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PRELIMINARY EVALUATION OF A TURBINE/ROTARY COMBUSTION COMPOUND ENGINE FOR A SUBSONIC TRANSPORT

by Kestutis C. Civinskas and Gerald A. Kraft
Lewis Research Center and
U.S. Army Air Mobility R&D Laboratory
Cleveland, Ohio 44135
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16. Abstract

A study was performed comparing the fuel consumption of a modern compound engine with that of an advanced high pressure ratio turbofan. The compound engine was derived from a turbofan engine by replacing the combustor with a rotary combustion (RC) engine. A number of boost pressure ratios and compression ratios were examined. Cooling of the RC engine was accomplished by heat exchanging to the fan duct. Performance was estimated with an Otto-cycle for two levels of energy lost to cooling. The effects of added complexity on cost and maintainability were not examined and the comparison was solely in terms of cruise performance and weight. Assuming a 25 percent Otto-cycle cooling loss (representative of current experience), the best compound engine gave a 1.2 percent improvement in cruise TSFC. Engine weight increased by 23 percent. For a 10 percent Otto-cycle cooling loss (representing advanced insulation/high temperature materials technology), a compound engine with a boost PR of 10 and a compression ratio of 10 gave an 8.1 percent lower cruise TSFC than the reference turbofan.

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SUMMARY

A study was made of a compound engine for possible use in subsonic commercial transports. The engine was derived from a conventional turbofan by replacing the combustor with a rotary combustion (RC) engine. The RC engine provided shaft power as well as exhaust gases that could be further expanded through a power turbine. The compression ratio and boost pressure were varied parametrically in an attempt to maximize the overall cycle's performance. Four boost pressure ratios (1.75, 4, 10 and 20) and three compression ratios (5, 7, and 10) were examined. The highest overall cycle pressure ratio considered (before combustion) was 240. The RC engine's performance was estimated using a throttled Otto-cycle with an equivalence ratio of 1.0. The Otto-cycle assumed octane fuel which has about a 4% higher heating value than the JP used in the reference turbofan. Cooling of the RC engine was achieved by heat exchanging to the fan duct flow. Two levels of Otto-cycle input energy lost to cooling were considered. A 25% loss case was run as being indicative of Otto-cycle experience to date. A 10% loss case was run as being representative of advanced insulation/high-temperature materials technology that would reduce the heat loss from the Otto-cycle. The same level of turbine cooling technology was assumed for the compound engine as for the reference turbofan. The effects of manifold ducting losses and of unsteady flow on turbine efficiency were initially not included, but the sensitivity of the results to these effects was examined in later perturbations. The effective backpressure on the Otto-cycle being unknown, the simple approach was taken of varying it parametrically. This had the effect of varying work split between the rotary and turbine parts of the engine. In short, a simple, somewhat optimistic approach was taken in calculating compound engine performance on the assumption that it should show improvement under these conditions before any more detailed evaluation is attempted.

The compound engines were compared to an advanced high pressure ratio turbofan in terms of fuel plus engine weight. For the comparison, cruise conditions of 10668 m (35000 ft)

and Mach 0.80 were chosen. The advanced turbofan weight was estimated component by component and suitable adjustments were then made to account for the substitution of an RC engine in place of a combustor. The engines were sized and compared at the cruise condition only, and no attempt was made to estimate off-design or takeoff performance. The effects of added complexity on cost and maintainability were not examined and the comparison was solely in terms of cruise performance and uninstalled engine weight.

The cycles with lower fuel consumption generally turned out to be heavier than the reference turbofan. The weight of the rotary engine and manifolding was not entirely offset by the elimination of booster stages, combustor, and, in some cases, turbine stages. There was some SFC improvement in going to the higher pressure ratios by compounding, but the size of the gain was also highly dependent upon the amount of input energy assumed lost by the Otto-cycle due to cooling. Assuming a 25% Otto-cycle cooling loss (representative of current Otto-cycle engines), a compound engine with a boost PR of 10 and a compression ratio of 10 gave a 5.1% improvement in cruise TSFC over the reference turbofan. As the fuel used in the compound engine had a 4% higher heating value, however, only a 1.2% improvement can be attributed to compounding. As far as weight is concerned, the compound engine was 23% heavier than the reference turbofan. For a 10% Otto-cycle cooling loss (representing advanced insulation/high-temperature materials technology), the same compound cycle as before showed an 11.8% improvement in cruise TSFC over the reference turbofan. Again adjusting for the different fuel heating value, however, reduces this to an 8.1% improvement.

INTRODUCTION

The recent awareness of increasingly scarce and costly fuel supplies led to the formation in early 1975 of a NASA-sponsored, joint government agency task force to define the technological opportunities for fuel conservation in air transport. A summary of the task force's findings and the recommended technology plan can be found in reference 1. Basically, the plan includes specific technology development efforts in the areas of propulsion, aerodynamics, and structures, directed at achieving both near- and far-term fuel savings.

NASA's Lewis Research Center is engaged in several of the propulsion areas. One is an advanced high pressure ratio turbofan which would see service about 1990. The performance improvements in this engine are due mainly to higher cycle pressures and temperatures which would pose some tough component development problems even for this otherwise rather conventional concept. Alternative, less-conventional approaches have also been examined. These include the turboprop described in reference 2 and the regenerative turbofan of reference 3.

Another unconventional approach examined in this report is one that combines the high compression ratio of a displacement machine with the high expansion ratio of a turbine. This is the compound cycle - or a gas turbine plus a positive displacement engine combination where both engines produce useable shaft power. The best example of this type of engine is the Napier Nomad described in reference 4. The Nomad's brake SFC was excellent compared to the relatively low pressure ratio turbomachines of its day. It flew over 20 years ago, but apparently was overtaken by the higher speed that jets offered plus the availability of cheap fuel at the time. The Nomad consisted of a 12-cylinder, 2-stroke Diesel plus a turbine/compressor set driven off the Diesel's exhaust. This engine achieved an overall compression ratio* of 36. The two parts of this engine were interconnected through a variable gear that allowed the two shaft speeds to be optimally matched over the flight regime. The Nomad engine's volume was about 2/3 reciprocating Diesel and 1/3 turbomachine, which gave it a specific weight of about 0.6 kg/kW (1 lb/HP).

The objective of this study was to reevaluate the concept of compounding in light of more improved technology. Where uncertainty arose in assuming losses, efficiencies, and the like, optimistic assumptions were made.

Numerous technology advances could be applied if the compound engine concept were executed today, so the configuration examined here is obviously quite different from that of the Nomad. Instead of a reciprocating engine, a rotary combustion engine was chosen for its lower weight and volume. The RC engine would essentially replace the conventional combustor in a turbofan or turboshaft engine. The positive displacement machine would now be the smaller part of the entire engine in contrast to the Nomad situation. Also, the Nomad's turbine was restricted to fairly low inlet temperatures and, as a result, the exhaust

*Note: The terms pressure ratio and compression ratio can be easily misinterpreted. Compression ratio, which is the ratio of volumes, is related to pressure ratio by the expression $p_1/p_2=(v_2/v_1)^{\gamma}$.

gases had to be diluted with large quantities of scavenge air to bring turbine inlet temperature down. Present-day turbines could reduce or eliminate entirely the need for this and allow for more work extraction from the turbine. Other anticipated improvements would be in the axial-flow components where efficiencies have increased and where higher stage pressure ratios could reduce the total number of stages.

SYMBOLS

A, A_r, A_R	rotor geometry areas, m^2
A_s	swept area, m^2
B	rotor depth, m
BSFC	brake specific fuel consumption, kg/kW-hr
C_v	velocity coefficient
c_p	specific heat at constant pressure, J/kg-°K
e	eccentricity
E	total internal energy, J
F_n	net thrust, N
f	clearance fraction
f/a	fuel/air ratio
$\dot{m}$	mass flow, kg/sec
N	number of stages
P	total pressure, N/m^2
PR	pressure ratio
R	generating radius, m
r	compression ratio
S	cruise range, km
T	total temperature, °K

TSFC	thrust specific fuel consumption, kg/N-hr
$\mathcal{V}$	volume, m^3
V	swept volume, m^3
v	cruise speed, km/hr
W	work, J
WT	weight, N
w	specific work, J/kg
β	ratio of total turbine cooling bleed to turbine inlet flow
β_s	ratio of stator cooling bleed to turbine inlet flow
γ	ratio of specific heats
Δ	"change in"
η	adiabatic efficiency
ρ	density, kg/m^3
σ	maximum allowable stress, N/m^2
ϕ	leaning angle, radians

Subscripts

acc	accessories
act	actual
bdc	bottom dead center
bp	backpressure
comp	compressor
corr	corrected
crf	cruise fuel
exh	exhaust
id	ideal

ind	indicated
int	intake
max	maximum
min	minimum
rot	rotor
str	structure
t	turbine
tdc	top dead center

ANALYSIS

Mission

The figure of merit was uninstalled engine weight plus cruise fuel weight. Cruise fuel weight was calculated simply from

$$WT_{crf} = 9.807(TSFC)\,F_n\,S/v.$$

Flight conditions were selected as Mach 0.80 at 10668 m (35000 ft). The range was varied to observe the break-even point for those cases where increased engine weight would be offset by improving TSFC.

Reference Turbofan

__Configuration__.- The engine used for reference in comparing compound cycle performance is the advanced, high-pressure ratio turbofan study engine of reference 5. This is a two-spool engine with a single-stage fan, 3 booster stages, and a 10-stage compressor. The cooled high and low pressure turbines have two and five stages, respectively.

__Cycle__.- At the cruise conditions of this study, the reference turbofan engine had a fan pressure ratio of 1.75, overall pressure ratio of 45, and a bypass ratio of 7.78.

__Size and performance__.- The sea level static thrust of this engine was 111000 N (25000 lb). The installed thrust at the selected cruise conditions was 29000 N (6530 lb). For convenience, this is the thrust that all of the study engines were then sized for. Thrust specific fuel consumption of the reference engine was 0.029 kg/N-hr (0.284 hr^{-1}) at sea level and 0.0553 kg/N-hr (0.542 hr^{-1}) at cruise.

Compound Engine

__Configuration__.- The sketch in figure 1 shows conceptually the compound engine configuration being considered. Essentially, it is the reference turbofan with the conventional combustor replaced by an RC engine. Instead of two spools with individual shafts, the compressor, RC engine, and turbine are all on a single shaft. The RC rotors orbit directly about the main engine shaft. The fan would be geared down. A typical high-spool rotational speed of 1260 rad/sec (12000 rpm) was selected for the main shaft speed. Since part of the compression work is done in the RC engine, the boost PR into that engine need not be as great and this will allow the booster stages and several compressor stages to be eliminated, as will be seen later. Also, there being only one high-speed shaft allows the turbine to be combined into one unit, often of fewer stages, depending upon the cycle. The turbine was assumed cooled by a convection+film cooling scheme with bleed air from the compressor discharge. Blade metal temperatures for 1990 technology were assumed. This level of turbine cooling technology is comparable with that of the reference turbofan. The only exception is that the compound engine would require the addition of an auxiliary bleed air compressor to boost the cooling air up to the RC engine discharge pressure. The compound engine also requires the addition of intake and exhaust manifolds. These would be scroll-type devices to take annular, axial flow and gradually feed it to inlet and outlet side ports on the RC engine. Since the RC engine is a cyclic output device, the intake and exhaust manifolds would also have to be designed to act as settling chambers to damp out flow fluctuations into the turbine and compressor. The fan and duct on the compound engine were assumed to be the same as on the reference turbofan as far as pressure ratio and duct losses were concerned. The bypass ratio, however, was varied to match the available work per unit mass of core flow.

Cycle.- The compound cycles chosen to be examined had boost pressure ratios of 1.75, 4, and 10. The 1.75 boost represents the case for which there is no compressor but only a fan. For each of the above boost PRs, RC engine compression ratios of 5, 7, and 10 were considered. The highest value of compression ratio here is about the present limit for apex seal technology. One higher boost pressure ratio of 20 was examined together with a compression ratio of 7. The overall range of boost and compression ratios resulted in peak cycle pressure ratios of from 15 to 240, before combustion. Some adiabatic component efficiencies and loss coefficients were as follows:

Inlet recovery	1.00
Fan efficiency	0.87
Compressor efficiency	0.87
Core nozzle C_v	1.00
Duct nozzle C_v	0.991

The fan and duct parameters on the compound engine were taken to be the same as on the reference turbofan. Pressure losses in the intake and exhaust manifolds were initially assumed zero. The sensitivity of the results for one cycle was determined for the two cases when the intake and exhaust manifold pressure drops were each 5%. The mechanical efficiency of the compound engine gearbox was taken to be 1.0.

__Size and performance__.- Since the study was to compare engines for fuel + engine weight at the one cruise condition, all the engines were sized to the cruise data available on the reference turbofan - 29000 N (6530 lb) thrust at Mach 0.8 and 10668 m (35000 ft). Off-design or sea-level performance was not attempted in this preliminary analysis where the goal was merely to see if the concept justified further consideration. It is known from experience though that a turbomachine has a greater lapse rate as far as shaft power with altitude is concerned than a turbocharged reciprocating engine. For the compound engine, this might imply a sizing condition other than cruise. The comparisons between compound and turbofan engines were generally done in terms of thrust parameters, but where it was equivalent or more convenient, it was done in terms of shaft power.

__RC Engine__.- Even a cursory look at the field of rotary engines will reveal that there are a great number of possible configurations for these machines. The RC engine chosen for this study is a 2:3 epitrochoidal configuration. That is, the bore is an epitrochoid with two lobes and the rotor has three flanks. This is the familiar configuration used in some production automotive engines. In order to discuss weight and size calculations later, it is necessary to briefly present some fundamentals of rotary engine geometry from reference 6.

The outer case is an epitrochoid which is generated by rolling one circle around a base circle of twice the radius as shown in figure 2. The epitrochoid is the locus of point P on the radius of the rolling circle. The actual bore is often moved out an equidistant amount to generate a trochoid that is parallel to the true epitrochoidal shape. This is done to lessen the radial motion of the apex seals as they move over the lobes of the bore. In practice, the displacement is much smaller than R, and for the purposes of estimating compression ratio and size, it will be assumed negligible. Looking at the epitrochoidal bore with rotor in figure 3, R and e are noted. The generating radius R becomes the dimension of the rotor from its center to the apex and the eccentricity e defines the orbiting path of the rotor center. With this configuration, the output shaft rotates at three times the rate of the rotor. The leaning angle defines the maximum angle contained within the radial lines from the center of the rotor through each apex and the normal to the epitrochoidal bore at the point of contact. A simple relationship exists between the radius R, the eccentricity, and the leaning angle, namely,

$$\sin\phi = 3e/R.$$

The relationship is plotted in figure 4 and it will be noted that ϕ cannot exceed $\pi/2$ rad (90°) and R/e may not be less than 3.

For the ideal case where there are no depressions in the rotor flank or in the bore, the maximum theoretical compression ratio is given by

$$r_{id} = V_{bdc} / V_{tdc} = BA_{bdc} / BA_{tdc}$$

or,

$$r_{id} = A_{bdc} / A_{tdc} . \qquad (1)$$

From figure 5, though, it can be seen that

$$A_{bdc} = A_{max} - A_r$$

and

$$A_{tdc} = A_{min} - A_r .$$

Furthermore, for this particular configuration,

$$A_{min} = (R^2+3e^2)\pi/3 - \sqrt{3}R^2/4 - 3\sqrt{3}eR/2$$

$$A_{max} = (R^2+3e^2)\pi/3 - \sqrt{3}R^2/4 + 3\sqrt{3}eR/2$$

and

$$A_r = A_R - \sqrt{3}R^2/4$$

where A_R is given by

$$A_R = (\pi(R^2+2e^2) - 6eR\cos\phi - (2R^2/3+12e^2)\phi)/3 .$$

Substituting these relations into equation (1) enables the ideal compression ratio to be finally written solely in terms of R/e as:

$$r_{id} = \frac{\pi/3 + 3\sqrt{3}(R/e)/2 + 2\sqrt{(R/e)^2-9} + (2(R/e)^2/9+4)\sin^{-1}(3/(R/e))}{\pi/3 - 3\sqrt{3}(R/e)/2 + 2\sqrt{(R/e)^2-9} + (2(R/e)^2/9+4)\sin^{-1}(3/(R/e))} \qquad (2)$$

In a real engine though, to allow for a better combustion chamber, for scavenging, and to allow for ignition devices, there are depressions in the rotor flanks and bore. It is possible for the volume of the depressions alone to be equal to the entire ideal volume at top dead center. Obviously, the depressions lower the compression ratio. Following the suggestion in reference 6 regarding the approximate volume of depressions for typical Otto and Diesel RC engine applications*, the actual compression ratios were assumed to be:

$$r_{Otto} = (A_{bdc} + A_{tdc}) / (A_{tdc} + A_{tdc})$$

$$r_{Diesel} = (A_{bdc} + A_{tdc}/2) / (A_{tdc} + A_{tdc}/2) \ .$$

That is, for the typical Otto-cycle, the depression volume is just equal to the top dead center chamber volume when there are no depressions. For the Diesel, the depression volume is one-half the ideal top dead center volume. Making the same substitutions as before, it is possible to reduce these equations down to functions only of R/e:

$$r_{Otto} = f_1 \, (R/e) \qquad (3)$$

$$r_{Diesel} = f_2 \, (R/e) \, . \qquad (4)$$

The parameter R/e, then, is an important geometry parameter for the RC engine and is needed for estimating displacement volume and weight. Equations (2), (3), and (4) are plotted in figure 6 and they enable the R/e parameter for a typical Otto or Diesel RC engine to be approximated for any desired compression ratio.

Cycle Calculations

Reference turbofan.- Estimates of the reference turbofan's performance were obtained from reference 5 and no additional calculations were required.

Compound engine.- Given an ideal inlet with total pressure recovery of 1.0, the conditions T_1, P_1 at the fan face (fig.1) are determined simply by the cruise condition. The conditions at the compressor exit are given by:

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*Note: To avoid confusion, it will be noted here that Otto and Diesel refer to thermodynamic cycles, whereas the terms reciprocating and rotary only describe the motion of mechanical parts. It is entirely possible, therefore, to speak of both Diesel and Otto RC engines.

$$T_2 = T_1 \left[\left((PR_c)^{\frac{\gamma-1}{\gamma}} - 1 \right) / \eta_c + 1 \right]$$

$$P_2 = P_1 (PR_c) .$$

At the compressor discharge, the core flow would be split to provide some cooling bleed for the turbine. The coolant flows were assigned as indicated in figure 1. The ratio of first vane coolant flow to the flow leaving the RC engine is β_1. The ratio of total coolant flow to RC engine exit flow is β. Because the turbine inlet pressure is greater than the compressor discharge pressure for this engine, a small auxiliary compressor is needed to boost the cooling bleed air. The required PR for this auxiliary compressor is determined by the boost PR and the Otto-cycle backpressure. Efficiency was taken to be the same as that of the main compressor. Assuming convection+film cooling and using 1990 blade metal temperatures, the coolant flow for each vane and rotor was estimated using the method outlined in reference 7. The first vane's coolant was added into the flow before the first rotor, and the turbine rotor inlet temperature was adjusted to take this into account. For purposes of calculating performance, all the remaining bleeds were added back to the main flow downstream of the turbine.

Although the total pressure loss in the intake manifold to the RC engine was initially assumed zero, one case was run where

$$P_3 = P_2 (1 - (\Delta P/P)_{int})$$

and

$$T_3 = T_2 .$$

The above are, then, the flow conditions entering the RC engine. In a positive displacement machine, however, a part of the exhaust gases, the clearance fraction, f, remains in the chamber and mixes with the fresh charge of each succeeding cycle. As a result, the initial condition of the mixture before compression is not known, and it must be solved for iteratively. Initial values for temperature and clearance fraction are chosen and the procedure followed as outlined in reference 8. The actual solution was done using an Otto-cycle computer code that calculated the thermodynamic properties of the working fluid by the chemical kinetics program described in reference 9 which includes dissociation. The fuel was taken to be octane (C_8H_{18}) with a heating value of 44.7 MJ/kg (19260 Btu/lb).

It should be noted that this is 4% higher than the heating value of the JP fuel used in the reference turbofan. After running a few cases, it became apparent that for the pressure ratios of interest, auto-ignition would most likely occur long before top dead center even for fuel such as octane which has a relatively high ignition temperature. The actual compound engine would therefore most likely be a compression-ignition device with only air undergoing compression and fuel being injected directly. Although Diesels have come to be regarded as more efficient than Otto engines, for the <u>same</u> compression ratio and energy input, the Otto-cycle is inherently more efficient than the Diesel-cycle, the former simply being restricted from going to such high pressures as the latter because of auto-ignition. This is because the Otto-cycle's entire heat addition takes place at constant volume compared to the Diesel's combination of constant pressure/constant volume heat addition. As a result, the Otto-cycle achieves higher peak temperatures and pressures. Using an Otto-cycle, then, to estimate performance of what most likely would be a Diesel, gives some advantage to the compound engine. An equivalence ratio of 1.0 was used in the analysis, the greatest effect of this parameter being to vary the specific output (work/unit mass of air) and change the required displacement accordingly. One cycle was run with an equivalence ratio of 0.5, to check the sensitivity of the estimated performance to this variable. Limiting considerations for the actual value used are the limits of flammability of the mixture and the onset of smoky exhaust.

Referring to the p-v diagram in figure 7(a) for a throttled Otto-cycle, step a-b represents adiabatic compression in the RC engine. Step b-c is constant volume combustion that assumes instantaneous burning and does not account for heat transfer out of the chamber. Step c-d is adiabatic expansion as the rotor moves away from top dead center. When the volume has reached its maximum ($V_d = V_{max}$) no further expansion can take place in the chamber and exhaust begins. As the exhaust ports open, pressure in the chamber will drop to the exhaust backpressure (the level of line f-e-d'). Step d-e is irreversible, but if all the losses are assumed to occur at the exhaust port, then the gas remaining in the chamber can be assumed to have undergone reversible adiabatic expansion, doing work on the gas expelled from the chamber. Conditions at point e, then, are the same as if the gas continued expanding adiabatically along the line d-d', down to the exhaust backpressure level but with a final volume of only V_d. Step e-f is that part of exhaust that occurs at constant pressure, by displacement of the rotor while exhaust ports are open. When minimum volume is reached at top dead center (point f), the exhaust ports are closed, and since the pressure of the gas remaining in the chamber is greater than intake pressure, the intake ports are not opened until the chamber volume has expanded adiabatically down to point f'. Step f'-a is then just drawing in fresh charge at constant boost pressure.

Still referring to figure 7(a), the indicated, or ideal net work done on the rotor by the working fluid in one cycle, is given by

$$W_{ind} = (E_c - E_d) - (E_b - E_a) - (P_e (V_a - V_b) - f(E_{d'} - E_{f'}) - P_a (V_a - fV_{f'})) .$$

The last term in this equation is called the pumping work. In the throttled Otto-cycle, it is a net loss.

To take into account the energy lost to cooling, friction, radiation, etc., all these losses were lumped together as a percentage of the total input energy into the Otto-cycle. A steady-state energy balance was then done on a control volume containing just the RC engine and considering the energy in by bulk flow, the addition of the fuel, the heat loss out, the shaft power out, and the energy out by bulk flow. This calculation allowed the average total temperature leaving the RC engine to be estimated for the two levels of Otto-cycle heat loss considered in this study- 25% and 10%. The former value represents experience to date with engines of this sort, and the latter represents what might be expected if cooling losses could be significantly reduced for the Otto-cycle by advanced insulation/high-temperature materials technology. The heat lost from the Otto-cycle due to cooling was partially recovered in the overall cycle by heat exchanging with the duct air as indicated in figure 1. Practically, the RC engine rotor would be oil-cooled and the case would have cooling fins that protrude directly into the duct stream.

The effective backpressure that the RC engine would exhaust to was not known. The backpressure that could actually be expected would depend upon the losses across the exhaust ports, the design of the exhaust manifold, how many chambers were exhausting at any instant, etc. It was decided, therefore, to simply allow the backpressure to vary as an independent parameter. Referring to figure 7(a), the backpressure could vary between the boost pressure and the ideal maximum chamber pressure after expansion and before valve opening, P_d. For each cycle, values of backpressure were run between the limits

$$P_{boost} < P_{bp} < P_d .$$

As the ratio P_{bp}/P_d goes to 1, the upper limit is approached for turbine inlet pressure.

Just as in the intake manifold, the total pressure loss in the exhaust manifold was initially assumed zero, so that

$$P_5 = P_4 = P_{bp} \, .$$

The sensitivity of the results to an exhaust manifold pressure loss was examined for one case where

$$P_4 = P_{bp}$$

and

$$P_5 = P_{bp} \, (1 - (\Delta P/P)_{exh}) .$$

With total temperature and pressure into the turbine known, the turbine performance was calculated using the code described in reference 10. All the turbines were allowed to expand down to a static pressure of 3.45 N/cm^2 (5 psi). With an ambient pressure of 2.39 N/cm^2 (3.47 psi) at the cruise condition, enough energy remains in the core flow to generate some core thrust. For each cycle, a sufficient number of stages were selected to give turbine efficiencies roughly between 0.88 and 0.89. The turbine specific work was finally calculated by the equation

$$w_t = \eta_t \, c_p \, T_5 \, (1 - (P_6/P_5)^{\frac{\gamma-1}{\gamma}}) \, (1 + \beta_s) \, (1 + f/a) / (1 + \beta \, (1 + f/a)) .$$

Possible losses in turbine efficiency due to unsteady flow from the RC engine were not initially considered. A perturbation on this was done, however, in one case where the turbine efficiency was degraded by 5%. The size of the real penalty is unknown, and the 5% only represents a guess.

For the duct, a value of thrust per unit mass of duct flow derived from the reference turbofan data was used for the compound engine case. Fan pressure ratio, efficiency, and nozzle velocity coefficient are therefore the same for both engines. An additional 2% duct pressure drop was included in the compound engine to account for the RC engine cooling fins.

This, of course, is a highly simplified analysis of the actual cycle. A more realistic p-v diagram would look like the one shown in figure 7(b). A finite rate of heat release during combustion; heat conduction to and from the working fluid and the chamber walls over the entire cycle; and mixing, intake, and exhaust losses all combine to modify the real p-v diagram considerably. Also, to simulate Diesels, a pressure-limited diagram (figure 7(c)) is often used. It serves to simulate the longer duration, constant pressure combustion caused by the need to limit peak cylinder stresses in high compression ratio Diesels by delayed addition of fuel. Several cases were calculated by hand using this type of diagram, but for the same compression, fuel/air ratio, and typical limiting peak pressures, the results did not differ substantially from those calculated with an Otto-cycle.

Engine Weight

Reference turbofan.- The total weight of the reference turbofan was given in reference 5 as 1787 kg (3940 lb). This does not include thrust reverser, tailpipe, or noise suppression. A component by component weight breakdown was generated for the reference turbofan using the equations of reference 11. This percentage breakdown was used to estimate the component weights for the reference engine.

Compound engine.- For the compound engine weight, appropriate adjustments had to be made to the reference turbofan weights to reflect the major differences.

Turbomachinery weights were recalculated using the reference 11 correlations. The fan, for instance, could be scaled as

$$WT_{fan} \propto (\dot{m}_{act})^{1.35} .$$

The compressor weight was scaled by using

$$WT_{comp} \propto N_{comp}^{1.2} (\dot{m}_{corr})^{1.1} .$$

The intake and exhaust manifolds were assumed to consist of an annular scroll that eventually must feed into intake and exhaust tubes for the RC engine. If they are treated as cylindrical pressure vessels, and simple hoop stress is combined with continuity, the result for weight is:

$$WT_{int,exh} \propto \dot{m}_{act} \sqrt{T_{int,exh}} .$$

For the constant rotational shaft speed assumed here, the turbine weight correlation becomes

$$WT_t \propto N_t D_t^{3.1} .$$

To be consistent with the reference turbofan configuration, a short fan duct, downstream from the fan stator exit plane was included. It was scaled according to:

$$WT_{duct} \propto \sqrt{\dot{m}_{act}} \, .$$

Accessories weight was assumed to be dependant primarily on fuel flow according to reference 11, so that

$$WT_{acc} \propto (1+K(TSFC)) .$$

The proportionality constants used to actually evaluate the above quantities were the values of the corresponding quantities in the reference turbofan. One exception was that for the intake and exhaust manifolds, twice the reference engine's combustor weight was used to account for the more complicated flow path than in an ordinary combustor. Added to this was the weight of the auxiliary cooling bleed compressor. Its weight was taken to be proportional to the power that it required and was roughly based on available small turboshaft data.

The RC engine's weight was estimated from the cycle calculation of specific work. Since the conditions into the RC engine are known, specific work can be converted into work per unit volume of air. Given the 1260 rad/sec (12000 rpm) shaft speed and that the rotor, therefore, rotates at 420 rad/sec (4000 rpm) allows the swept volume per chamber to be determined. And since

$$A_s = A_{max} - A_{min} = 3\sqrt{3}\,eR,$$

swept volume becomes

$$V_s = 3\sqrt{3}\,eRB.$$

Using a typical value of 2/3 for the ratio of B/R, R can be solved for:

$$R = \left[\frac{V_s \, (R/e)}{2\sqrt{3}} \right]^{1/3} .$$

The log-log plot of this equation is shown in figure 8. Knowing the characteristic R/e for any compression ratio and the required swept volume per chamber, allows the generating radius R of the RC engine to be determined. Given the characteristic R for the engine, the weight can be roughly estimated in three parts - case, cooling fins, and rotors. The case was modeled as a cylinder whose wall thickness was determined from the peak cylinder pressure hoop stress. The final equation for the case weight was

$$WT = \frac{\pi R^2 (1+(e/R))^2 P_S}{(\sigma/\rho)} \left[N_{rot}(2R/3) + (N_{rot}+1) R (1+(e/R)) \right].$$

Values of 138 MN/m^2 (20000 lb/in^2) and 7830 kg/m^3 (0.286 lb/in^3) were used for σ and ρ, respectively. Note that the value used for σ, the maximum allowable stress, assumes a large safety factor for cyclic stressing, concentrations, non-uniformity, etc. The weight of cooling fins was taken as 1/2 of the case weight. Rotor weight was determined from the rotor volume and material density, allowing 50% off for the center hole, cooling passages, and flank depressions.

Structures weight, which includes mounts, bearings, frames, shafting, and transition sections, was taken as

$$WT_{str} = 0.18 \sum WT_{components}$$

where $\sum WT_{components}$ includes all but the fan duct and accessories weights.

A gearbox weight was included using the equation found in reference 12.

RESULTS AND DISCUSSION

Compound Engine Configuration

RC engine.- One of the first topics of discussion will be the implications that the chosen compression ratios have on the RC engine geometry, particularly on the parameters R/e and leaning angle. Looking back to figure 6, it will be seen that with an ideal 2:3 epitrochoidal configuration (i.e., no depressions in the rotor flanks or bore), the lowest compression ratio that can be had is about 7. This, however, is at the minimum R/e of 3 and implies a leaning angle of $\pi/2$ rad (90°), which is an impossibility. It might appear at first, that there would be difficulty in getting the desired compression ratios with the type of rotary configuration selected. However, real engines do require rotor flank and other depressions, so that in practice, compression ratio varies with R/e according to the lower curves of figure 6. Specifically, to get a compression of 5 requires a total depression volume that would be at least 1/2 the top dead center volume (this is the curve labeled "Diesel application"). To also get a reasonable leaning angle, it would be necessary to increase the depression volume further, to the "Otto application" curve where it is just equal to the tdc chamber volume. For this condition, the leaning angle for a compression of 5 becomes 0.96 rad (55°), still high compared to the design practice of keeping this number below 0.524 rad (30°). The compression ratio 7 and 10 cases result in leaning angles of 0.646 rad (37°) and 0.419 rad (24°), respectively. These are the values used in the study, realizing that the compression ratio 5 case might require a lower leaning angle.

Bypass ratio and core size.- One result of the higher fuel/air ratio in a positive displacement engine compared to a turbomachine is that the specific output is much higher. So while turbomachines generate about 330 kW/kg of air/sec (200 HP/lb/sec), the core of the compound engine yields about three times that. If the extra output is to be absorbed by a fan of equal pressure ratio, the bypass ratio must increase. Figures 9 and 10 show what happens to bypass ratio over the range of variables examined. Bypass ratios of 20 and 30 may not be entirely feasible, at least not in the exact configuration envisioned here. Core flows are such that centrifugal compressors might replace axial ones. The fan may be replaced by a prop-fan or propeller. These considerations though should not greatly affect the results of the performance comparison.

Turbine cooling.- To get good turbine efficiencies between 0.88 and 0.89, the number of turbine stages shown in figure 11 were required for each cycle. The trends are straightforward. Increasing the Otto-cycle backpressure increases the total conditions into the turbine and, therefore, its work potential, so the number of stages increases. Increased boost also has the same effect as more work is required to drive the compressor.

The estimated turbine rotor inlet temperatures are shown in figure 12 for the two levels of Otto-cycle cooling loss. The lower this cooling loss, the higher the temperature into the turbine. The higher the boost PR and backpressure, the higher the temperature also. It is interesting that the turbine inlet temperature drops with increasing compression ratio, though. The higher compression ratios achieve higher peak chamber temperature, but the greater expansion ratio more than makes up for this to finally give a lower temperature after expansion.

The amount of cooling bleed required for the turbine is dependent upon the turbine inlet temperature, the coolant temperature, and the number of stages that need cooling. The cooling bleed air requirements are shown in figure 13 for a cooling scheme with blade metal temperatures comparable to that of the advanced 1990 turbofan. Plotted is β, the ratio of total cooling bleed air to turbine stator inlet mass flow. The increasing cooling bleed requirements with increasing number of stages, higher turbine inlet and coolant temperatures (with higher boost PR), can be readily seen.

Performance

<u>Breakdown of input energy</u>.- As mentioned previously, the effective backpressure on the Otto-cycle was allowed to vary over the range

$$P_{boost} < P_{bp} < P_d .$$

As backpressure varies, one would expect the relative Otto-cycle and turbine outputs to vary also. This effect is illustrated in figures 14 and 15, which show a breakdown of the input energy to the core of one compound cycle by percent. The compression ratio is 7 and the boost PR is 10. Figure 14 is for an Otto-cycle cooling loss of 25% and figure 15 is for 10% cooling loss. The total input energy into the core is known from the fuel/air ratio and the heating value of the fuel. Where this energy goes can be divided into the six bands shown in the figures. First, of course, are the net shaft outputs of the RC engine and the turbine. Increasing backpressure clearly causes the Otto-cycle output to fall and the turbine output to rise. Note that there is an optimum backpressure where the sum of the two is a maximum. The reason for this will be discussed later. Besides the Otto and turbine shaft outputs, some useful work also comes from the core thrust. The band labeled "gross thrust power" represents the core's total gross thrust expressed in terms of power units. The dashed line separates out the ram drag power. The remainder is of course, the net thrust power. This, plus the Otto and turbine net shaft outputs, is the net useful work produced by the core of the compound engine. The supercharging work, based on the boost PR, is very nearly a constant in the two figures. The only thing that causes it to vary is the small amount of work required to boost the cooling bleed. The cooling loss is simply the constant percentage input energy loss assumed for the Otto-cycle (25% in one case and 10% in the other). Note that while lowering this loss from 25% to 10% increases the total useful work of the core, it also increases the amount of energy finally rejected as waste heat through the exhaust - core thrust notwithstanding. This is due to higher gas temperatures downstream of the RC engine when the Otto-cycle cooling loss is reduced. It should be recalled that here, the cooling loss energy is transferred to the duct stream where it is partially recovered in the overall cycle by increasing duct thrust.

Fuel consumption.- The estimated cruise performance of the compound engine is shown in figures 16 and 17, for two levels of Otto-cycle cooling loss - 25% and 10%, respectively. The TSFC generally improves with increasing compression ratio over the range of variables examined. It reaches a minimum with increasing backpressure, and the minimum occurs at a lower backpressure with the higher boost PR's. This is caused by the cooling bleed requirements. As the backpressure increases, the number of turbine stages increases. Increasing with backpressure also is the turbine inlet temperature. Consequently, more turbine cooling air is required which eventually begins to hurt the cycle. Also, as the cooling air temperature depends on the boost PR, the higher the boost, the larger the coolant fraction required. As a result, at the boost PR of 20, the performance drops off rapidly with increasing backpressure, while at the lower boost PRs, it improves up to P_{bp}/P_d of about 0.6 to 0.8. The level of the reference turbofan's cruise TSFC is drawn across all the plots for comparison. For an Otto-cycle cooling loss of 25%, typical of experience to date with engines of this sort, the compound engine's best TSFC improvement over the reference turbofan was 5.1% at a boost of 10 and a compression ratio of 10. The heating value of octane is 4% higher, though, than the JP used by the reference turbofan. When this is taken into account, this study's best compound engine can attribute only a 1.2% improvement in TSFC to its higher pressure ratio cycle. For a 10% cooling loss, the improvement over the turbofan is 11.8%. Taking again the difference in fuel heating value into account, reduces this improvement to 8.1%.

To compare on the basis of shaft performance alone, with no fan or thrust parameters involved, figures 18 and 19 are presented. The trends with compression ratio, boost PR, and backpressure are essentially the same as before. The shaft performance of the reference engine's core is drawn on the plots for comparison. When compared on a BSFC basis, the results are a little different than in the TSFC case. At 25% Otto-cycle cooling loss, none of the compound cycles showed better BSFC than the turbofan core. This is because for shaft performance calculations, the Otto-cycle cooling loss leaves the cycle completely, with no recovery of this energy by heat exchanging to a duct. There is no comparable loss of energy in the core of the turbofan. At 10% Otto-cycle cooling loss, where the cooling loss is less of a factor in the overall cycle, the compound engine shows an improvement in BSFC over the turbofan core very similar to that in the TSFC comparison.

The estimated cruise thrust performance of the compound engine is finally summarized against overall cycle PR in figures 20 and 21 for the two values of Otto-cycle heat loss. The plots are for a fixed backpressure ratio P_{bp}/P_{d} of 0.6, very nearly the optimum for all cycles. The solid and dashed lines represent peak cycle pressure ratios before and after combustion, respectively. It will be seen that many of the combined boost and compression ratios examined in the study resulted in overall cycle pressure ratios far above that of the reference turbofan.

It should be remembered that the above performance figures were all for the Mach 0.8, 10668 m (35000 ft) cruise condition.

Dimensions and Weight

RC engine size.- Neglecting the cooling fins which protrude into the fan duct, and neglecting the case wall thickness because it's small compared to the overall dimensions, the maximum RC engine width is just equal to 2(R+e). This dimension is plotted in figure 22 for 1, 3, and 5 rotors, over the range of boost PR and backpressure. The compression ratio is 7. The engines are all sized for the constant cruise thrust condition at Mach 0.8, 10668 m (35000 ft). The maximum width can be seen to vary mainly with the number of rotors and boost PR. Increasing boost PR increases the incoming mass flow density and therefore decreases the required volumetric displacement. Increasing the number of rotors decreases the volumetric displacement per rotor and hence the diameter of each one. Varying the backpressure has minimal effect on RC engine size. Increased backpressure increases the clearance fraction of hot gases which mix with the cool fresh charge. As a result, the final mixture at start of compression is hotter, less dense, and requires more chamber volume.

The RC engine length is directly related to R since we have already assumed a fixed ratio for the rotor's diameter to its depth or thickness, B. Assuming as before, the ratio of B/R to be 2/3, the approximate length is simply

$$L_{RC} = N_{rot} R(2/3).$$

This neglects wall thicknesses, room for bearings, etc. The results of estimating the length of the RC engine by this equation are plotted in figure 23 for the same cycle parameters as figure 22.

Choosing the number of rotors to actually use involves several factors. To obtain a more uniform, steady flow into the turbine, more rotors are desireable. But the number cannot be too high because of practical limits on length and the necessity to pass a shaft through the rotor centers as the individual rotors shrink in size. Some limit exists where e will be less than the shaft diameter will allow, as indicated by the broken and shaded area in the lower portion of figure 22. Similarly, the RC engine should not have so few rotors that the engine's maximum width is much greater than the booster tip diameter at the fan face. This is to insure a neat packaging of the RC engine into the overall engine. The upper shaded area of figure 22 shows this upper limit for these engines based on the reference turbofan's fan face Mach number and hub/tip ratio.

<u>RC engine weight</u>.- Three rotors seemed to strike a reasonable compromise based on the above factors. Figure 24 shows the RC engine weight assuming 3 rotors, for the range of boost PR, compression ratio, and backpressure. The trends with boost PR and backpressure are the same as for engine width. Increasing compression ratio, however, is a weight penalty for the RC engine as wall thicknesses increase with increasing peak chamber pressures.

<u>Compound engine</u>.- Finally, the plots in figure 25 show the variation of the uninstalled compound engine weight over the range of cycle parameters. These all assume 3 rotors in the RC engine. The reference turbofan's weight is indicated across all the plots for comparison. Some of the lower pressure ratio cycles are actually lighter than the turbofan, but their SFC performance was poor. The compound engine weight generally decreases with increasing boost, although it has a diminishing return as exhibited by the boost PR 20 case which actually came out heavier than the boost PR 10 case. The additional booster stages, plus the poorer thrust performance due to large bleed making the engine larger than otherwise, offset the effect of higher density on core size. The cycle with the best TSFC (boost of 10 and compression of 10 at a P_{bp}/P_d=0.6), is about 23% heavier than the turbofan.

Figure 26 is a plot of the same engine weight information but at constant P_{bp}/P_d ratio of 0.6 and versus overall cycle pressure ratio. This plot is a companion to the performance plot of figure 20.

Table I summarizes and compares the weight breakdown for one of the compound engines with the reference turbofan. The particular cycle is a boost PR of 10 and a 3-rotor, RC engine with compression ratio of 7. Figure 27 is an attempt to compare the layout of this compound engine with that of

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the reference turbofan. As can be seen, the elimination in this case of all the booster stages, some of the compressor stages, and combination of the turbines into one high-speed unit would not quite make up for the added length of the RC engine plus manifolding. The addition of a gearbox doesn't seem to necessarily require an increase in length.

<u>Engine plus fuel weight</u>.- To show the cruise range at which the compound engines would break even with the reference turbofan in terms of engine plus fuel weight, figures 28 and 29 are presented. These figures were constructed taking into account the difference in fuel heating value between the two cycles. Figure 28, for 25% Otto-cycle cooling loss, is the same engine weight versus cycle PR plot as in figure 26. Superimposed on it, though, are a shaded region and some curves of constant cruise range. The shaded area represents cycles that have poorer TSFC than the reference engine. Only the small upper right-hand corner of the plot in figure 28, the highest cycle pressure ratios, falls outside this shaded region. In this area, lines of constant cruise range can be drawn to show the break-even range for the compound and reference engines in terms of engine plus fuel weight. Along the line with value infinity, lie compound cycles whose TSFCs just equal that of the turbofan. The boost PR of 10 and compression of 10 cycle, the one showing the best TSFC, can be seen to need quite a long cruise range before it would make up for its greater weight. Remember that here, the compound cycle TSFCs have been adjusted to account for the difference in heating value. Figure 29, for 10% Otto cooling loss, shows a much greater area where compound cycles can compete with the reference turbofan. The same cycle as before (boost PR=10, r=10) can be seen to match the reference turbofan's engine plus fuel weight at a range of about 2800 km (1500 n.mi.).

<u>Drag considerations</u>.- As all of the compound engines' fan diameters fell within about ±4% of the reference turbofan's diameter, differences in nacelle drag were not considered to be a large factor in the comparison of the engines.

Perturbations

All the results presented thus far were based on certain fixed assumptions and losses. Some of these were perturbed in order to gage their effects on performance. The results of these perturbations are summarized in figure 30 and discussed in the following paragraphs.

Equivalence ratio.- All results thus far were based on an equivalence ratio of 1.0, that is, they assume the stoichiometric fuel/air ratio for octane of 0.0661. One case (boost PR=10 and r=10) was run with an equivalence ratio of 0.5 (fuel/air=.03305). This resulted in a 4.3% improvement in cruise TSFC over the original case. However, cutting the fuel/air ratio in half resulted in roughly twice the core flow and dropped the bypass from about 28 to 14.5. With a doubling of core mass flow, the RC engine weight increased by 51% which translated to an 11% increase in the overall compound engine weight when compared to the original case. The improvement in TSFC though, more than makes up for the increase in engine weight when the effect on break-even range with the turbofan is examined. The break-even range decreased from some 18000 km (9500 n.mi.) to 6300 km (3400 n.mi.) when the fuel/air ratio was cut in half. The improvement here is somewhat exaggerated by how close the TSFCs for these two engines originally were after adjusted for the heating value difference. The break-even range even with this improvement is still quite long for a realistic mission. Typical equivalence ratios for Diesels at full power were found to generally lie in the range 0.6 to 0.75, so a somewhat less than 4.3% improvement might be more realistically expected over the baseline TSFCs calculated for an equivalence ratio of 1.0.

Ducting losses.- Originally, no pressure drops were specifically assigned to the intake and exhaust manifolds to the RC engine. Two cases were run where a 5% pressure drop was included between stations 2-3 and 4-5. A 5% pressure drop in the intake manifold caused a 0.54% increase in TSFC. An identical pressure drop in the exhaust manifold caused a 0.72% increase in TSFC. For a 1% increase in the fan duct pressure loss (i.e.,from 0.02 to 0.0202), a 1.1% penalty in TSFC was observed.

Turbine efficiency.- One case (boost PR=10, r=7) was run where the turbine efficiency was penalized 5% to simulate a poor, non-steady flow condition into the turbine from the RC engine. The result of this perturbation was a 2.9% increase in TSFC. The 5% penalty in efficiency was just a guess and should not be taken as being indicative of what the actual unsteady-flow penalty might be.

CONCLUDING REMARKS

A study was performed in which the fuel-conservative potential of a modern compound cycle was examined and compared to an advanced, high-PR turbofan. The comparison was done strictly on the basis of uninstalled engine weight plus fuel weight for a typical subsonic cruise mission. The benefit of decreasing the Otto-cycle heat loss to cooling was estimated by assuming advanced insulation/ high-temperature material technology. The effects of the compound engine's complexity on maintenance, reliability, or cost were not examined. Obviously, numerous questions in these areas can be raised, but this study's objectives were limited to fuel consumption and performance potential.

The results have shown that, allowing for a 25% Otto-cycle cooling loss (i.e., the combined result of cooling requirements, radiation, friction, etc.), the best TSFC improvement over an advanced turbofan was about 1.2% when adjusted for differences in fuel heating value between the two engines. The uninstalled engine weight was estimated 23% higher than the reference turbofan. If cooling losses can be decreased from 25% of the Otto-cycle input energy down to 10% (by advanced insulation/high-temperature materials technology that is highly speculative at this time), the TSFC improvement over a turbofan is 8.1%.

The compound cycle's major inefficiency when compared with a conventional turbofan, seems to lie in its cooling requirements. The hot section of the engine is larger and practical cooling schemes inherently imply transferring heat out of the core flow and bypassing the turbine. Even though this heat is recovered in the duct flow, this is not as efficient overall as recovery in the turbine would be. The coolant flows of a conventional combustor do just that.

The success, then, of a very high PR compound cycle seems to lie in very advanced insulation/high-temperature materials technology of a level which is not in the forseeable future. While the complexity and weight of a modern compound engine seems to have potential for improvement over the Napier Nomad level of technology, SFC-wise, both engines have reached that region of peak cycle pressure ratios where the difference in PR will not dictate the choice between them so much as the losses, efficiencies, etc. at these high pressures and temperatures.

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TABLE I. ENGINE WEIGHT BREAKDOWN, N (lb)

REFERENCE TURBOFAN		COMPOUND ENGINE; r=7, 3 ROTORS, BOOST=10	
FAN	4346 (977)	4322 (972)	FAN
BOOSTER	1317 (286)	– –	–
–	– –	968 (218)	GEARBOX
COMPRESSOR	1517 (341)	386 (87)	COMPRESSOR
–	– –	372 (84)	INTAKE MANIFOLD
BURNER	725 (163)	3654 (822)	RC ENGINE
–	– –	645 (145)	EXHAUST MANIFOLD
HP TURBINE	1005 (226)	3484 (783)	TURBINE
LP TURBINE	4074 (916)	– –	–
STRUCTURE	2335 (525)	2490 (560)	STRUCTURE
ACCESSORIES	1908 (429)	1932 (434)	ACCESSORIES
FAN DUCT	298 (67)	297 (67)	FAN DUCT
TOTAL	17525 (3940)	18550 (4170)	TOTAL

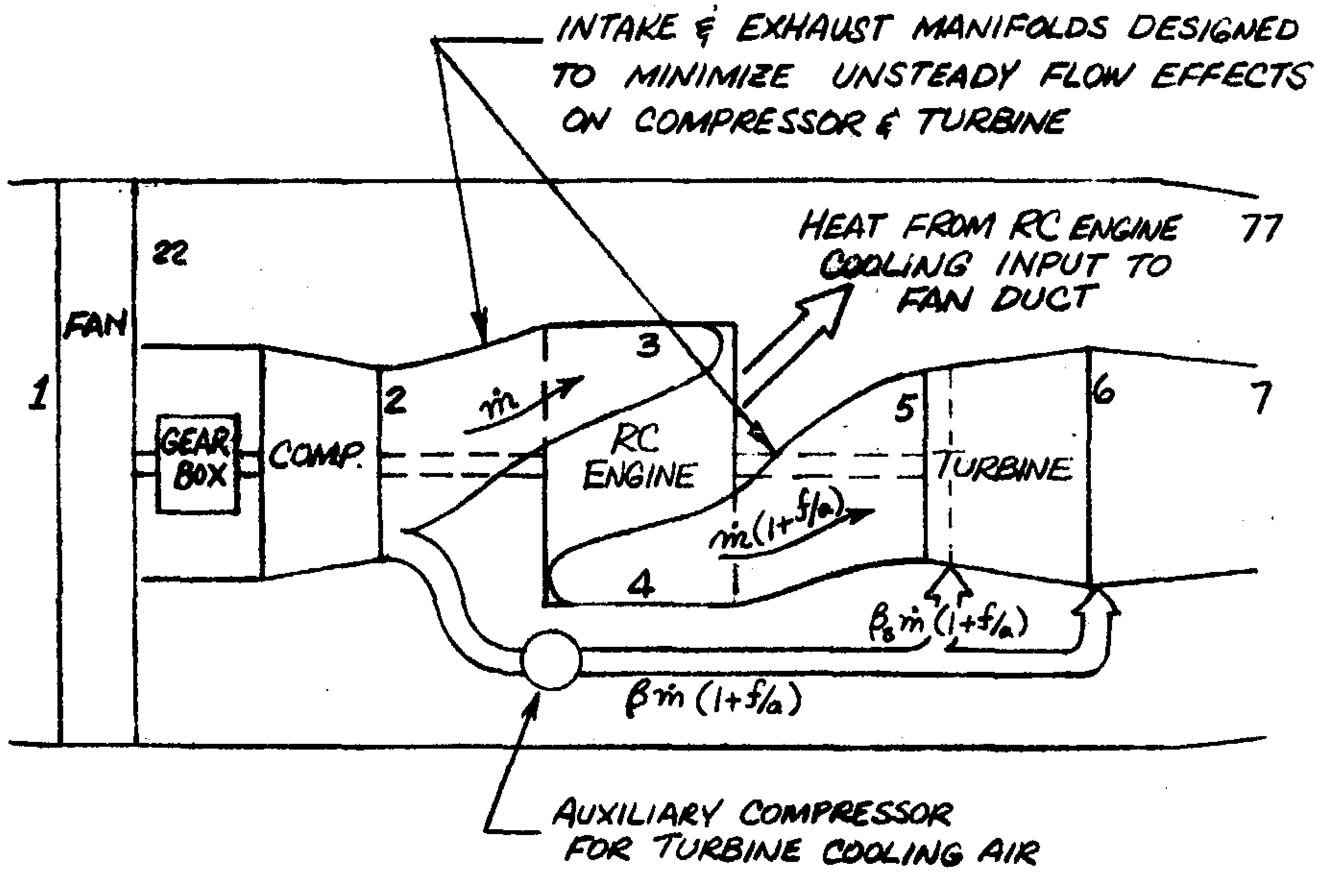

FIGURE 1. - CONCEPTUAL SKETCH OF COMPOUND ENGINE SHOWING FLOW STATIONS.

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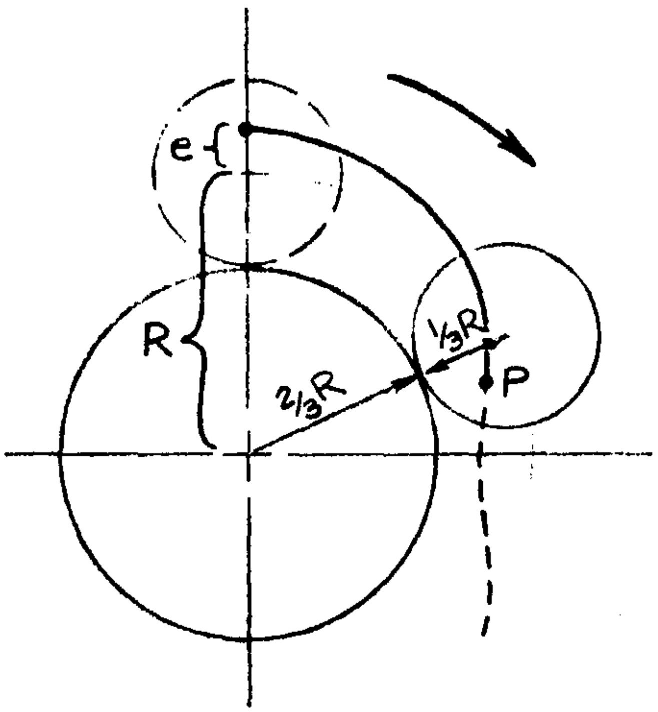


FIGURE 2.— GENERATING EPITROCHOID.

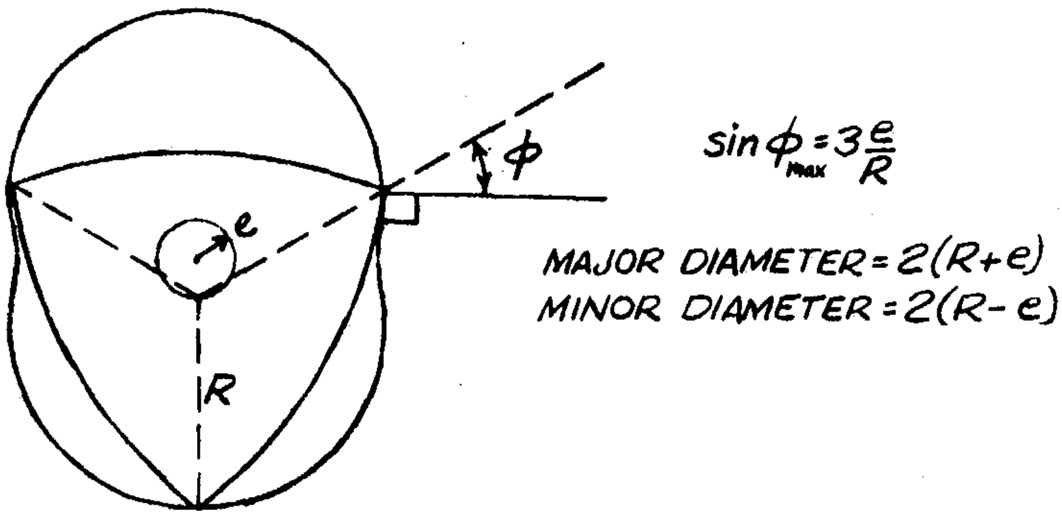


FIGURE 3.— BASIC RC ENGINE RELATIONSHIPS.

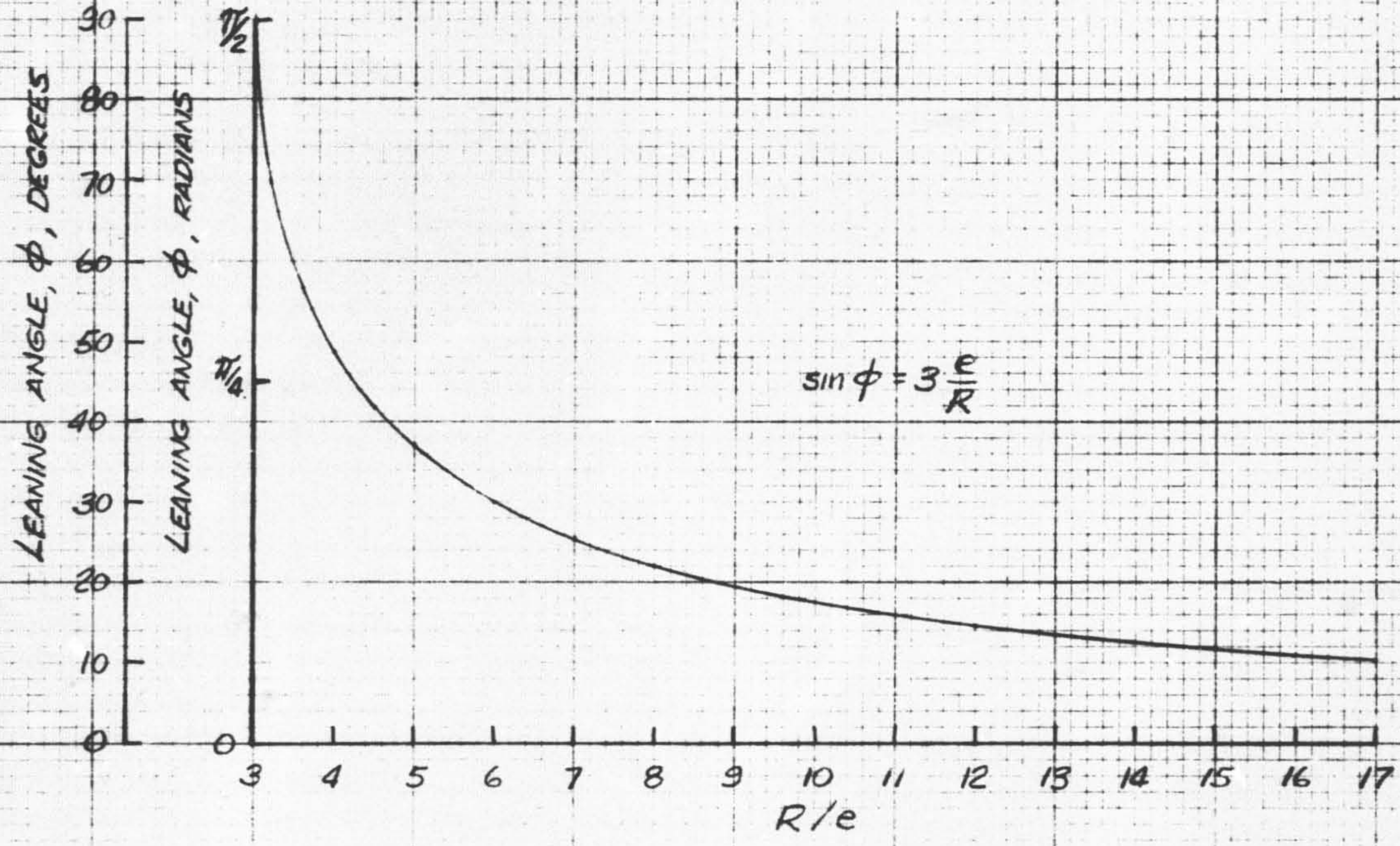
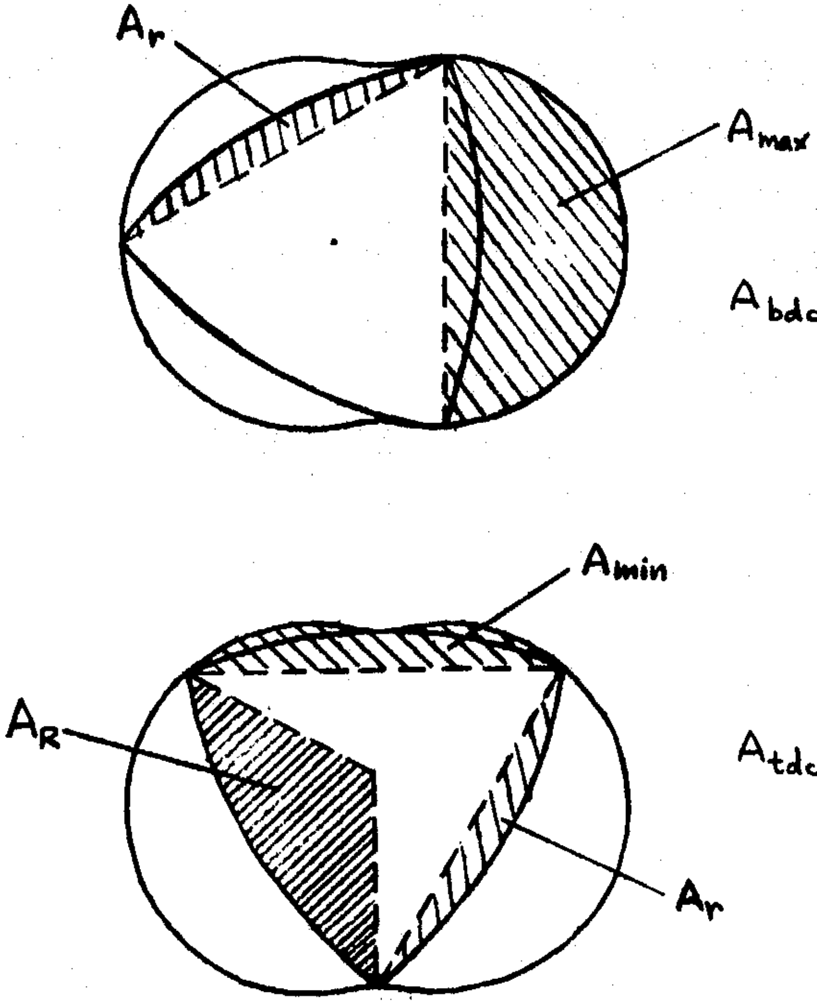


FIGURE 4. – LEANING ANGLE AS A FUNCTION OF RC ENGINE GEOMETRY.



$$A_{bdc} = A_{max} - A_r$$

$$A_{tdc} = A_{min} - A_r$$

FIGURE 5. – AREAS FOR CALCULATING COMPRESSION RATIO OF RC ENGINE.

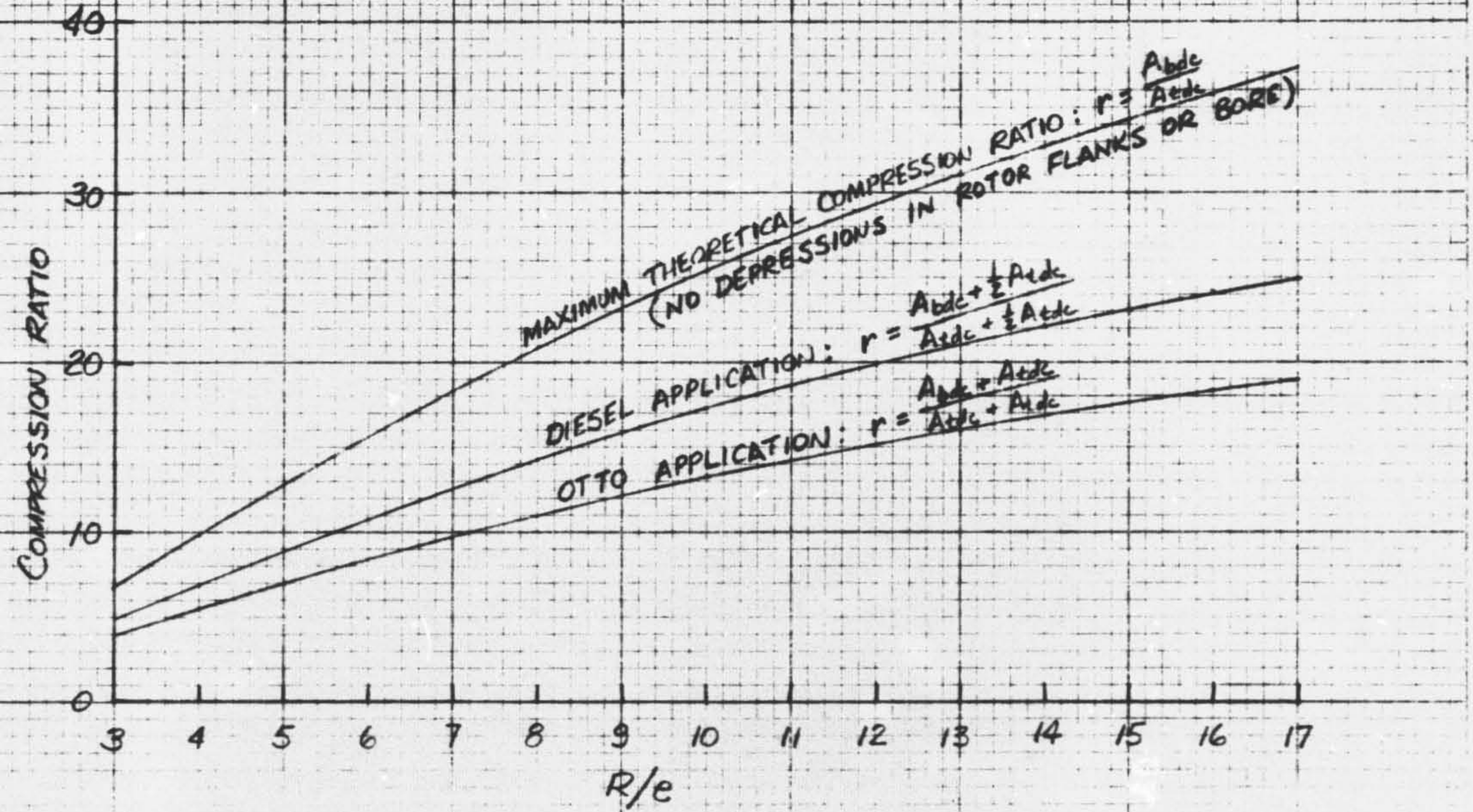


FIGURE 6. – COMPRESSION RATIO AS A FUNCTION OF RC ENGINE GEOMETRY.

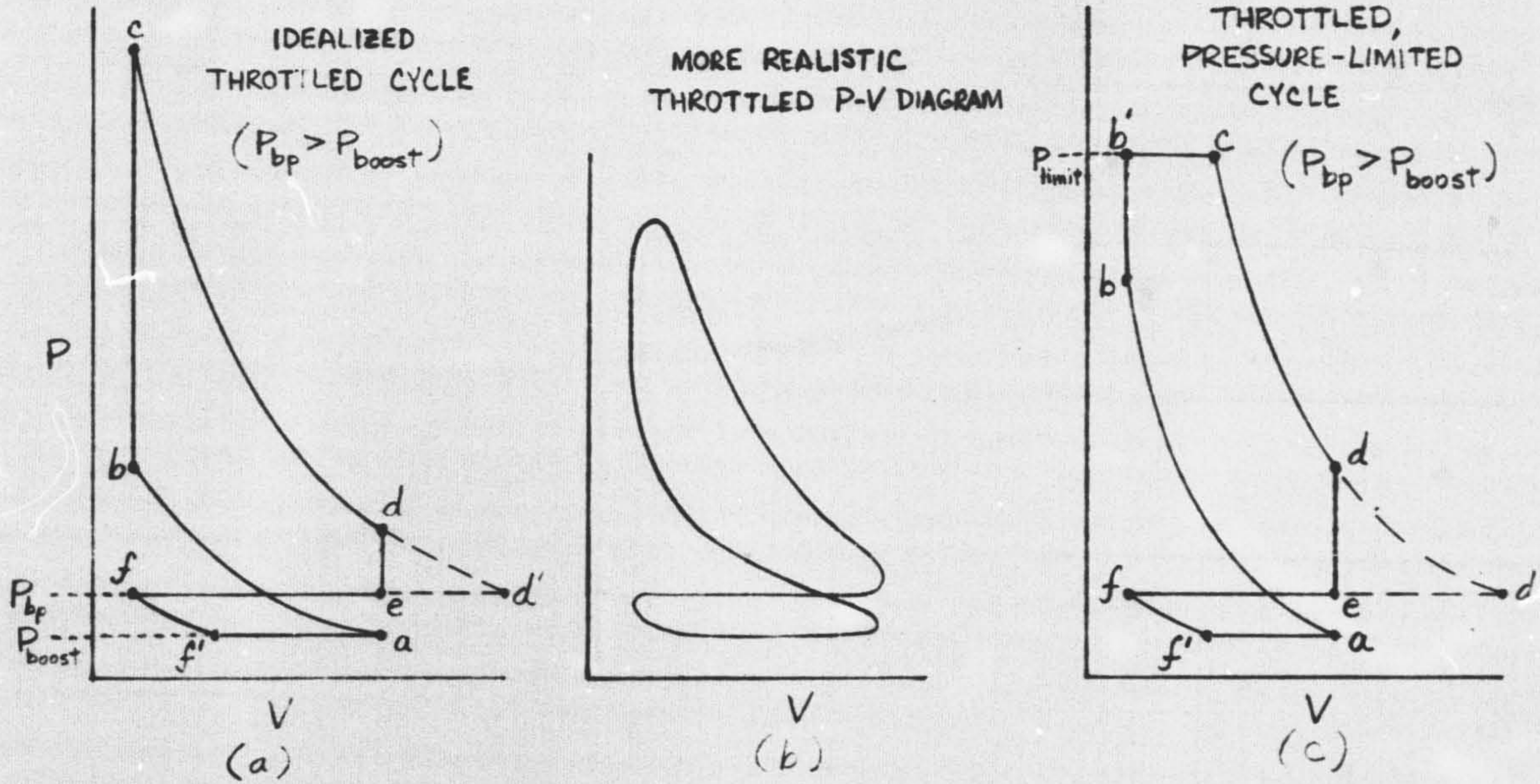


FIGURE 7. – P-V DIAGRAMS

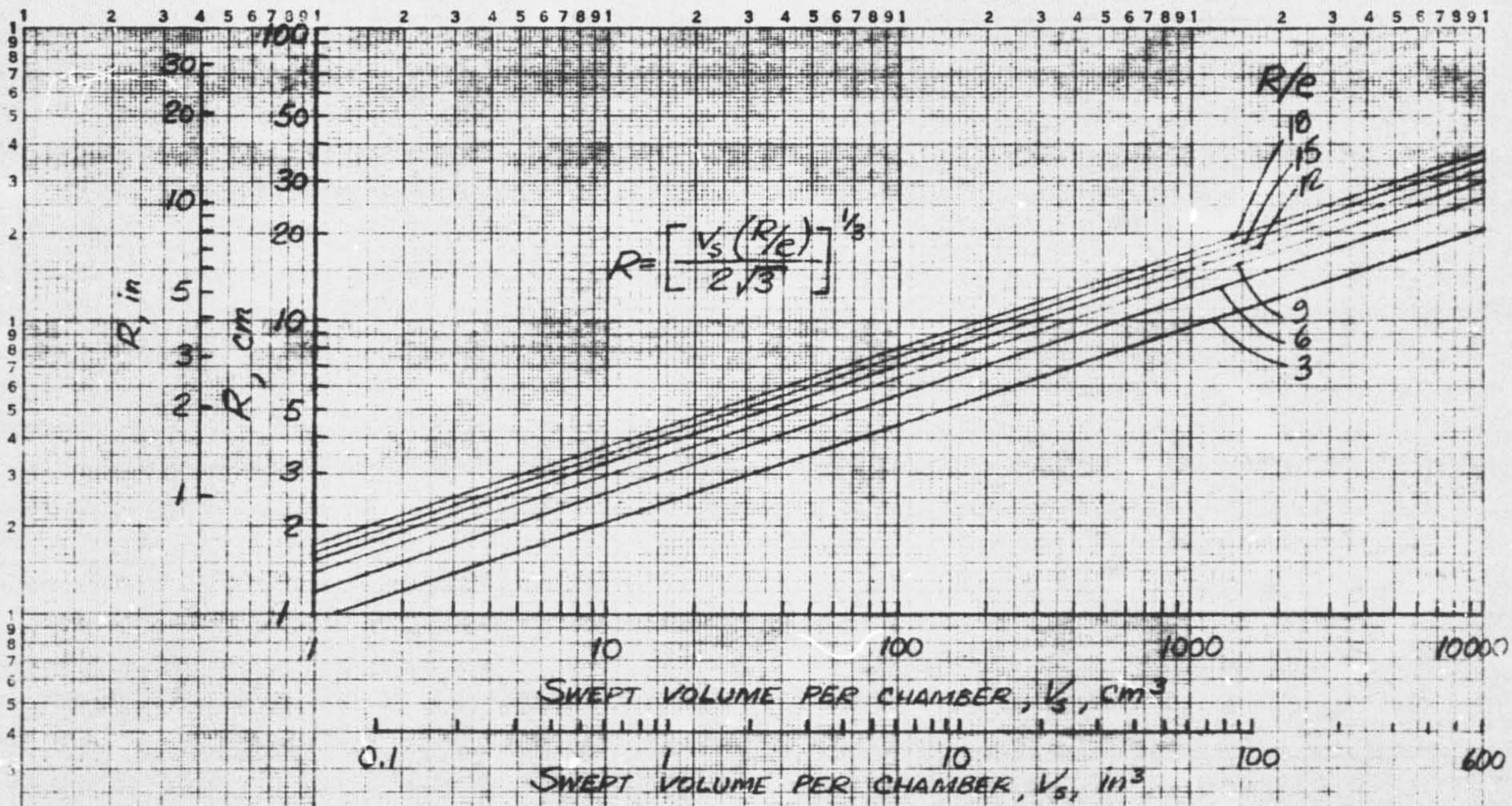


FIGURE 8. – SWEPT VOLUME PER CHAMBER OF RC ENGINE.

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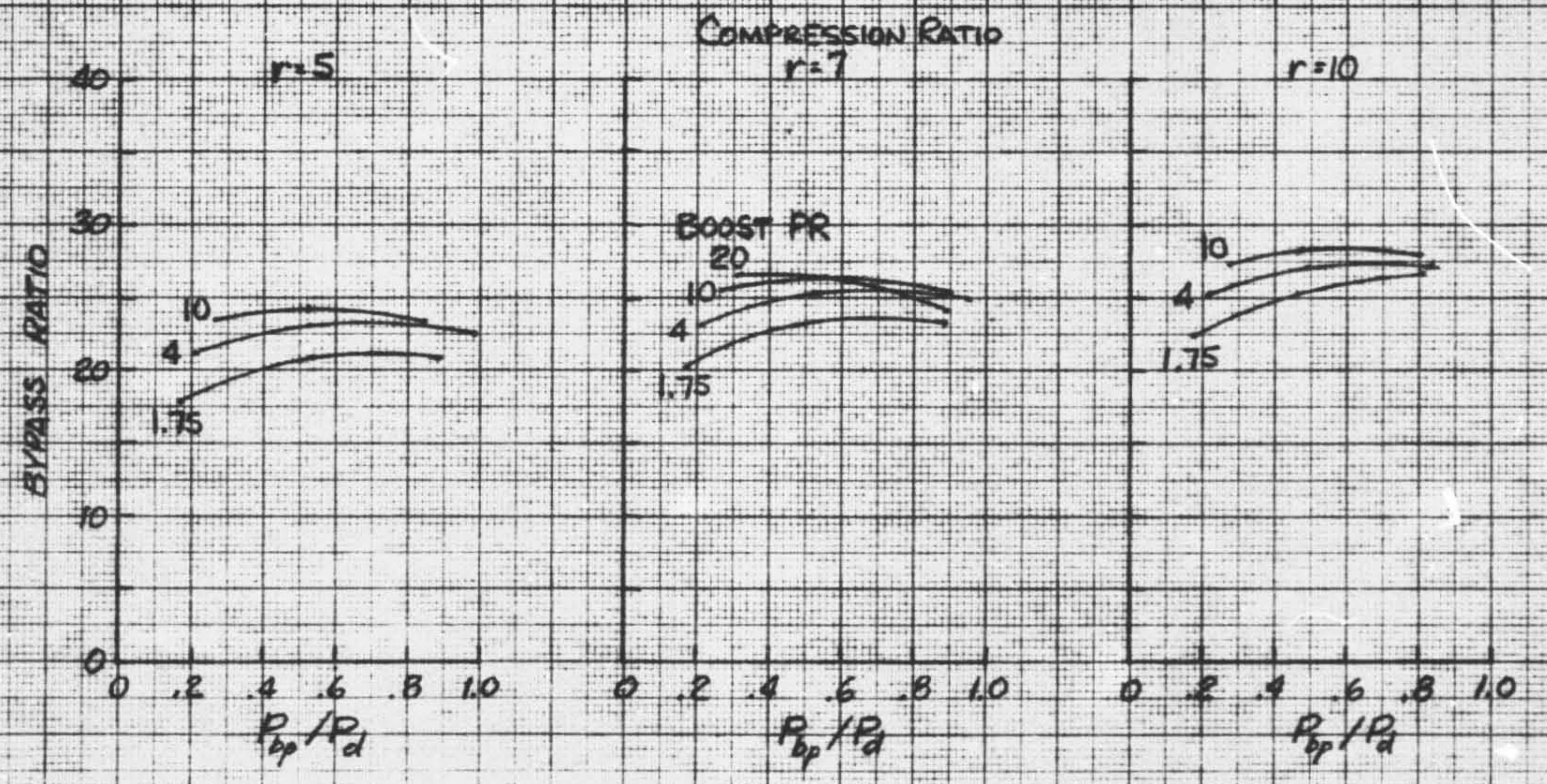

FIGURE 9.– COMPOUND ENGINE BYPASS RATIO FOR 25% OTTO-CYCLE COOLING LOSS.

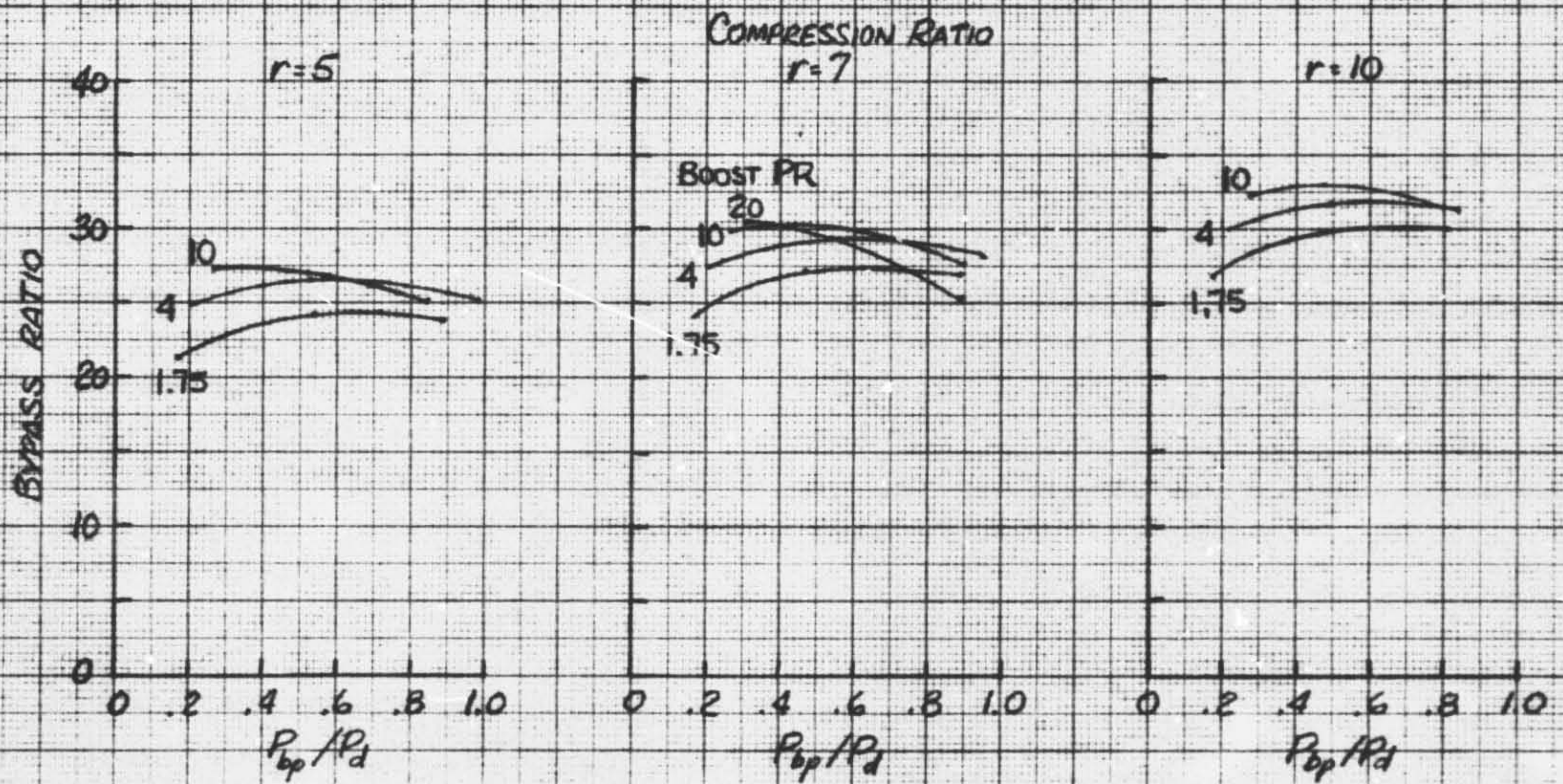

FIGURE 10. – COMPOUND ENGINE BYPASS RATIO FOR 10% OTTO-CYCLE COOLING LOSS.

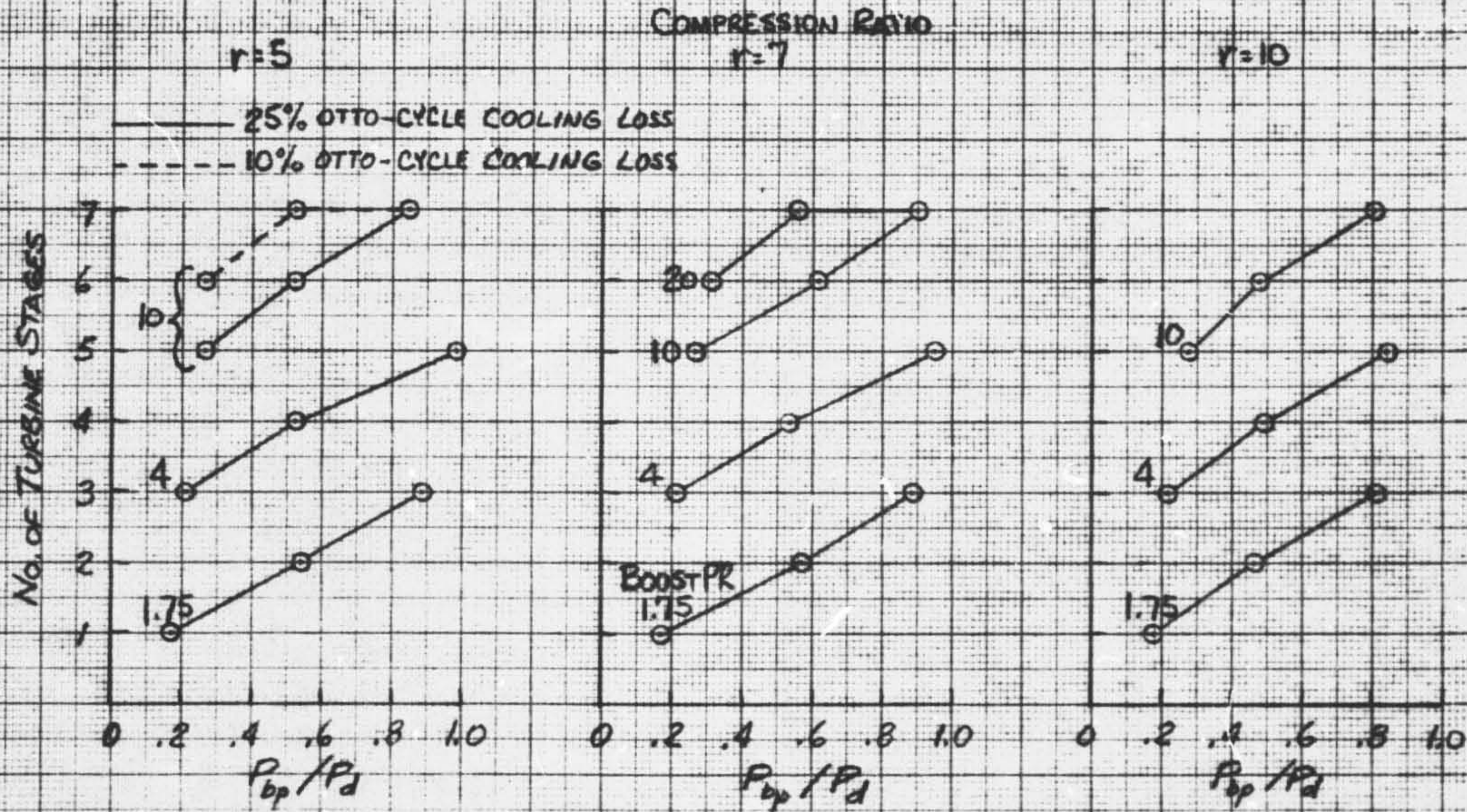

FIGURE 11.— NUMBER OF TURBINE STAGES IN COMPOUND ENGINE.

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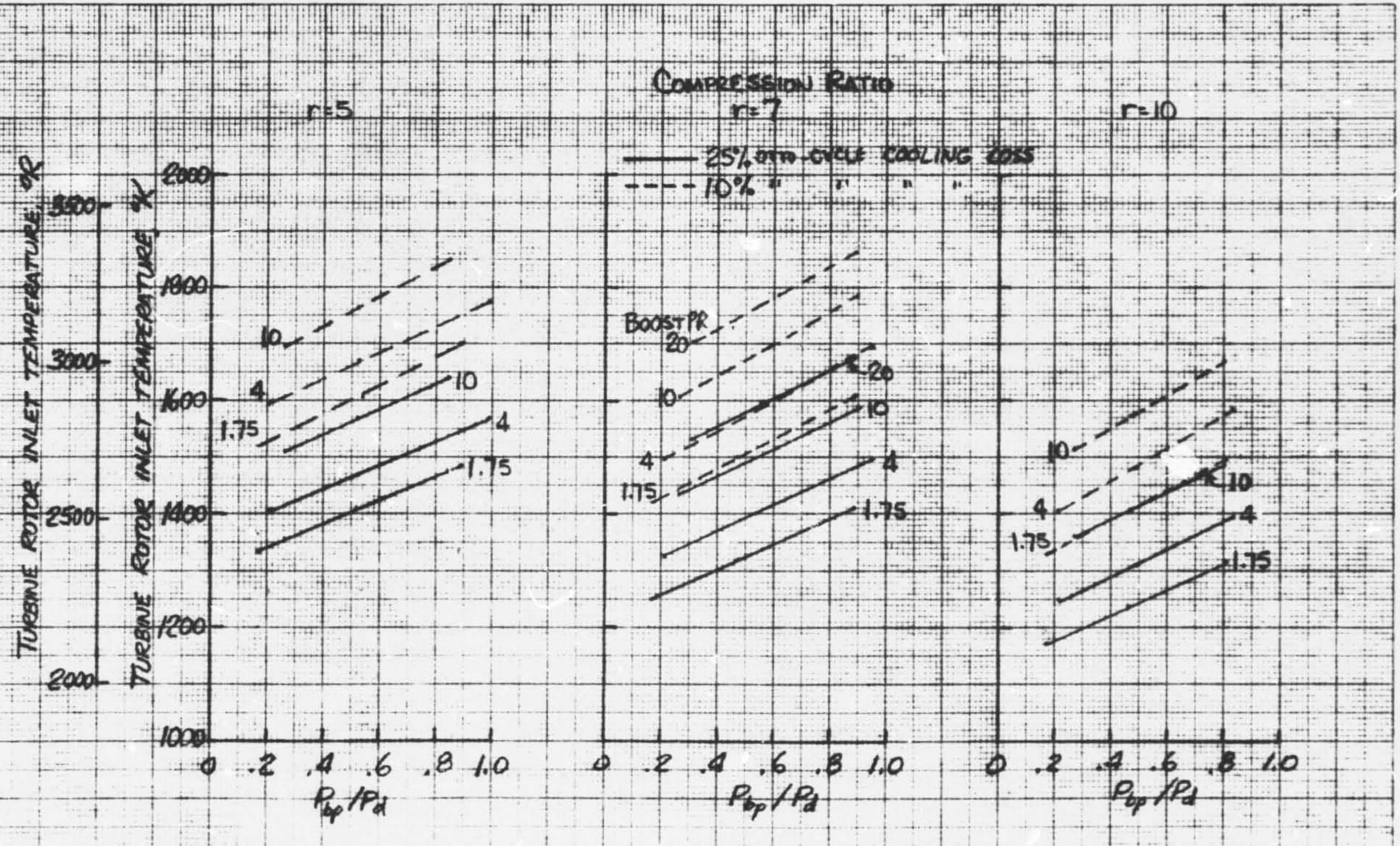

FIGURE 12.- TURBINE ROTOR INLET TEMPERATURE FOR COMPOUND ENGINE.

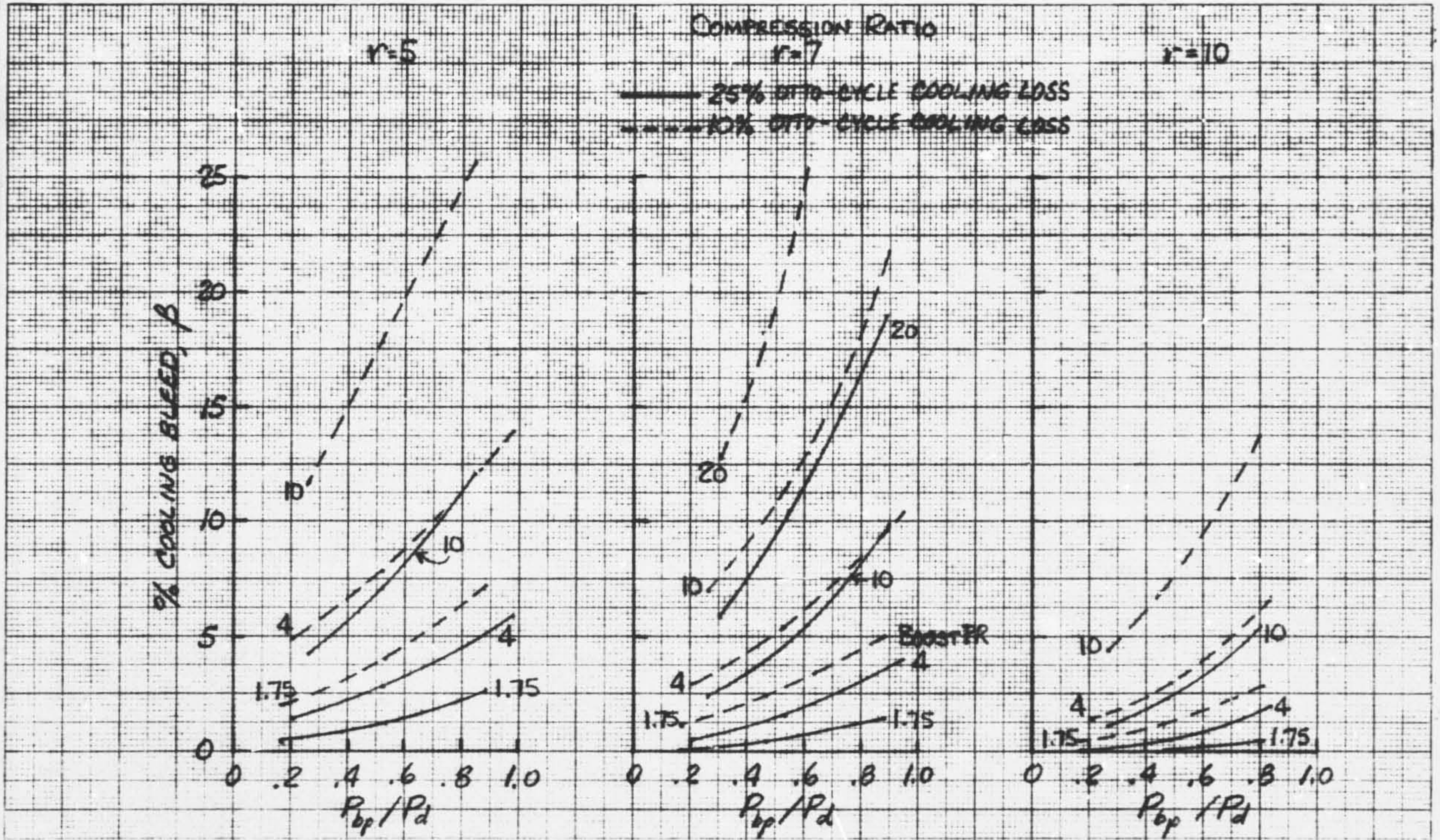

FIGURE 13.— TURBINE COOLING BLEED REQUIREMENTS FOR COMPOUND ENGINE.

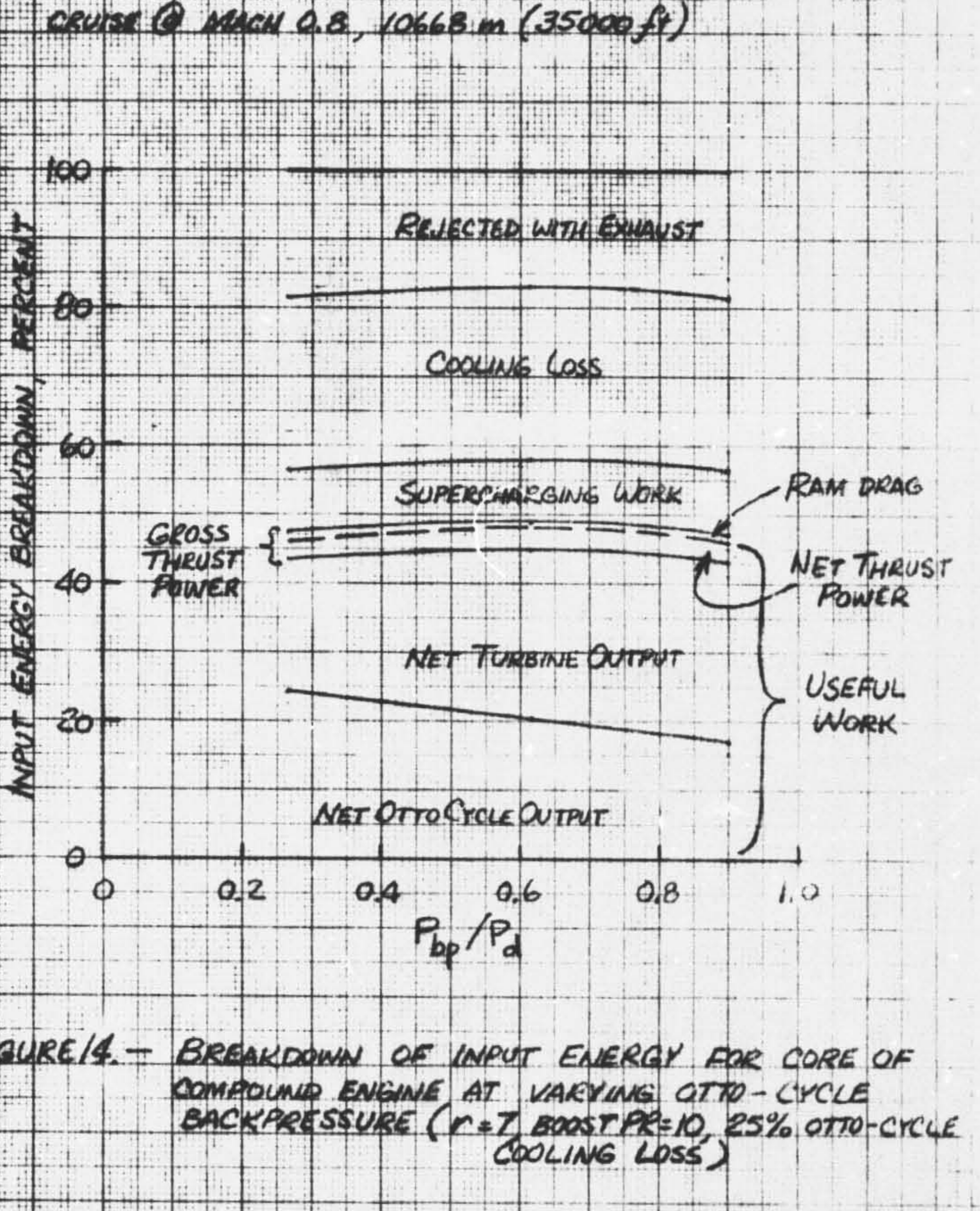

FIGURE 14.— BREAKDOWN OF INPUT ENERGY FOR CORE OF COMPOUND ENGINE AT VARYING OTTO-CYCLE BACKPRESSURE (r = 7, BOOST PR = 10, 25% OTTO-CYCLE COOLING LOSS)

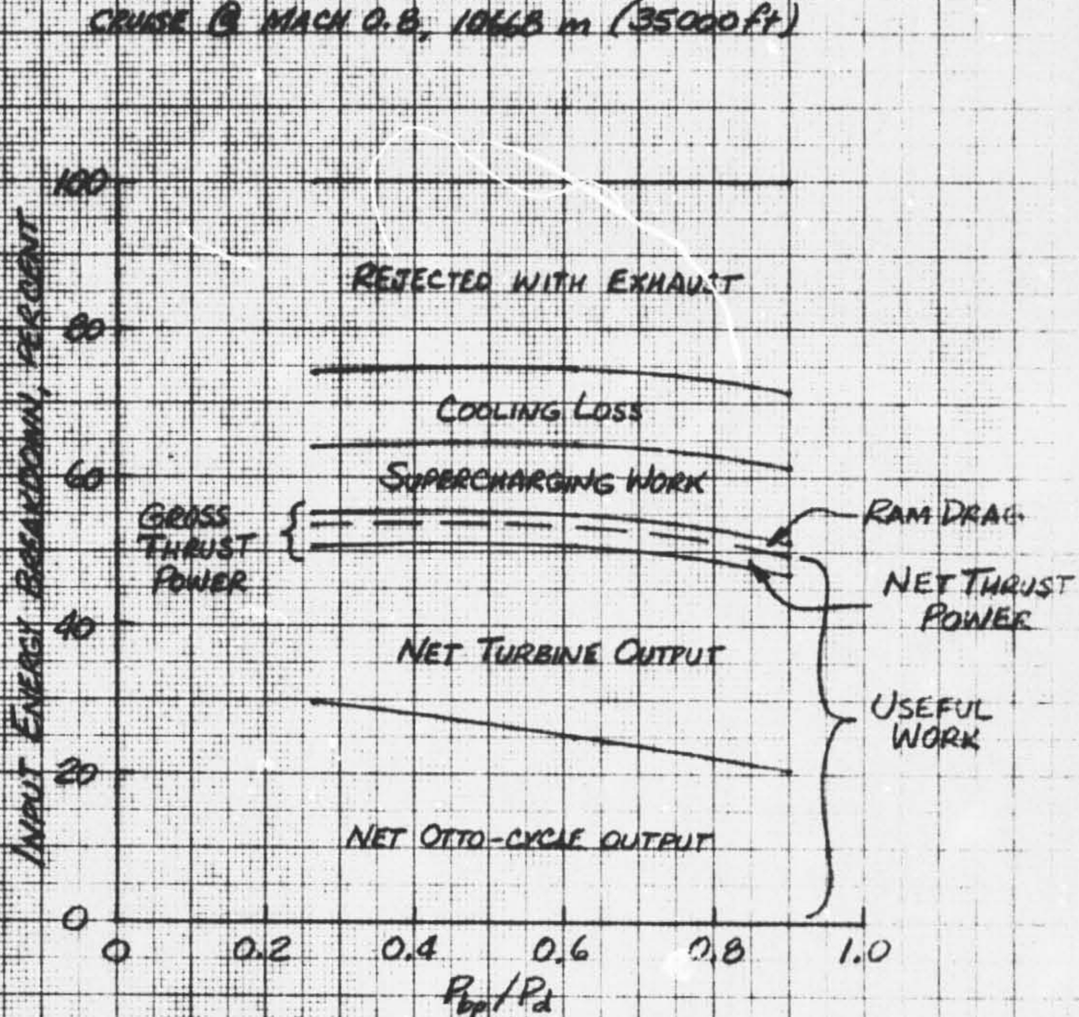

FIGURE 15. – BREAKDOWN OF INPUT ENERGY FOR CORE OF COMPOUND ENGINE AT VARYING OTTO-CYCLE BACKPRESSURE (r=7, BOOST PR=10, 10% OTTO-CYCLE COOLING LOSS)

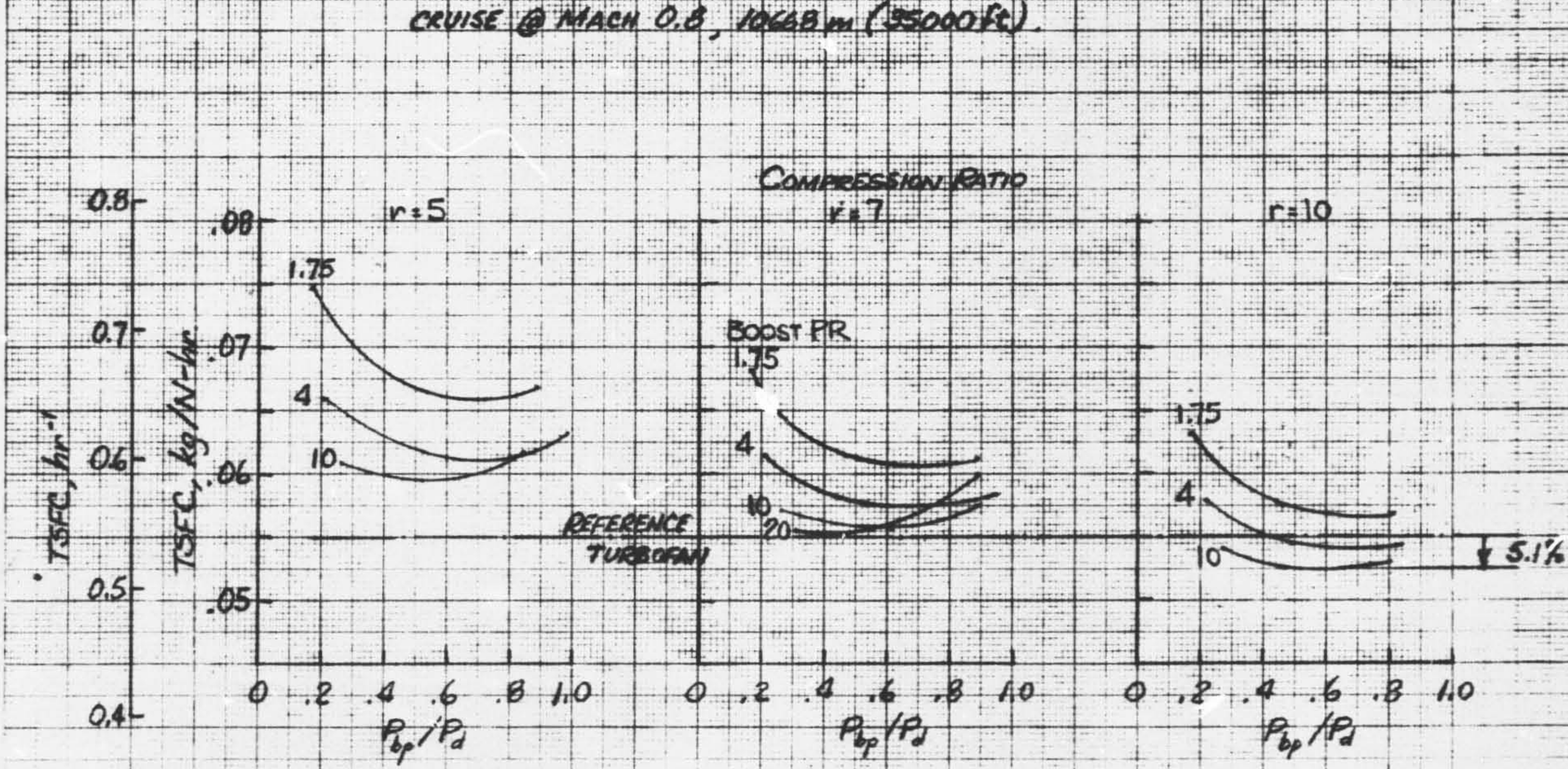

FIGURE 16. – COMPOUND CYCLE THRUST SFC FOR 25% OTTO-CYCLE COOLING LOSS.

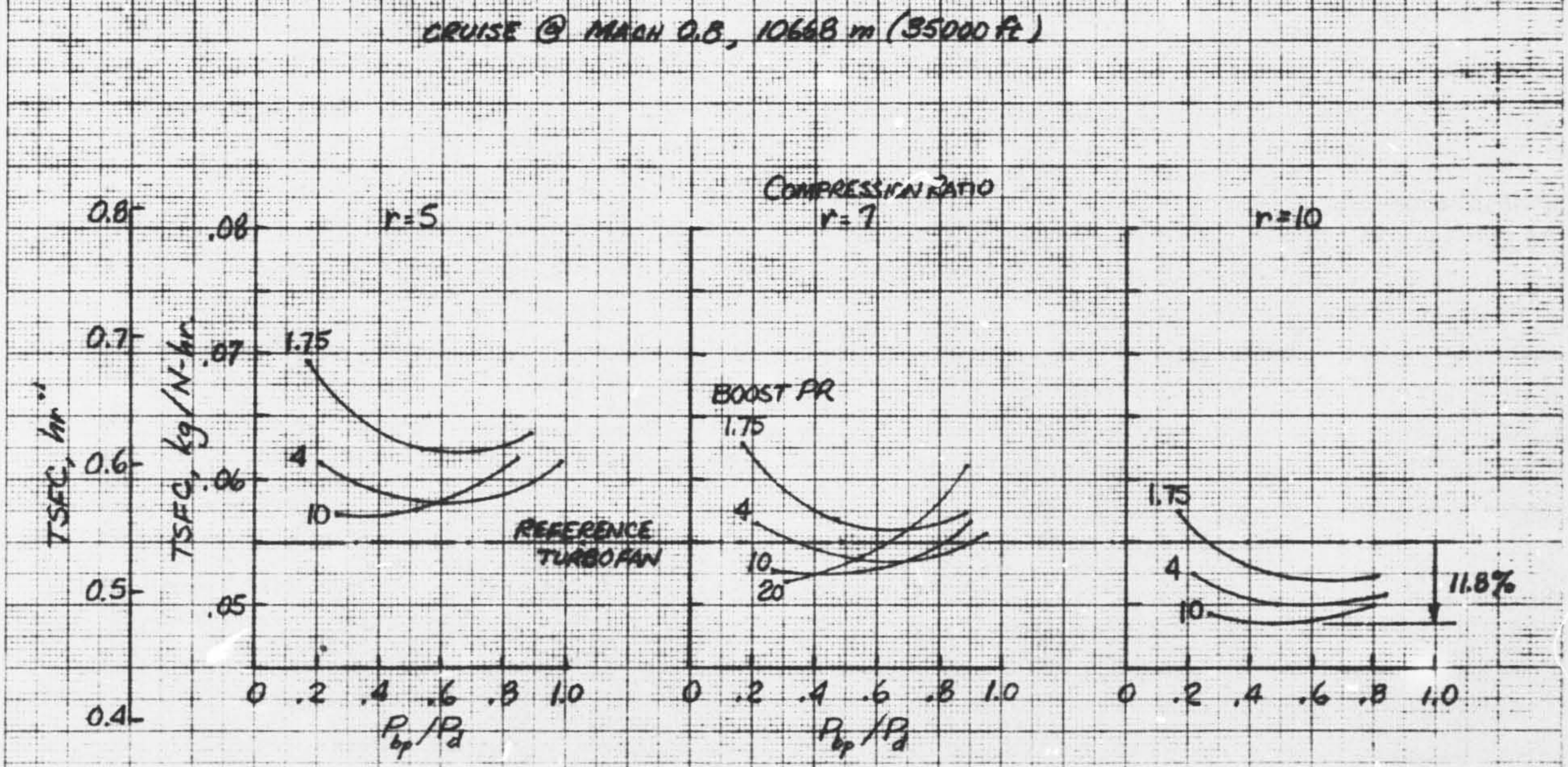

FIGURE 17. - COMPOUND CYCLE THRUST SFC FOR 10% OTTO-CYCLE COOLING LOSS.

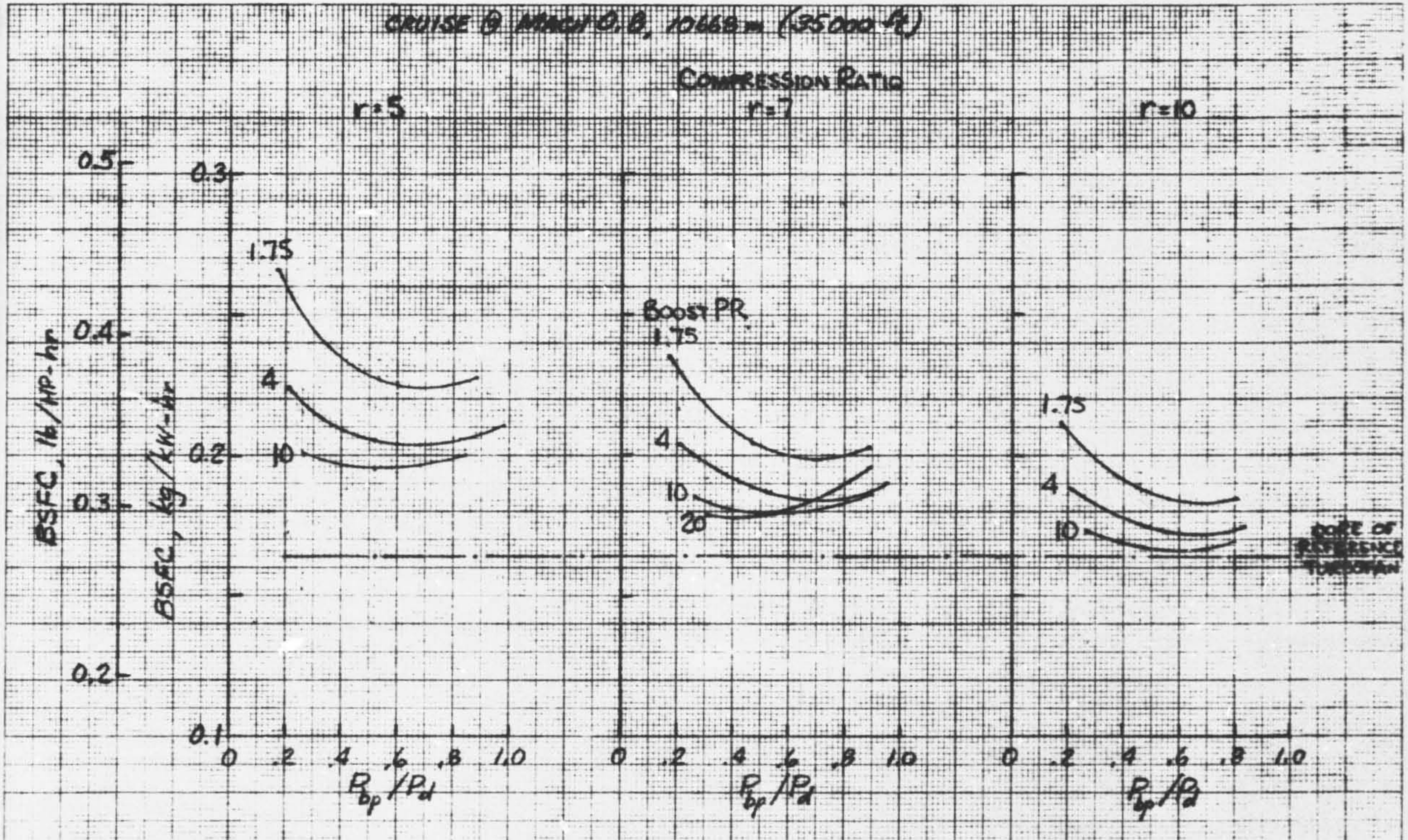

FIGURE 18.- COMPOUND CYCLE BRAKE SFC FOR 25% OTTO-CYCLE COOLING LOSS.

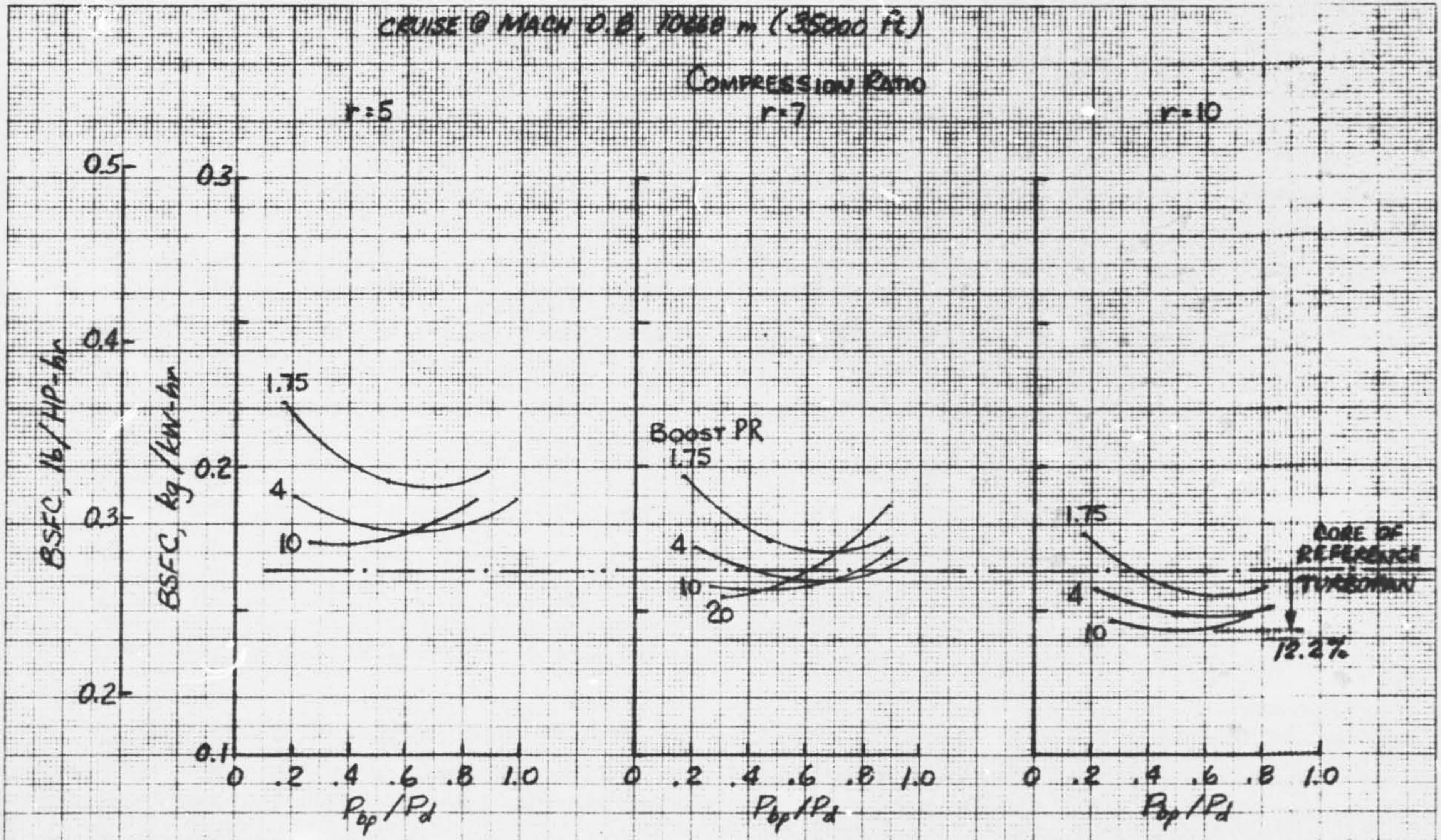

FIGURE 19.- COMPOUND CYCLE BRAKE SFC FOR 10% OTTO-CYCLE COOLING LOSS).

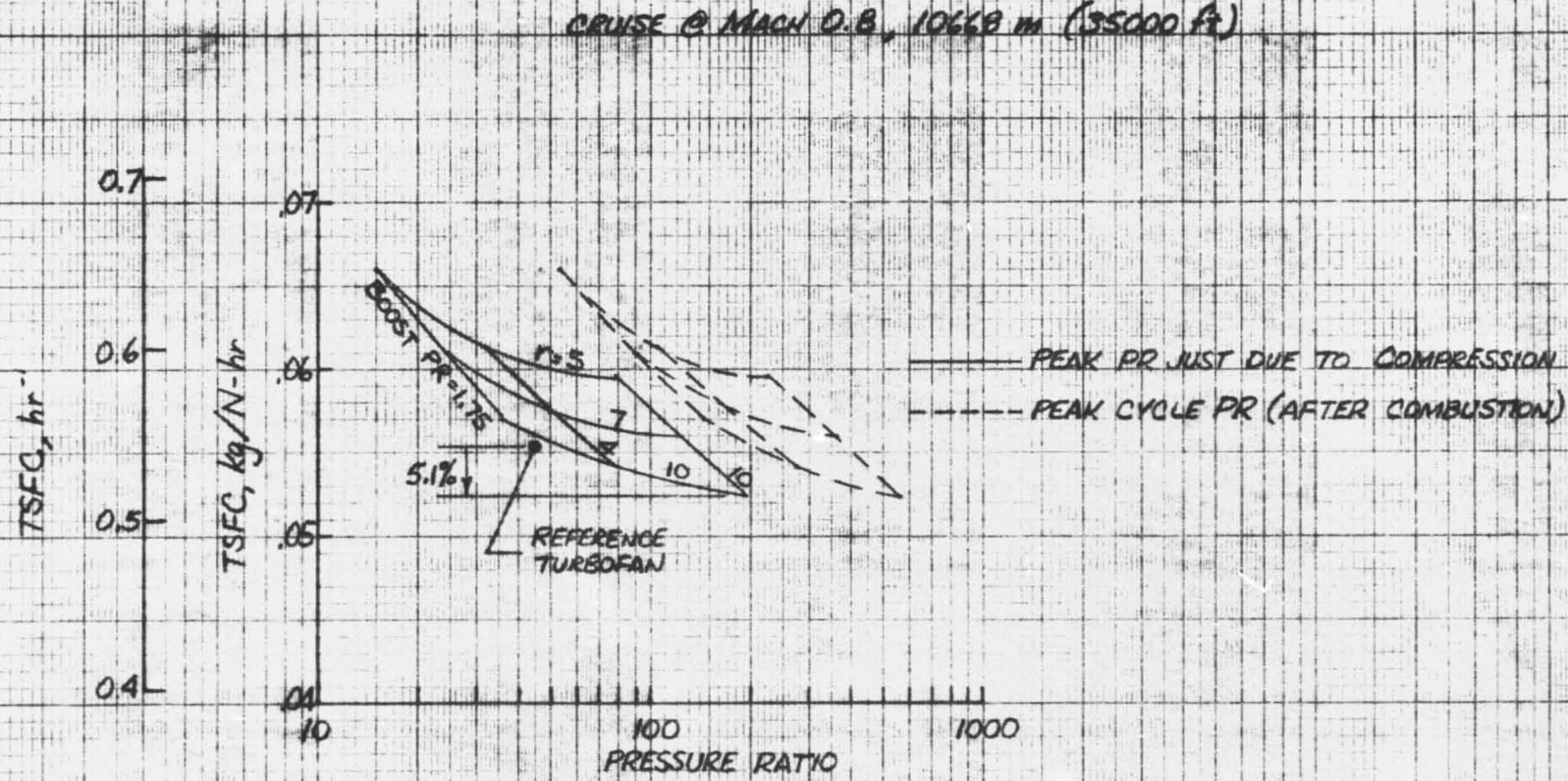

FIGURE 20. – EFFECT OF PEAK CYCLE PRESSURE RATIO ON THRUST SFC FOR 25% OTTO-CYCLE COOLING LOSS.
($P_{b_p}/P_d = 0.6$)

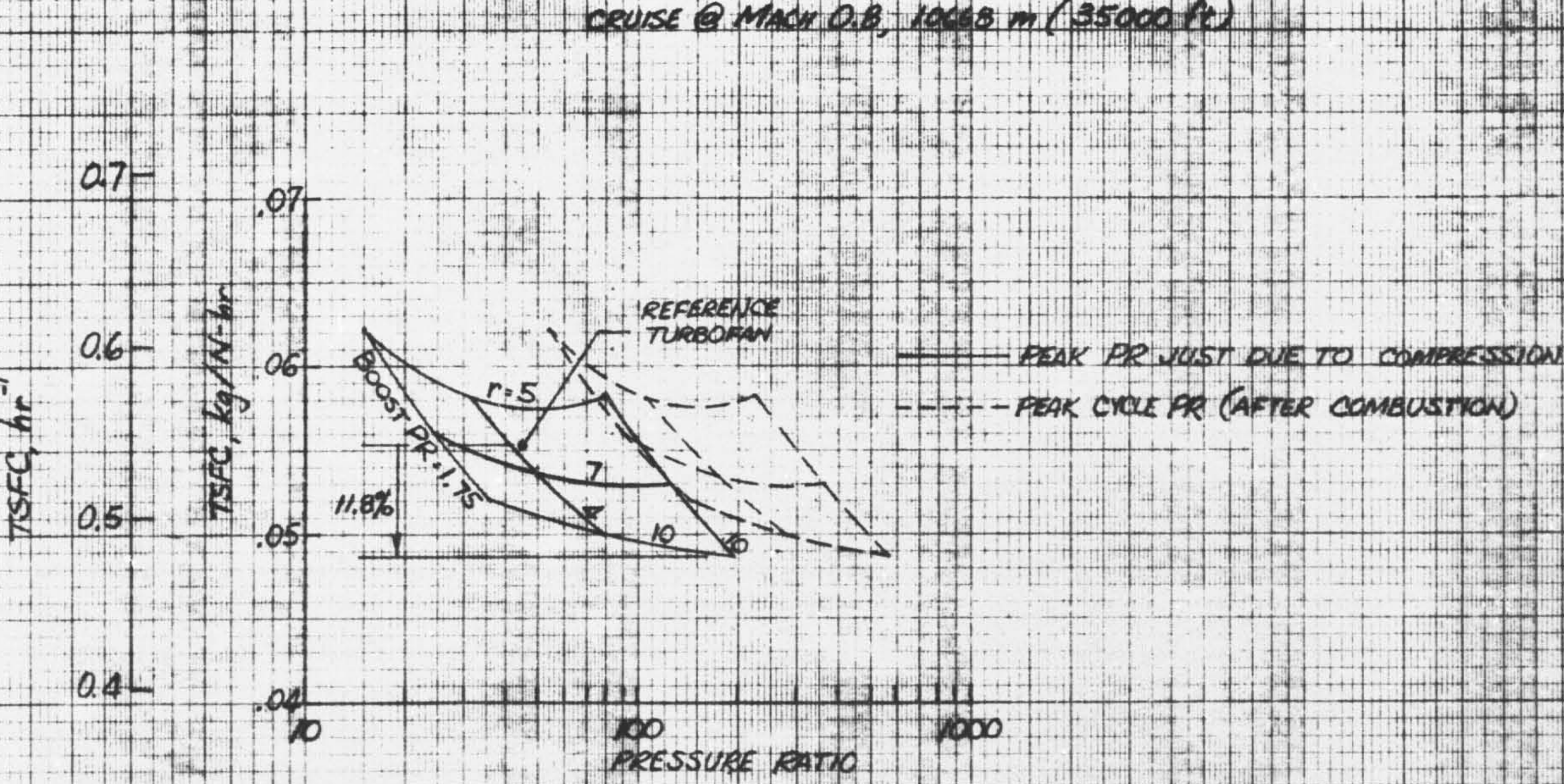

FIGURE 21.- EFFECT OF PEAK CYCLE PRESSURE RATIO ON THRUST SFC FOR 10% OTTO-CYCLE COOLING LOSS. ($P_{bp}/P_d = 0.6$)

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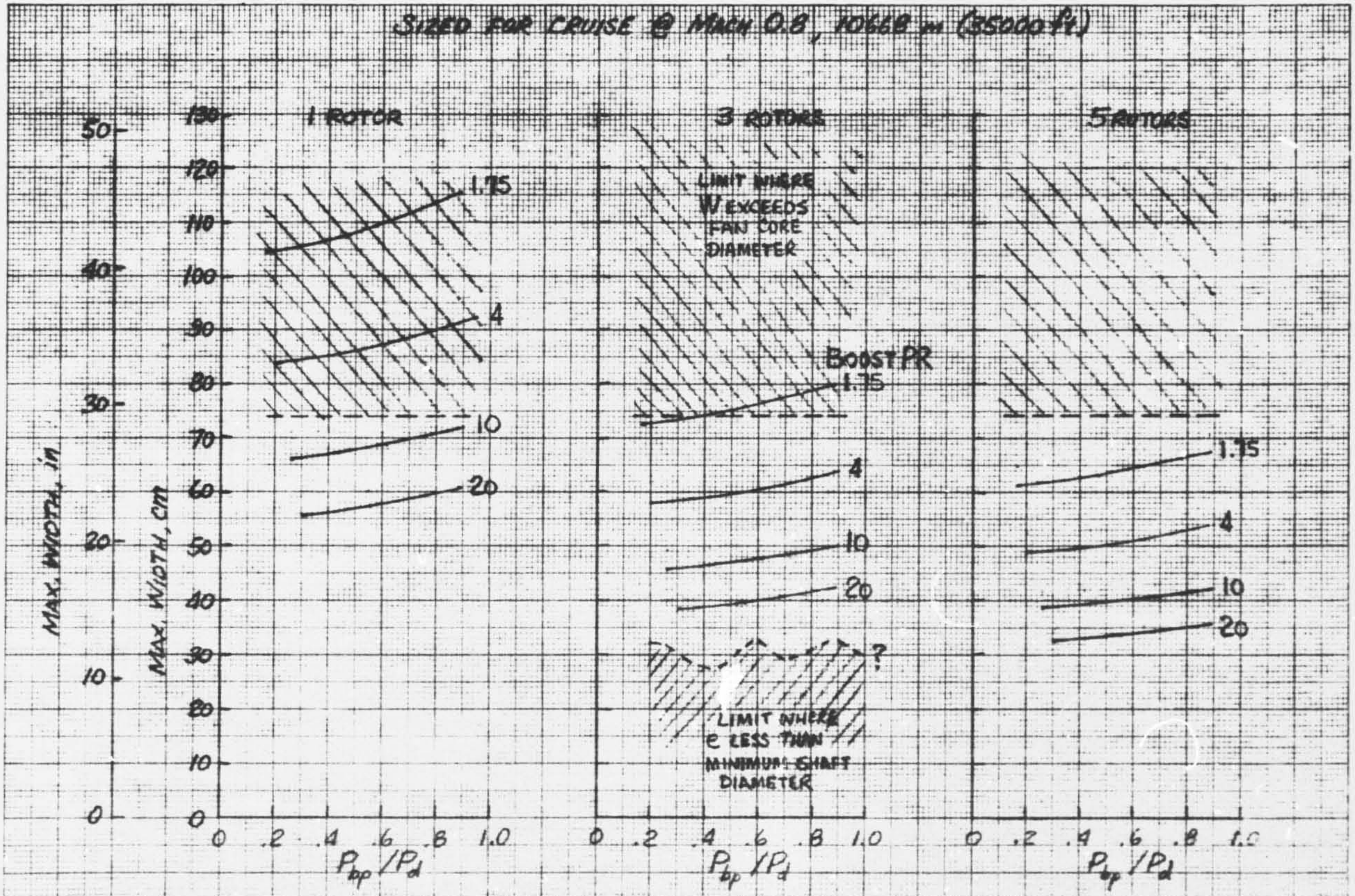

FIGURE 2?. - MAXIMUM WIDTH 2(R+e) OF RC ENGINE FOR VARYING BOOST, BACKPRESSURE, AND NO. OF ROTORS (r=7, 25% OTTO-CYCLE COOLING LOSS)

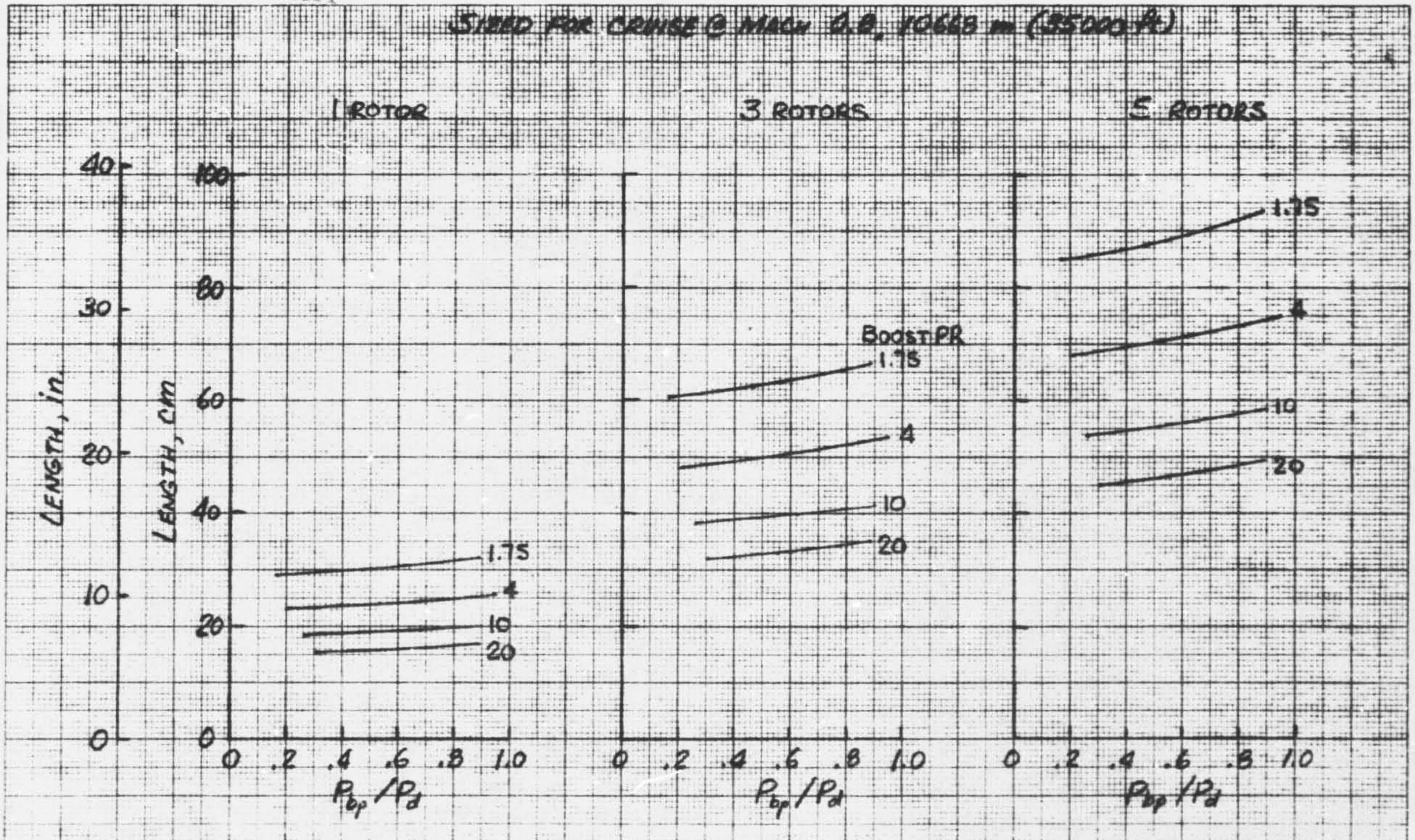

FIGURE 23. - LENGTH OF RC ENGINE FOR VARYING BOOST, BACKPRESSURE, AND NO. OF ROTORS ($r = 7$, 25% OTTO-CYCLE COOLING LOSS)

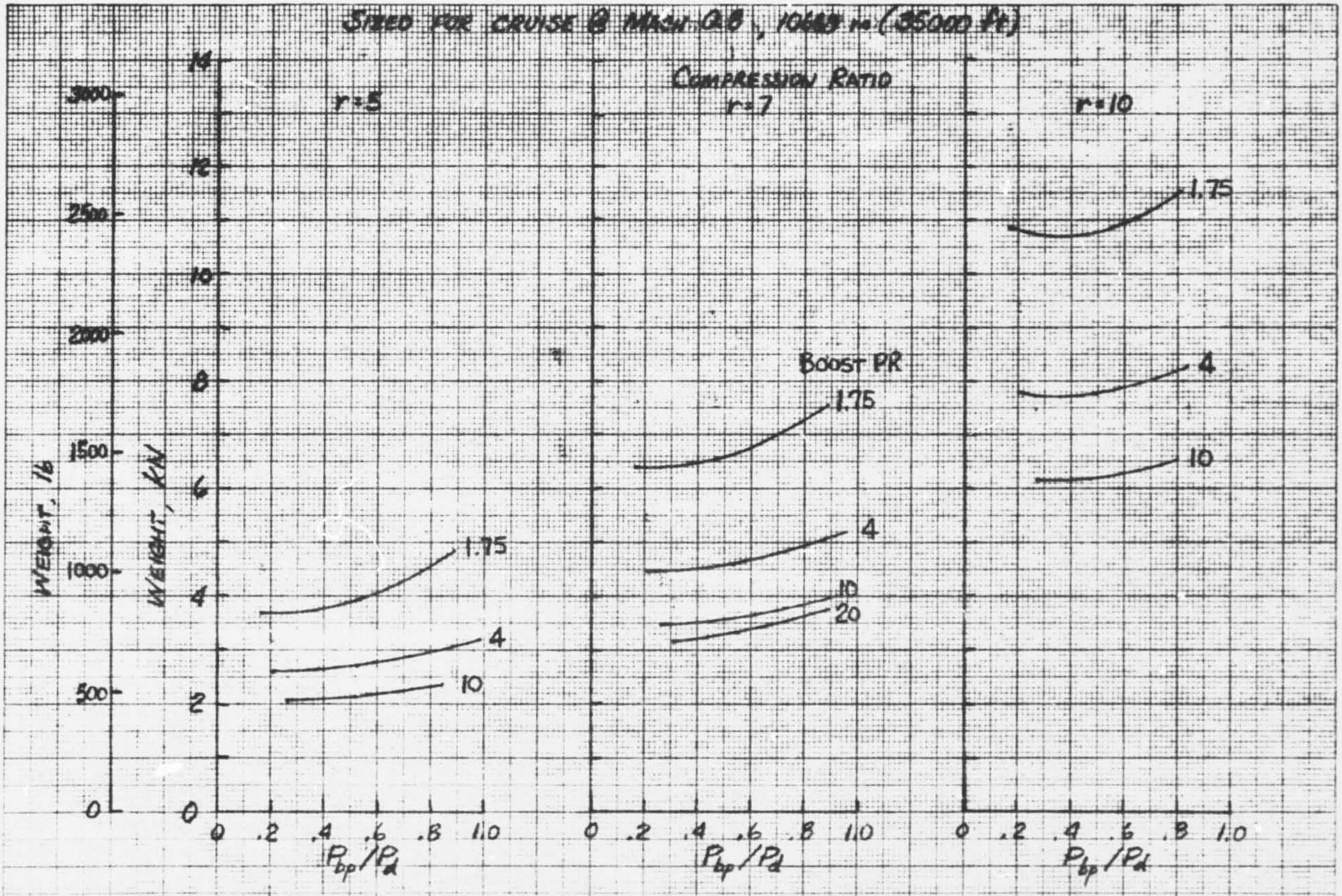

FIGURE 24.– RC ENGINE WEIGHT FOR VARYING BOOST, BACKPRESSURE, AND COMPRESSION RATIO (3 ROTORS, 25% OTTO-CYCLE COOLING LOSS).

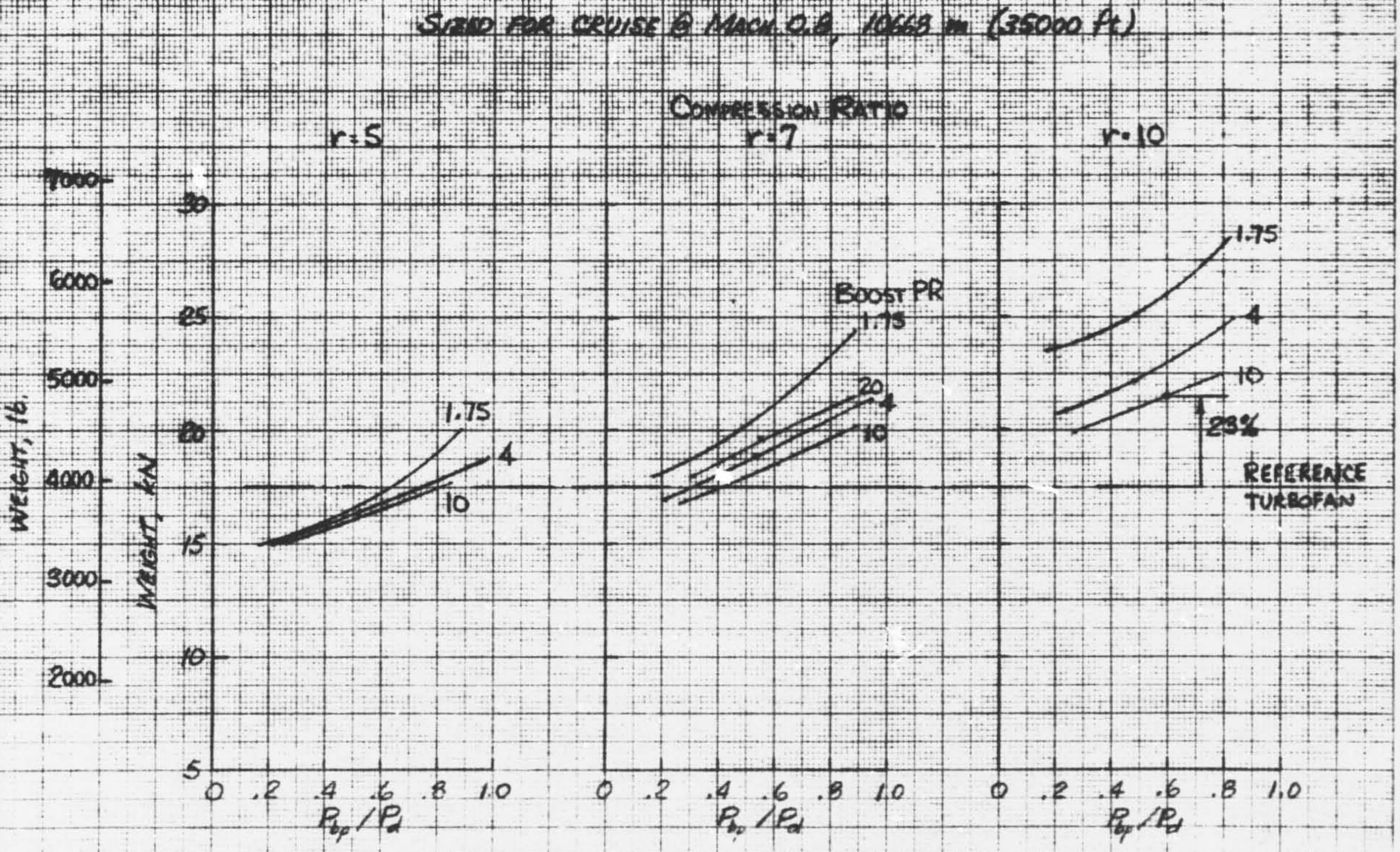

FIGURE 25.– COMPOUND ENGINE WEIGHT FOR VARYING BOOST, BACKPRESSURE, AND COMPRESSION RATIO (3 ROTORS, 25% OTTO-CYCLE COOLING LOSS).

SIZED FOR CRUISE @ MACH 0.8, 10668 m (35000 ft)

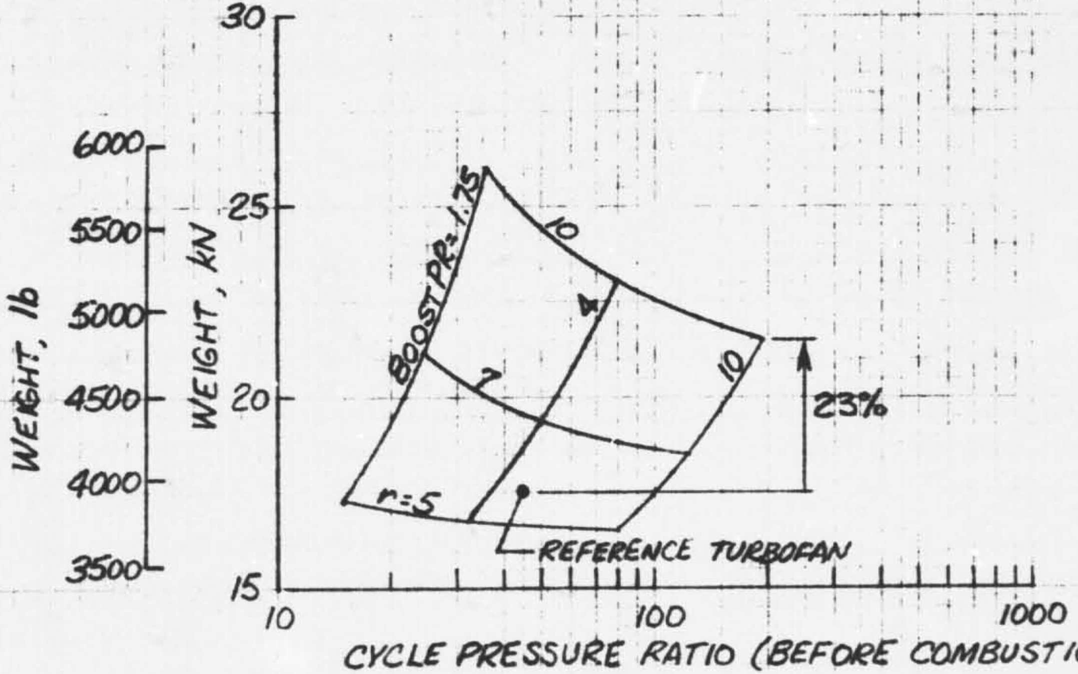

FIGURE 26. - EFFECT OF CYCLE PRESSURE RATIO ON COMPOUND ENGINE WEIGHT FOR 25% OTTO-CYCLE COOLING LOSS. ($P_{bp}/P_d = 0.6$)

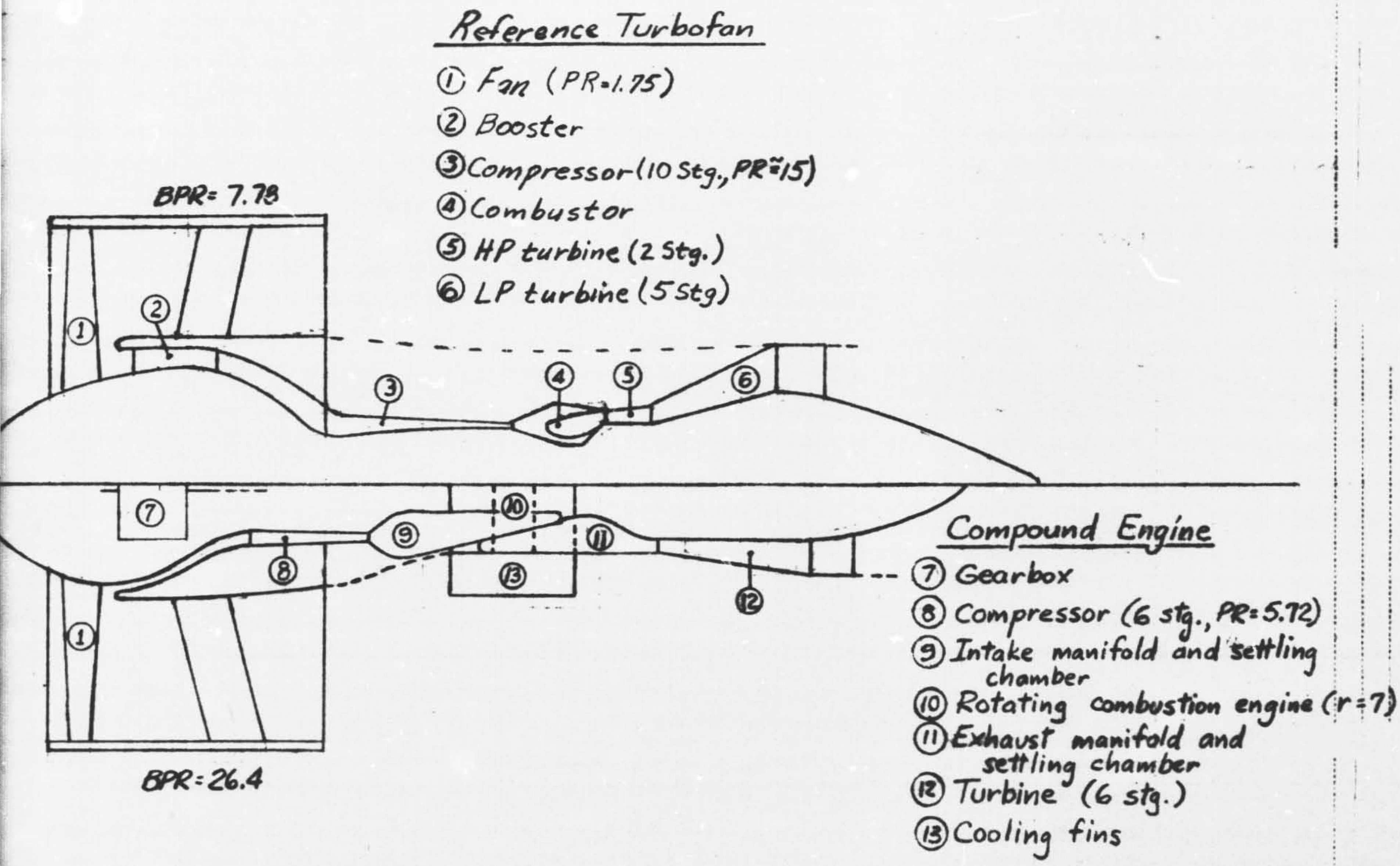

Figure 27. – Comparative sketch of reference turbofan and compound cycle turbofan using a supercharged rotary combustion engine. (Sized for cruise @ Mach 0.8, 10668 m (35000 ft))

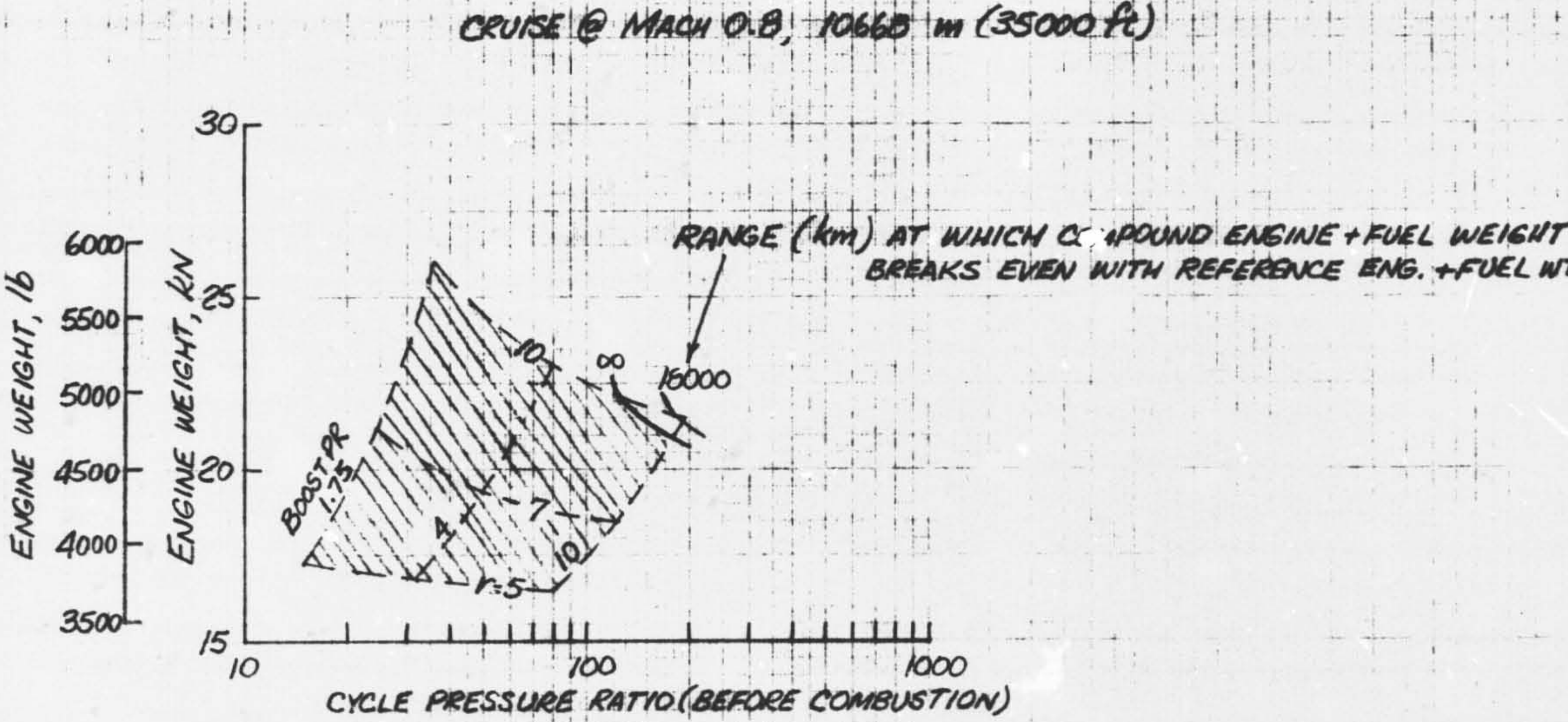

FIGURE 28.— BREAK-EVEN RANGES FOR COMPOUND & REFERENCE ENGINES FOR 25% OTTO-CYCLE COOLING LOSS (3 ROTORS, P_{0p}/P_d=0.6).

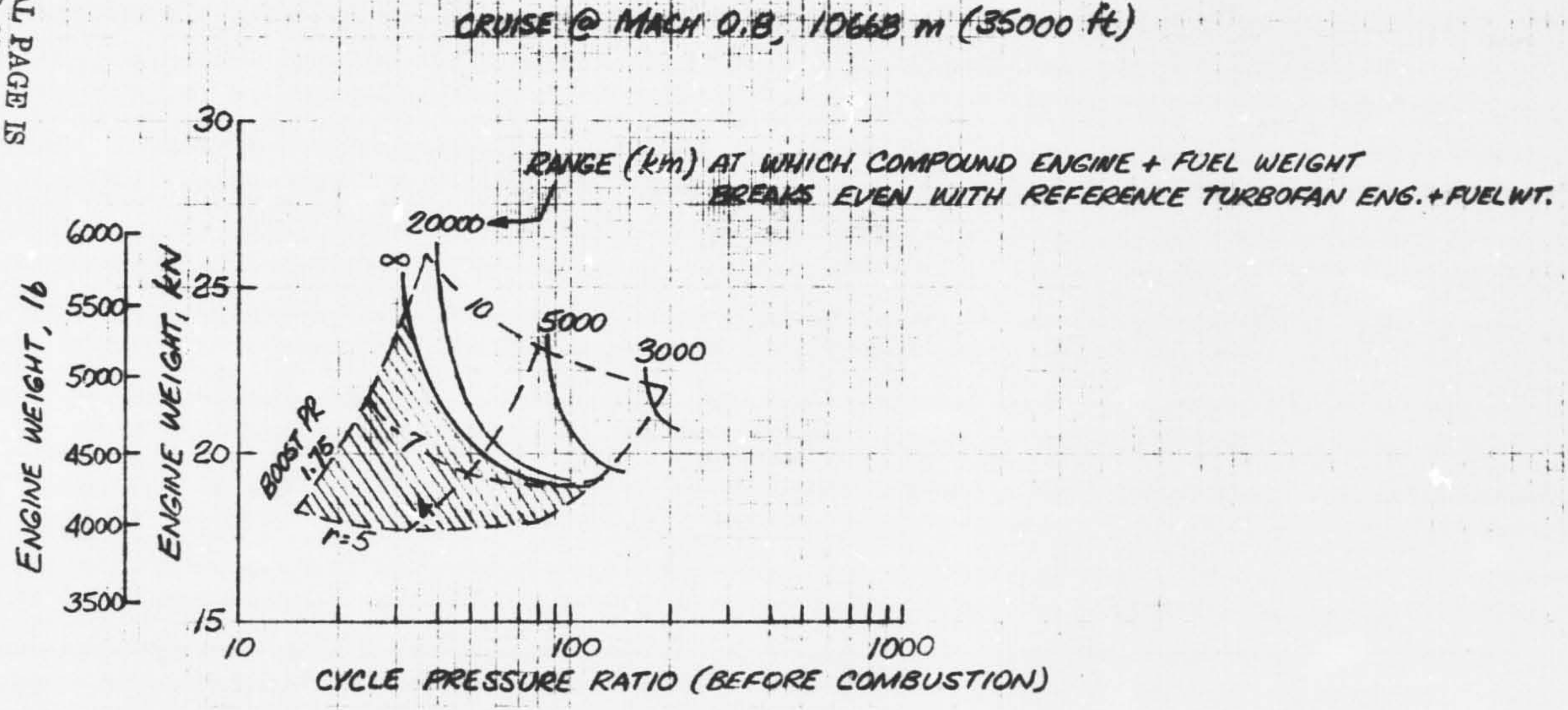

FIGURE 29. - BREAK-EVEN RANGES FOR COMPOUND & REFERENCE ENGINES FOR 10% OTTO-CYCLE COOLING LOSS (3 ROTORS, $P_{bp}/P_d = 0.6$).

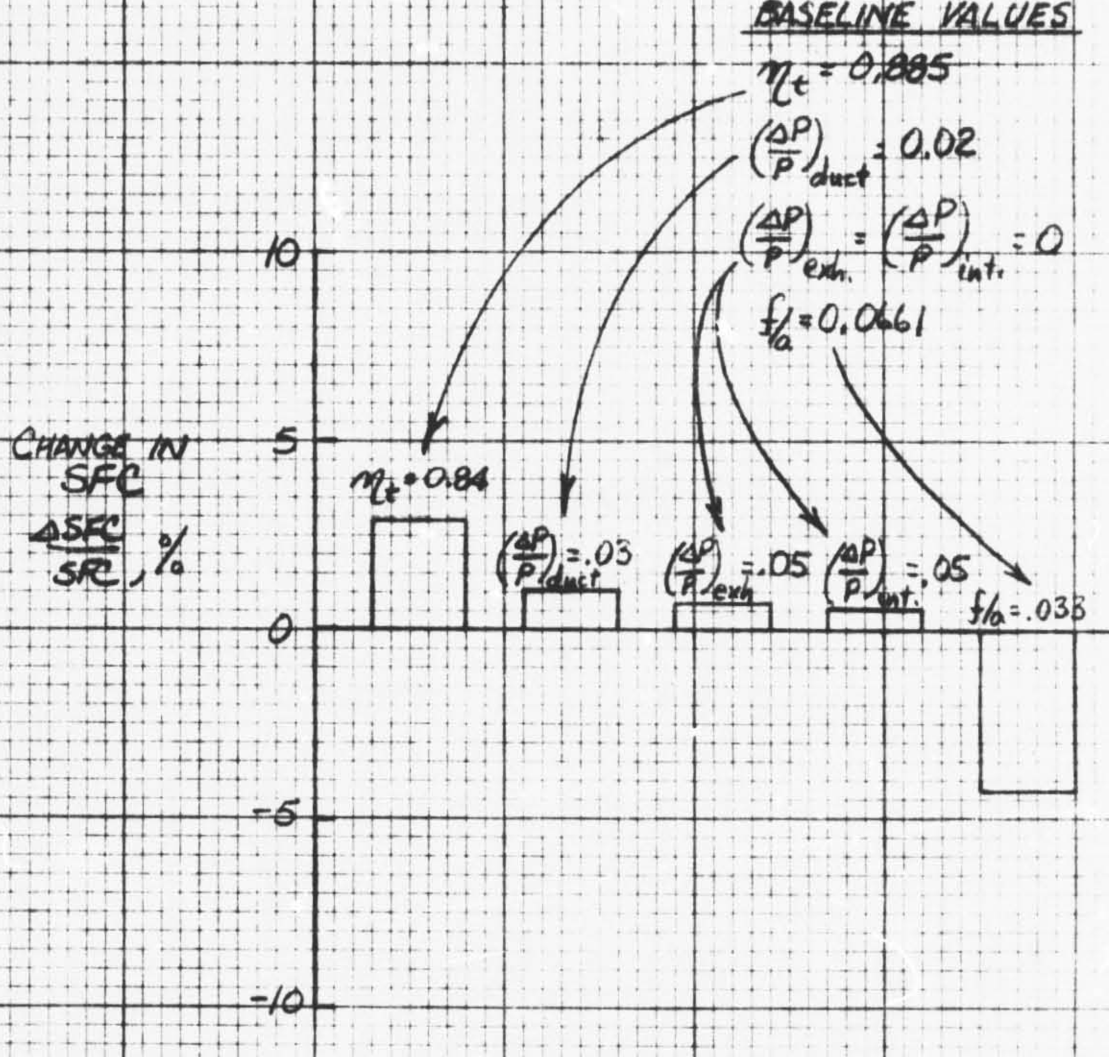

FIGURE 30. - EFFECT OF PERTURBATIONS IN TURBINE EFFICIENCY, MANIFOLD LOSSES, ETC., ON SFC.