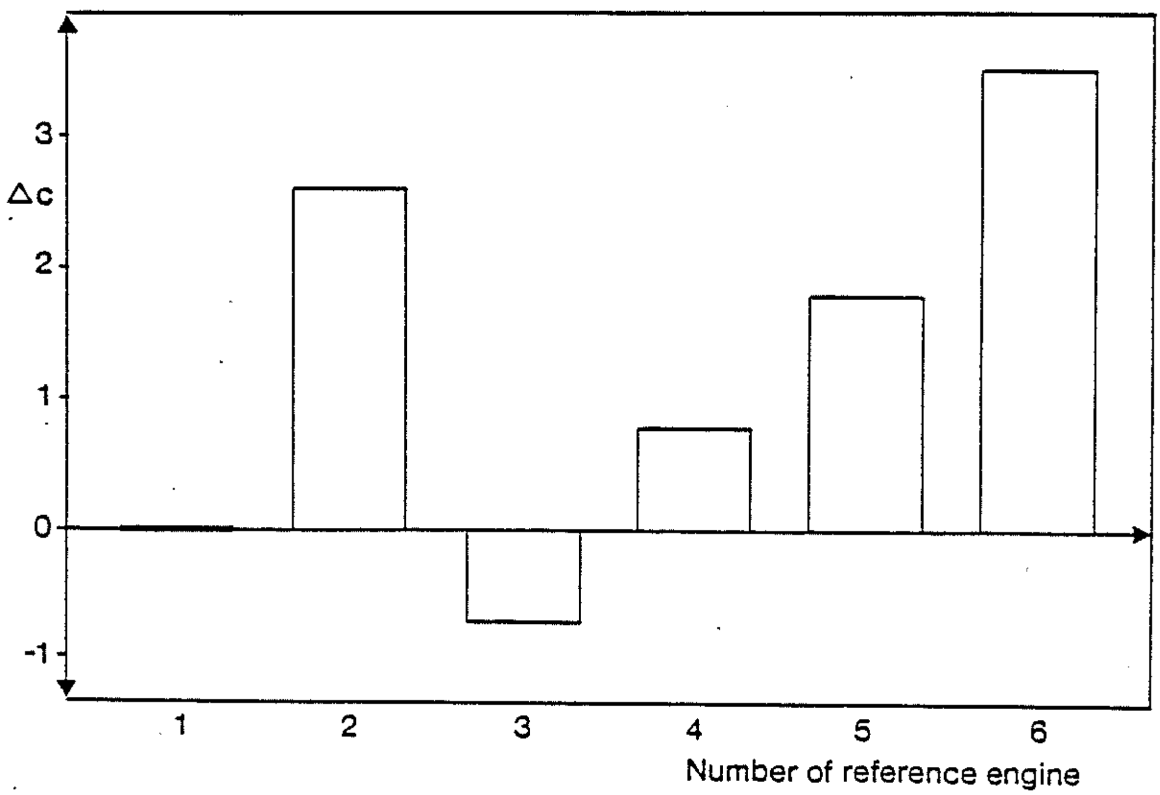

Fig. 11