General Considerations in the Design of Combustion Chambers for Aircraft and Industrial Gas Turbines

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THE BASIC FUNCTION of the combustion chamber in all gas turbine engines is to accept air from the compressor, or from the heat exchanger in a regenerative or recuperative industrial unit, add energy to it by the process of burning fuel, which is normally gaseous or liquid, and deliver the products at an elevated temperature to the turbine, ideally with no loss of pressure.

Although the burning of the fuel as such is seldom the limiting factor, the problem arises in designing for satisfactory combustion performance with long life equipment and with low loss in pressure in a size of combustor compatible with the overall engine.

Review of Requirements

TECHNICAL DESIGN REQUIREMENTS - The more important technical requirements of the combustion unit are:

1. Complete Combustion of Fuel - Inefficiency of combustion is directly reflected in the fuel consumption or thermal efficiency.
2. Maximum Space Utilization - The combustion process is generally required to be accomplished in the minimum volume possible. This is particularly true in aircraft gas turbines, where space utilization and weight are of paramount importance; therefore the demand is for high intensity combustion.
3. Minimum Loss of Total Pressure - Although a pressure loss is always necessary in order to promote the turbulence necessary for efficient high intensity combustion, this has to be minimized because of its injurious effect on cycle performance.
4. Controlled Exit Temperature Distribution - In order to avoid permanent damage to the moving turbine blades or nozzle guide vanes, or both, and to permit optimization in the turbine blade design, a controlled temperature distribution both radially and circumferentially is required at exit from the combustion chamber.
5. Acceptable Metal Temperatures - The flame tube metal temperatures have to be controlled to a level and distribution commensurate with the desired life of the chamber. Although this is essentially a mechanical requirement, it affects the technical design because it necessitates the allocation of a given quantity of the total engine air for cooling the flame tube.

Apart from the preceding five requirements, the chamber should have stable and smooth combustion, rapid and reliable ignition, and freedom from carbon deposits in the flame tube or smoke in the exhaust.

The combustion system has to be capable of fulfilling the above requirements in most cases at not only the full load or design point condition, but also over a wide range of conditions. Variations in load or compressor rotational

Abstract

This paper reviews those requirements that are common in the design of all gas turbines combustion equipment. Where necessary, a distinction is made between the demands of industrial and aircraft chambers. The problem of designing equipment for long life and low pressure loss, in a size compatible with the overall engine, is discussed in detail, and the application of combustor characteristics and design factors to the demands of new aircraft and industrial turbines are anticipated.

speed, altitude, and forward speed create variations in pressure, air inlet temperature, air and fuel mass flows, and air to fuel ratio.

Although both pressure and mass flow rate may vary considerably, they are interdependent to a large extent on aircraft gas turbine engines, with the result that the air velocity at entry to the chamber is relatively constant. This is particularly significant, since velocity is an important paramater in combustion performance.

In certain industrial gas turbines the combustion chamber must also be capable of burning a range of fuels from natural gas to the heavier residual fuel oils.

MECHANICAL DESIGN REQUIREMENTS - The combustion equipment of a gas turbine engine is subjected to extremely arduous conditions of operation arising from the combustion process, static and dynamic pressure loadings, engine vibrations, and acceleration loadings.

The combustion chamber design must therefore fulfill the following major requirements:

1. Reliability of the Structure - The materials of construction and the design structure must withstand, with adequate safety margins, the thermal, pressure, and vibratory loadings imposed in service.

2. Consistency of Operation - To ensure consistency of performance between chambers, the design must avoid assemblies that cannot be repetitively and accurately reproduced. Furthermore, the design should wherever possible exclude features that, owing to dimensional changes, affect the technical performance during the operating life of the unit.

3. Longevity - Metal temperatures and stress levels must be compatible with an economic life expectancy.

4. Minimum Weight - This is a critical factor for aircraft applications where weight savings bring economic benefit to the operator by increasing operational range or pay load.

5. Robustness - In the case of static industrial and marine engine applications, where weight is less important, the design should allow for the rougher handling likely to be encountered and possible exposure to the elements and salt water corrosion.

6. Low Production Cost - The design must avoid overelaboration, particularly because material costs are high and manufacturing standards are exacting.

7. Serviceability - The combustion equipment must be integrated with the engine design to allow servicing accessibility and handleability. Loose parts, split casings, and flame tube locations must be "foolproofed" to prevent operation with incorrect assemblies.

Technical Design

RANGE OF OPERATING CONDITIONS - As stated in the preceding section, the combustion chamber has to be capable of operating satisfactorily over a wide range of throughput conditions. In industrial application the range is dictated by the variation in output power required from the shaft; in aircraft application the range of conditions is further widened because of varying atmospheric conditions at different altitudes and the varying degree of compression due to aircraft forward speed.

The important variables affecting the combustion chamber are air pressure, air inlet temperature, and the air and fuel mass flow rates. Fig. 1 illustrates the range of these variables (in terms of their full load values) over the useful working range of a typical industrial gas turbine. It will be appreciated that the complete operating range demanded from the combustion chamber is wider than that indicated by Fig. 1 because of the necessity for satisfying starting and idling conditions, where the air and fuel flow rates may well be a half of those at 25% load. However, Fig. 1 does show the range of conditions over which efficient combustion is required.

Fig. 2 shows the data of Fig. 1 interpreted in terms of the parameters of direct concern in the design of combustion equipment. The throughput air velocity, Mach number, and chamber percentage pressure loss are sensibly constant over the full range of load conditions, provided the turbine nozzle area is nonvariable. The maximum combustion intensity is demanded at the full load or design point condition; satisfactory combustion also has to be achieved at the lower load conditions where the overall mixture strength is considerably leaner than at the design point.

Whereas in industrial application the air pressure and air inlet temperature are primarily dependent on the nominal

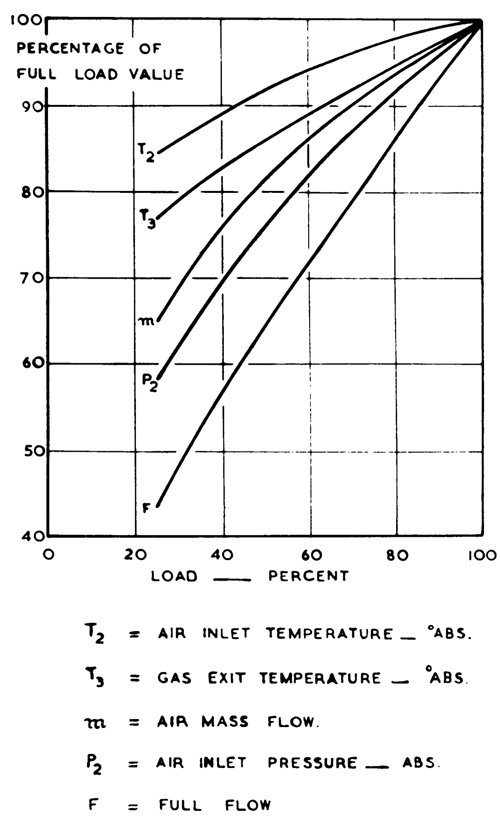


Fig. 1—Range of operating conditions of industrial combustion chambers

compression ratio, in the aircraft gas turbine engine the altitude and flight Mach number are further influencing factors.

Figs. 3 and 4 illustrate the dependence for both a low and a high compression ratio engine. It is immediately obvious that extremely high air pressures and temperatures are encountered in high flight Mach number aircraft operation at low altitudes. The high air pressure has to be taken into account in designing the strength of the outer casing. It also increases the flame emissivity and hence the problem of cooling the flame tube, which is further aggravated by the simultaneous high air-inlet temperature.

At the opposite end of the range (namely, flight at high altitudes), severe reductions in pressure are possible. The problem is then one of flame stability, which can be extremely difficult to achieve especially in modern engines that demand high throughput velocities in the combustion chamber.

In the case of aircraft engines a 25:1 fuel flow range may be required, owing to variations in power demand and altitude of operation. As a consequence, efficient combustion is often called for over a 2:1 range of air to fuel ratio, with stable combustion over an even wider range to permit operation for occasional limited periods at abnormally rich or weak mixtures.

THE COMBUSTION PROCESS - All practical combustion systems depend for their maintenance upon the interplay of their physical and chemical environments. In most gas turbine combustion chambers, the fuel is burned as it emerges as an atomized spray into the air stream. The combustion occurs near to the surface of the liquid drops as the locally vaporized fuel mixes with the adjacent air. Ignition is initially achieved by a high energy spark or electric arc and thereafter by heat transfer from the burned gases.

If the time for the physical diffusion and evaporative processes is small, then chemical kinetics will limit the reaction. Combustion consists of a large number of chemical reactions occurring in rapid succession, and hence a detailed kinetic study would be impossible. However, it is assumed that somewhere in the process, a single stage reaction is rate limiting in order to enable the rate of the reaction to be determined. For simplicity in hydrocarbon combustion, it is usual to assume a single unburnt product. If only weak mixtures are to be considered, then carbon monoxide is generally selected. However, if low combustion efficiencies prevail or rich mixtures are employed, then a closer representation of the unburnt products may be achieved by selecting the fuel itself as the only unburnt product of reaction.

The manner in which chemical kinetics can be used to perform such calculations is described in Ref. 1, from which it will be apparent that the activation energy and the orders of the reaction must be determined experimentally.

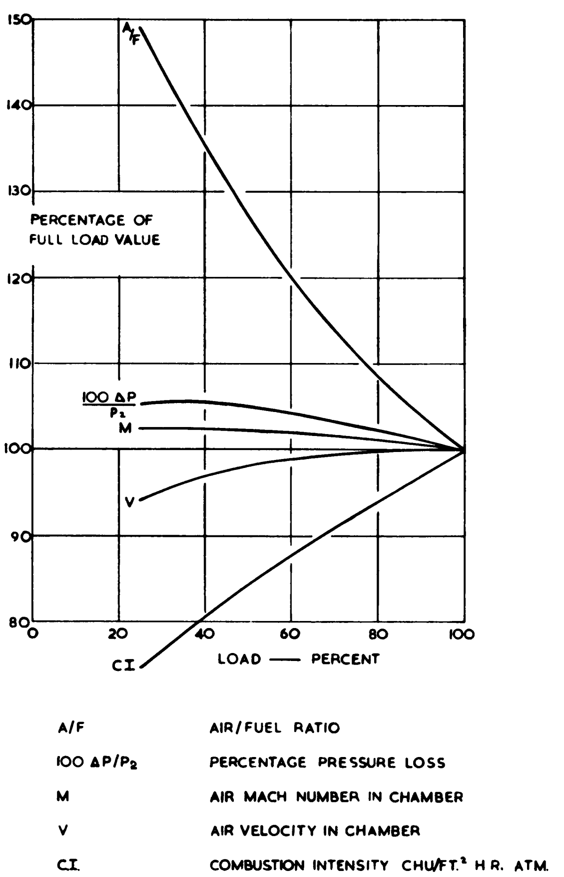


Fig. 2—Range of combustion chamber parameters for industrial combustion chambers

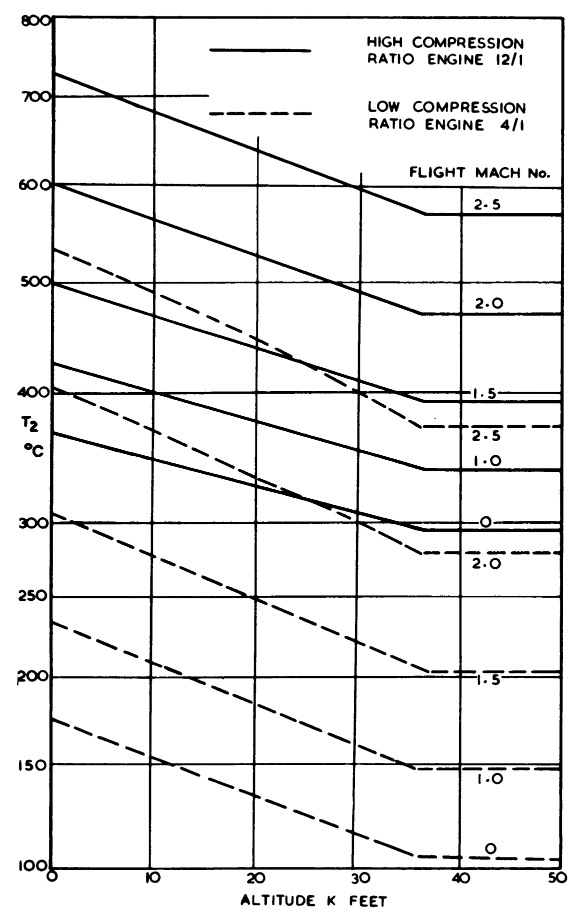


Fig. 3—Range of chamber inlet temperature

A suitable apparatus for accomplishing this is the spherical combustor illustrated in Fig. 5. This apparatus was first developed by Longwell and Weiss (2)* and was designed with the aim of reducing diffusion processes to a minimum and thereby producing a system entirely limited by chemical kinetics.

Experiments with Spherical Combustors - Longwell found that for isooctane, a combustion efficiency of some 80% existed at the point of maximum stability loading and that the limiting space heat release was about 170×10^6 chu/hr-ft^3-atm$^{1 \cdot 8}$ at inlet conditions of 400 K. This may be compared with 2×10^6 to 10×10^6 chu/hr-ft^3 at 1 atm given by typical gas turbine combustion chambers. In order to realize these high heat release rates, the experimental spherical system was designed to be as homogeneous as possible. This was achieved by utilizing a very high injection velocity and consequently a high pressure loss. For instance, at the peak loading, the injector pressure loss was some 75%, based on upstream conditions.

Fundamental work on spherical combustors at the Lucas Combustion Laboratories, Burnley, England, has been concerned with the exploration of the modes of injection and the effects of varying the turbulent energy (3). Flow pattern studies (4) using water with air bubbles as tracer indicated that the jets rapidly coalesced and gave rise to a recirculation pattern (Fig. 6). It was also shown that a failure to realize a strong recirculation pattern adversely affected the stability performance (Fig. 7). Later work (5) confirmed this and also showed that pressure loss had little, if any, effect upon performance for injectors having a loss between

*Numbers in parentheses designate References at end of paper.

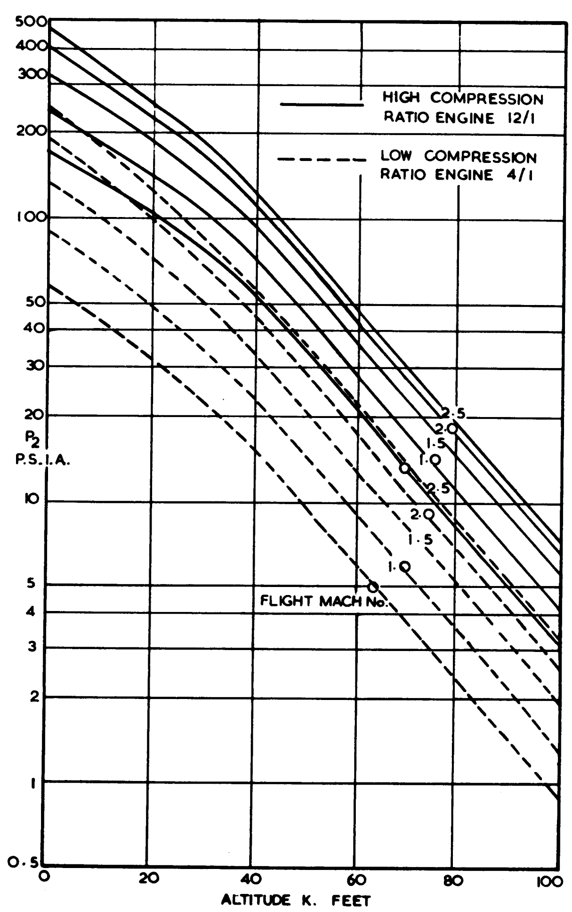


Fig. 4—Range of chamber pressure

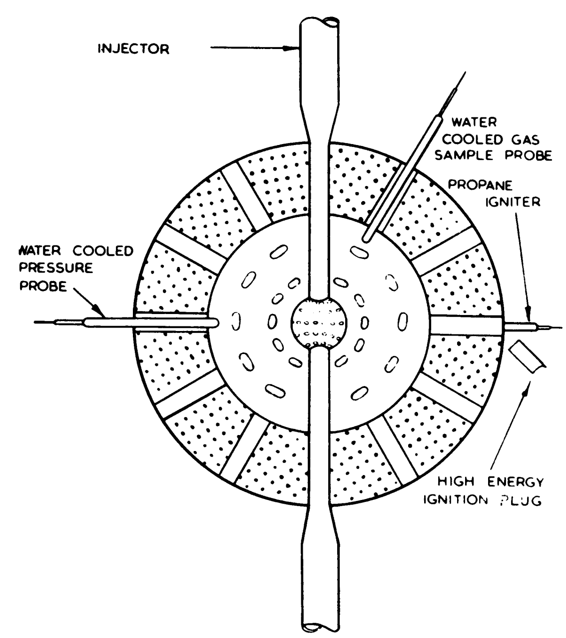


Fig. 5—Spherical combustor

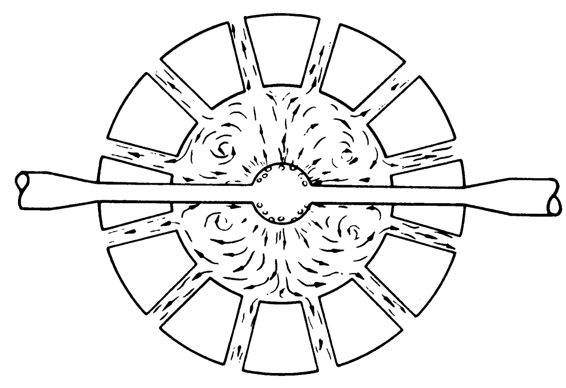


Fig. 6—Flow pattern in a spherical combustor

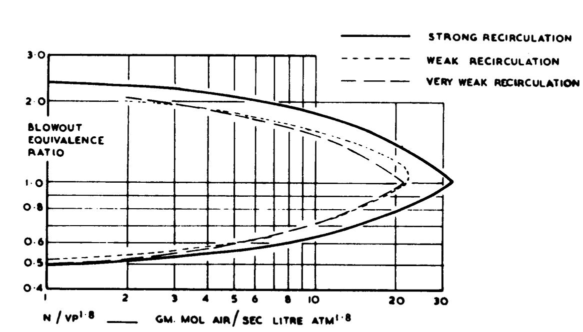


Fig. 7—Stability characteristics of spherical combustors

20% and 80%. More recently still, this has been extended to injectors having pressure losses of less than 5%.

Since the flow pattern and general combustion processes are similar for both practical systems and spherical combustors, it is not surprising that the data yielded by the latter can be applied to the former.

Correlation of Practical Chambers with Theory - The combustion efficiency (η) of practical chambers may be correlated (16) as follows:

$$\eta = \text{Function} \frac{adp^{1.75} e^{T/b}}{M}$$

where:

a = Maximum cross-sectional area of casing
d = Casing diameter or width
p = Reaction pressure
T = Inlet temperature
M = Air mass flow
b = Function of air to fuel ratio.

The correlation is satisfactory for a single air to fuel ratio, but so far it has not been possible to correlate varying air to fuel ratios. A typical set of results is indicated in Fig. 8.

If the stability data for the maximum kinetic load of practical chambers are calculated on the same basis as those for a spherical combustor (in the practical case, the reaction volume is approximated to the recirculation zone), then many conventional chambers have about one-quarter the loading of the spherical combustor. This factor may be roughly related to the geometry of the chamber and may be utilized in predicting limiting operating pressures at various chamber inlet conditions.

ALTERNATIVE CONFIGURATIONS - The combustion equipment for gas turbine engines can be either straight-through or partially or fully reverse flow. In addition, the straight-through equipment can be divided into the following three main categories:

1. Pipe chamber, in which the flame and combustion products are contained within a number of cylindrical flame tubes, each having an individual air casing.
2. Tubo annular, in which the flame and combustion products are contained within a number of cylindrical flame tubes positioned in the annular space formed by the two surrounding common air casings (outer and inner).
3. Fully annular, in which the flame and combustion products are contained within the annular space formed by two concentric flame tubes, which are surrounded by concentric air casings.

The three types are illustrated diagrammatically in Fig. 9 for purposes of comparison. The diagram shows that in a typical pipe chamber arrangement, only 67% of the total cross section is available for combustion chamber casings. Since in many engines the overall diameter has to be mini-

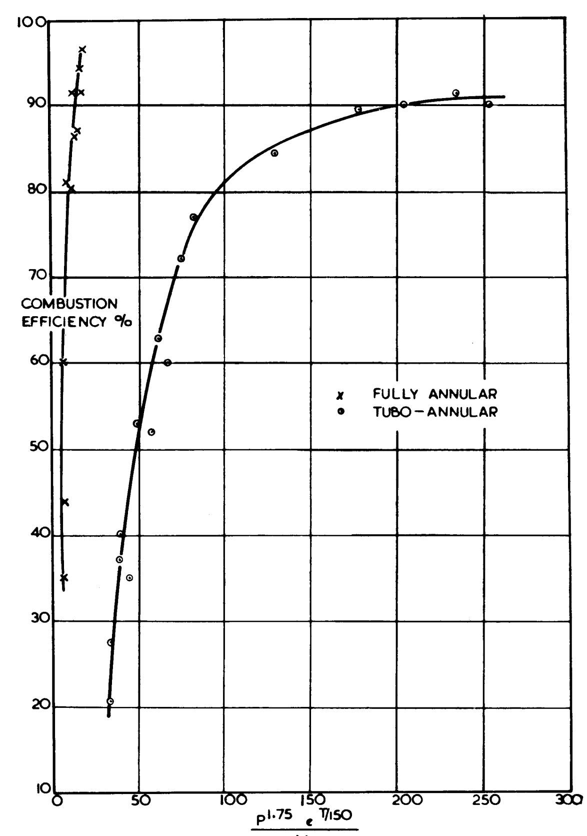


Fig. 8—Combustion efficiency correlation

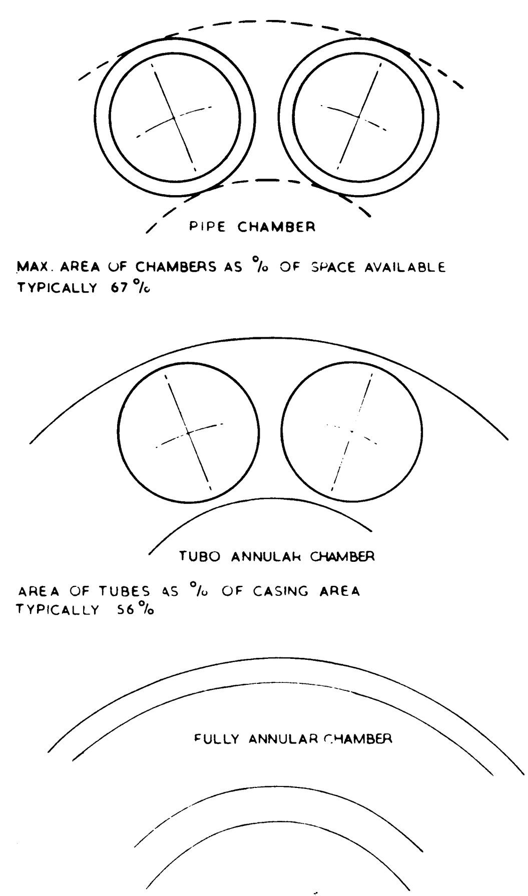


Fig. 9—Configurations of combustion chamber

mized to reduce drag at high flight speeds, considerable attention has been paid to tubo annular and fully annular combustion systems, both of which offer a greater efficiency of space utilization. The maximum attainable flame area on tubo annular chambers is limited to approximately 63% of the total casing cross-sectional area.

In the case of the fully annular chamber, there is complete freedom of choice of flame tube to casing cross-sectional area and flexibility in the selection of the areas of the inner and outer annuli.

A serious disadvantage with the tubo annular chamber is the reduced control of the air flow path in the annulus space surrounding the separate flame tubes, particularly when the axis of the flame tubes if offset from the mid-line of the compressor discharge.

AIR DELIVERY FROM COMPRESSOR - A feature of the engine performance which has become increasingly significant in the design and development of combustion chambers during the past ten years, is the manner in which the air is presented to the combustion chamber.

Typical Conditions - Most of the present-day aircraft gas turbine engines are straight-through units and employ axial flow compressors. It is usual for a radial variation in both velocity and pressure to exist at the discharge from the compressor, for a variety of reasons; in some cases there may also be residual swirl. This nonuniformity, of course, varies from engine to engine; in addition, for any particular engine, it may also vary with compressor rotational speed.

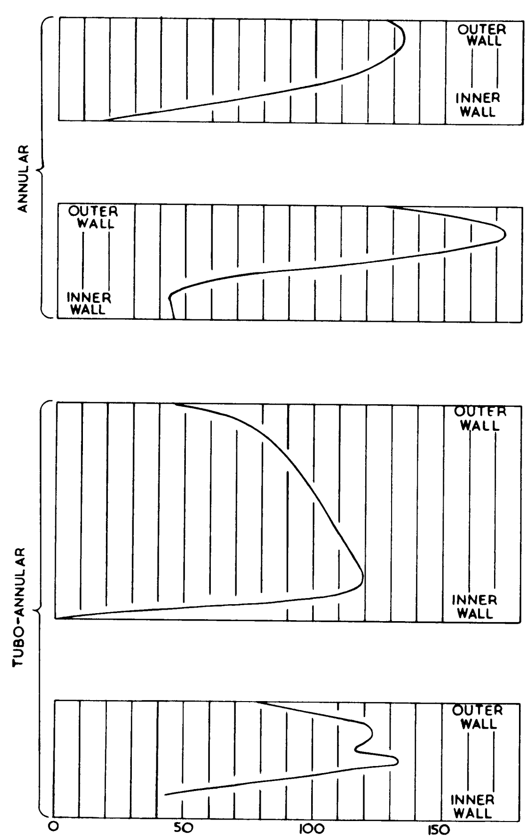


Fig. 10—Typical compressor discharge velocity profiles

Fig. 10 illustrates some of the inlet velocity profiles at full load SLS conditions experienced on aircraft engines for which combustion development work has been carried out at the Lucas Combustion Laboratories.

The air distribution at entry to the combustion unit in an industrial gas turbine engine is equally important, and the consequences of maldistribution inlet are similar to those in the aircraft application.

However, the cause of the nonuniform conditions is often quite different. In the industrial engine, it is frequently necessary for the combustion chamber to be of the "reverse flow" type or to have a side entry where the direction of the inlet air is normal to the flow direction through the chamber. This arises because of the use of heat exchange equipment to increase the overall cycle efficiency or because of the particular space limitations of the application. The nonuniform conditions at entry to the chamber are fore often created by pressure gradients induced by bends in the interconnecting duct work, by flow through heat exchangers, or by residual swirl from the compressor.

Effect on Combustion Chamber Performance - In an annular chamber in which air is admitted to the combustion zone from two discrete annuli, the air distribution and flow pattern within the chamber are very dependent upon the pressure levels in the two annuli. Consequently, in the conventional design of annular chamber in which the division of the compressor discharge air is achieved by annular rings, the performance of the chamber is seriously affected by radial variations in the compressor discharge pressure. Inferior flame stabilization, undesirable and variable exhaust gas temperature distribution, and radial temperature gradient at the turbine entry can result from nonuniform entry conditions.

A theoretical estimate of the effect on the air distribution of one of the inlet velocity profiles shown in Fig. 10 for an annular chamber is given in Table 1.

At a first glance, the tubo annular system would appear to be less sensitive to the compressor discharge conditions than would the fully annular system, since the air is not divided into two separate streams at different pressure levels. However, a nonuniform total pressure distribution in the annulus may be created by the compressor discharge velocity and pressure distribution, which will be aggravated by the severe change in flow path cross section.

The following example illustrates the effect of such an annulus total pressure distribution. The mean annulus conditions have been taken to be: total pressure, 100 psia; air density, 0.28 pcf; annulus velocity, 200 fps; and annulus dynamic pressure, 1.21 psi.

The velocity of injection, mass flow per unit hole area, and injection momentum of the air jets for the mean annulus conditions are compared in Table 2, with those resulting at local annulus points where the total pressure is ±1% removed from the mean.

Since the inlet velocity profile may vary with engine speed, it is impossible to overcome the resultant effects by hole trimming. In any case, circumferential variation of hole size would affect only the air flow distribution and not the velocity of injection.

Profile Correcting Devices - As will be appreciated from the preceding section, it is desirable and often necessary to employ a device that produces more equal pressure in the annulus or annuli at all engine conditions.

The Lucas patented EVS (Equal Velocity Sampling system) has been designed and proved for annular combustion systems, and is shown in Fig. 11. The compressor discharge is divided into a number of sector passages formed by radial walls, which are the full height of the compressor discharge annulus. Alternate passages feed the inner and outer annuli, respectively, and by suitable shaping of the walls, the pressure loss through the passages is minimized. The design

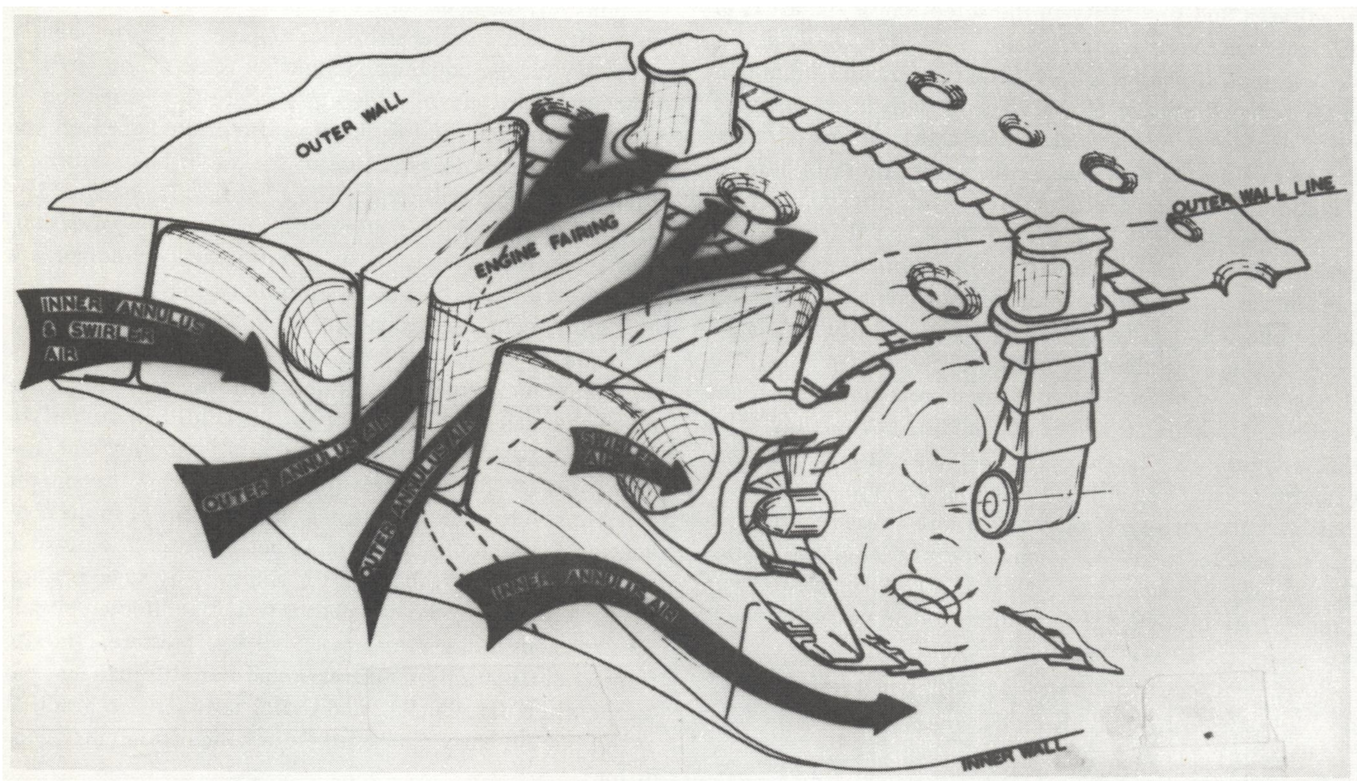


Fig. 11—Profile correcting device (EVS)

Table 1 - Effect on air Distribution of Inlet Velocity Profile

Compressor Discharge Profile	Loss in Total Pressure Across Flame Tube Wall, psi		Air Injection Velocity fps		Air Division Outer/Inner Flame Tube		
	Outer	Inner	Outer	Inner	Primary	Intermediate	Dilution
Uniform	6.8	6.4	479	464	1.0	1.25	1.3
Nonuniform	12.2	2.0	625	269	2.6	3.2	3.35

Table 2 - Comparison of Annulus Conditions

Total Pressure, psia	Annulus Velocity, fps	Velocity of Injection, V fps	Discharge Coefficient of Hole	Air Mass Flow per Unit Hole Area, m-lb/sec	Injection Momentum, $mV \times 10^{-2}$
101	270	440	0.81	99.8	439
100	200	400	0.875	98.0	392
99	83	356	0.9	89.7	319

principle behind the EVS is that both inner and outer annuli of the flame tube should be fed by air sampled from the total height of the compressor discharge annulus.

The application of the same design principle to the tubo annular combustion system is not easy, and it becomes necessary to consider alternative means of achieving the same objective. Such an alternative is the Lucas patented ADU (Air Distribution Unit, Fig. 12) whose purpose is to redistribute the air in the diffuser prior to its division into the air passages of the combustion chamber.

Much can be done to alleviate the problems of nonuniformity in the industrial engine by careful aerodynamic design of bends; that is, by fitting of cascade vanes or splitters and by the fitting of antiswirl vanes at the engine manufacturer's plant.

The difficulty of the side entry and the necessary change of section from circular or rectangular to annular is usually overcome by the fitting of a volute round the combustion chamber air casing. To allow the combustion air to enter the flame tube annulus, the air casing is perforated with slots or holes, which can be graded to produce a uniform distribution of air. It is desirable that the pressure loss across the distributor be sufficient to smooth out any prevailing pressure variations, but this allowance should not be so large as to damage the cycle efficiency or rob the combustion zone of useful energy.

Other remedies can be adopted for special engine configurations, but in certain cases it is preferable to provide a chamber that is designed to be less sensitive to variations in entry conditions.

PRESSURE LOSS - The injurious effects of the combustion chamber pressure loss upon the cycle performance are generally well known, and unless it is reduced to a minimum the overall efficiency may suffer seriously.

Effect on Cycle Performanee - Figs. 13 and 14 illustrate the effect of the chamber pressure loss on the thermal efficiency and specific output of a typical, simple cycle that generates shaft power only. It should be realized that an increase in the pressure loss not only adversely affects the cycle efficiency, but also necessitates a larger plant to fulfill the same required duty.

The effect of pressure loss on the specific consumption and specific thrust for a simple jet application is shown in Figs. 15 and 16, respectively. Again, the damaging effects are immediately obvious, and since the thrust of the engine is reduced by increasing pressure loss, the maximum attainable flight speed of a given application with fixed engine turbine inlet temperature will also be reduced.

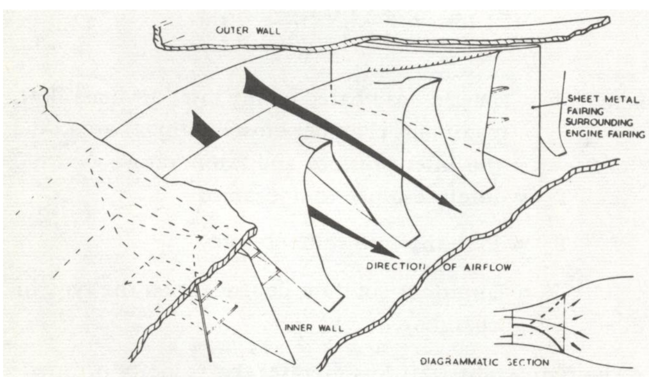


Fig. 12—Profile correcting device (ADU)

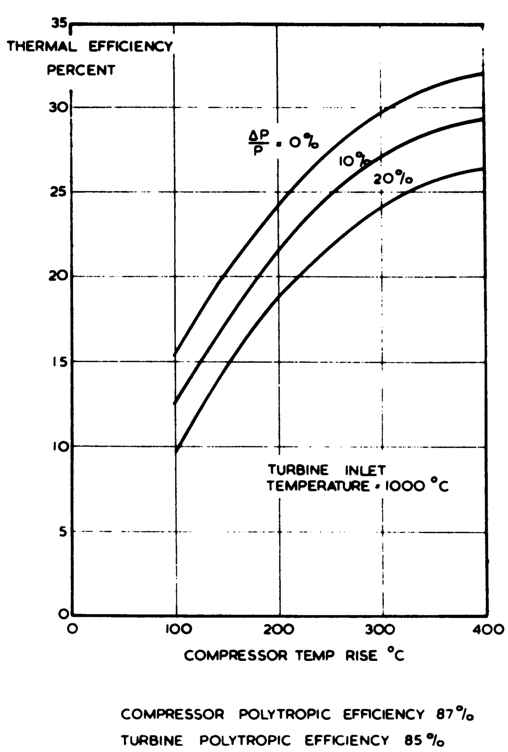


Fig. 13—Effect of chamber pressure loss on thermal efficiency

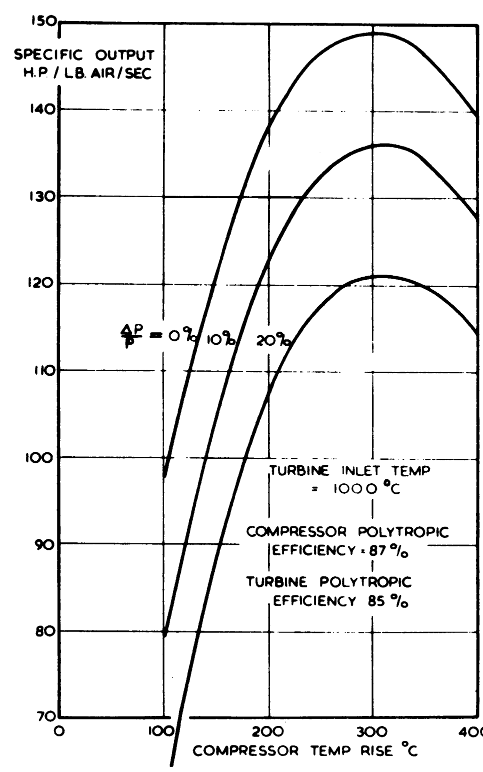


Fig. 14—Effect of chamber pressure loss on specific output

As a general rule, 1% loss in total pressure in the combustion chamber causes a rise in specific fuel consumption of approximately 1/2% on turbojet engines and 1% on turboprop engines. It is also interesting that a 1% loss in total pressure has the same effect on the thermal efficiency and specific output as a reduction of approximately 1/2% in either the compressor or turbine efficiency.

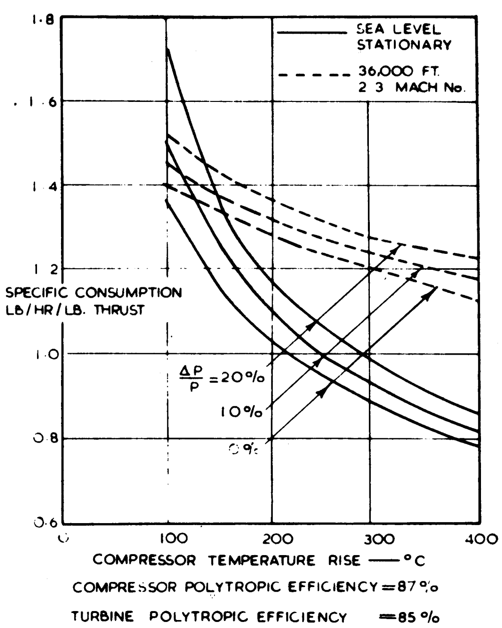


Fig. 15—Effect of chamber pressure loss on specific consumption

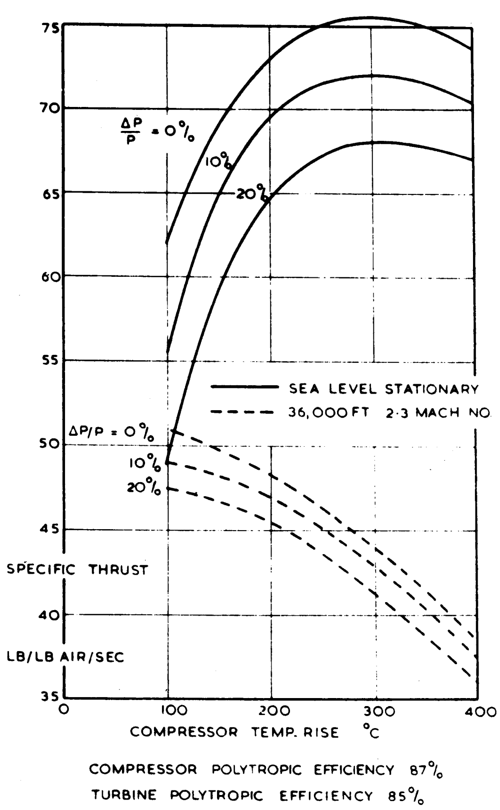


Fig. 16—Effect of chamber pressure loss on specific thrust

Component Losses - The pressure loss in a combustion chamber can be divided into three main types: the parasitic, the flame tube wall loss, and the hot loss; these are added in series to give the overall loss.

The parasitic loss of a chamber depends upon the compressor discharge and annulus velocities and the manner in which this change of velocity is accomplished. It is therefore largely aerodynamic in nature, and its reduction depends upon the provision of smooth ducts, gentle diffusion, generous radii of bends, and the fairing-off of any obstructions.

The flame tube wall loss is dependent to some extent on the density change due to combustion or heat addition loss. However, it is convenient in the design to calculate the flame tube wall loss based on "cold" conditions, and allow for the heat addition loss in the overall pressure loss assessment by adding, in series, a term known as the hot loss, which is given by

$$\text{Hot loss} = K \cdot h \cdot \left(\frac{T_3}{T_2} - 1\right)$$

where: h = Kinetic head based on the total air mass flow, maximum chamber cross-sectional area, and the Inlet pressure and temperature

T_2 = Inlet absolute temperature

T_3 = Exit absolute temperature

K = Empirical constant dependent on the type of chamber.

The flame tube wall loss dictates the velocity of injection of the primary air into the flame tube, and therefore determines the system of recirculating velocities in the primary zone flow pattern and the amount of injected air mass flow recirculated. This recirculated air plays an important part in determining the stability characteristics of the chamber and, to some extent, the combustion efficiency.

The achievable combustion intensity is dependent on the degree of turbulence within the flame tube, which promotes a high rate of formation of fresh interfaces between air and fuel. Since the degree of turbulence is dicated by the energy of the air entering the primary zone, a relationship can be expected to exist between combustion intensity and combustion pressure loss. Ref. 7 gives

$$I = \left(786 \cdot 10^6 \, \epsilon \eta r \eta v \cdot (T_2)^{1/2} / T_H\right) \cdot \left(\frac{\Delta P}{P}\right)^{1/2}$$

where: I = Combustion intensity

P = Inlet air pressure

T_2 = Absolute temperature of inlet air

T_H = Absolute temperature of vortex gas

ΔP = Loss in pressure across flame tube wall in the primary zone

ϵ = Excess combustion factor (= total fuel flow/ fuel flow burnt in vortex)

η_r = Vortex refreshment efficiency (= fresh air mass flow into vortex/total air mass flow in vortex)

η_v = Vortex velocity efficiency (= flow velocity in vortex/primary air injection velocity).

The preceding formula shows that the combustion intensity is proportional to the square root of the fractional pressure sure loss. The proportionality factor is, in practice, dependent on the geometry of the combustion chamber (that is, pipe, tubo annular, or fully annular), the method of achieving the primary recirculatory flow pattern, the application (aero or industrial), and type of fuel burnt. This is utilized at the design stage to establish a relationship between the required size of chamber and the necessary pressure loss.

The flame tube wall loss, in addition to being a source of turbulent energy, is also required to drive the air through the flame tube holes. The ratio of static pressure drop across the flame tube wall to dynamic pressure in the annulus affects the coefficient of discharge of the holes and the angle of penetration of the jets of air.

Although it is impossible to lay down hard and fast rules regarding the overall pressure loss of the chamber (since this depends on such factors as the application, type of fuel, symmetry of system, compressor discharge velocity profile, to name only a few), Table 3 gives some guide to the probable range.

AIR FLOW - The total air flow can be considered to be divided into three parts-combustion air, flame tube cooling air and dilution air.

Required Distribution - The combustion air is that air injected into the primary zone to promote and permit efficient combustion. In all combustion processes, it is usual to provide excess air, and in the normal gas turbine combustion chamber, the primary zone air to fuel ratio is arranged to be 18-20; the stoichiometric value would be 15 (that is, 20-33% excess air).

The generation of a vigorous and stable recirculatory zone with a swirler-flare type of system depends upon careful balancing of the swirler and primary hole air flows, or more correctly, their momentum. Although primary holes alone generate a recirculation, the swirler is required to centralize and stablize the upstream flow. Excessive swirler flow, however, leads to a breakdown in the desired flow pattern by creating a helical vortex with a core along the axis of the flame tube.

The optimum ratio between the swirler and primary hole air mass flow is found to be dependent upon their velocities of injection, the diameter of the flame tube, and the mean diameter of the swirler.

The flame tube cooling air is usually admitted through annular gaps or by injection onto an internal ring through small holes in the flame tube wall (splash cooling), thereby forming a film of cool air on the internal surface of the flame tube. The quantity of air admitted in this manner depends on the type of chamber, operating conditions, and permissible operating metal temperatures. High compression ratio aircraft chambers or heat exchanger industrial engines burning heavier fuels obviously require more film cooling air than do chambers burning kerosene with a low inlet temperature. However, the cooling air usually lies between 15% and 30% of the total air, and is normally admitted at four or five points along the length of the chamber.

It is desirable to minimize the quantity of cooling air in order to allow the maximum dilution air for mixing and the achievement of satisfactory turbine entry conditions, while at the same time maintaining acceptable metal temperatures. In this respect, it is interesting to note that the surface area of an annular chamber is in a typical case about 70% of that of a tubo annular chamber of equal length and contained within the same air casings.

Therefore, for systems of similar loading, the annular chamber would in general require less cooling air than would the tubo annular system, owing to reduced surface area.

In the case of the fully annular chamber, besides being necessary to divide the air into combustion air, cooling air, and dilution air, it is necessary to divide it into outer and inner flame tube air. Although this division depends upon the ratio of casing diameters, experience has indicated that the optimum outer to inner ratio is usually about 1.2.

Coefficients of Discharge - Since it is of major importance to control the air distribution and pressure loss across a combustion system to meet a specified performance figure, it is essential to relate the coefficients of discharge of the various air admission ports with the required pressure drop and the local geometric and air flow conditions.

To relate the various parameters controlling the flow through a hole in the wall of a flame tube, studies have been made on a number of single holes of different diameters, associated with a rectangular duct to simulate the annulus flow, as shown in Fig. 17.

Although plain holes were used in early combustion chambers, the necessity to position the holes just downstream of skin cooling flows resulted in significant reductions in angles of penetration. This led to the introduction of the plunged hole, which is simply shaped as a nozzle, the protrusion of

Table 3 - Range of Chamber Loss

Type of chamber	Industrial	Aircraft
Range of reference Mach Number based on full cross-sectional area	0.03-0.06	0.04-0.10
Range of overall pressure loss, %	3-6	4-10

which into the flame tube protects the jet from the direct impingement of the skin cooling flow. An additional advantage of plunging the holes is also shown in Fig. 17 for a typical case in which the resulting higher coefficients of discharge are compared with those obtained from the corresponding plain holes.

In the case of plunged holes, the range of variables influencing the discharge characteristics is quite extensive, and such geometric variables as radius of plunging to hole diameter, height of duct, circumferential pitch of holes, proportion of air bleed through hole, dynamic pressure upstream of the hole, and static pressure drop across the hole have to be related with respect to the subsequent discharge characteristics of a hole.

Jet Penetration and Mixing - The degree of mixing of the hot and cold gas streams in a flame tube depends mainly upon the temperature distribution of the hot gases upstream of the dilution section, the pressure drop across the dilution holes, and the relative momentum of the cold and hot gas streams. Where a severe temperature gradient of hot gases has to be pierced in order to effect a high degree of turbulent mixing, resort has to be made to the use of a small number of large holes. An example of this is shown in Fig. 18, in which it can be seen that the resulting penetration from the four holes is sufficient to present a barrier to the hot gas stream to such an extent that the subsequent mixing is completed in a very short space. In fact the hot gas stream is deflected outward to circumvent the penetrating jets of cold air. In the case of the system with eight holes, the resulting penetration is ineffective and merely tends to produce a hot core and thus concentrate a peak temperature to the center of the duct, with delayed diffusion mixing of a low order. Thus, in gas turbine combustion chamber practice, it has

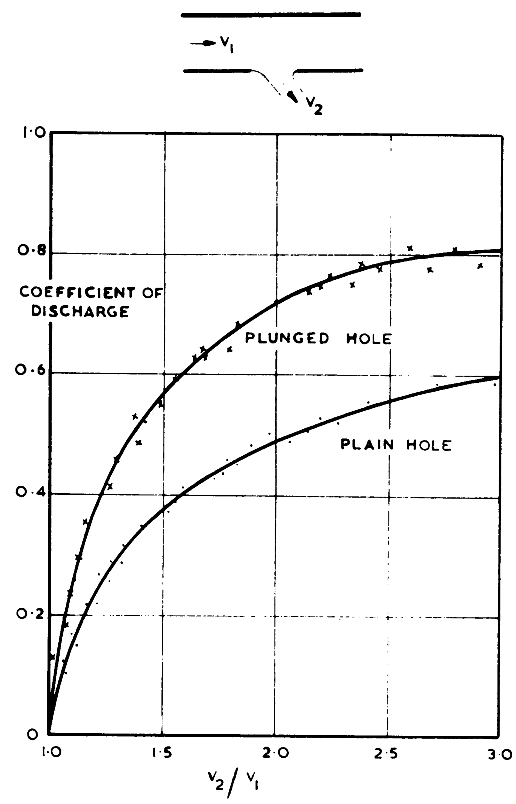


Fig. 17—Coefficient of discharge of plain and plunged holes

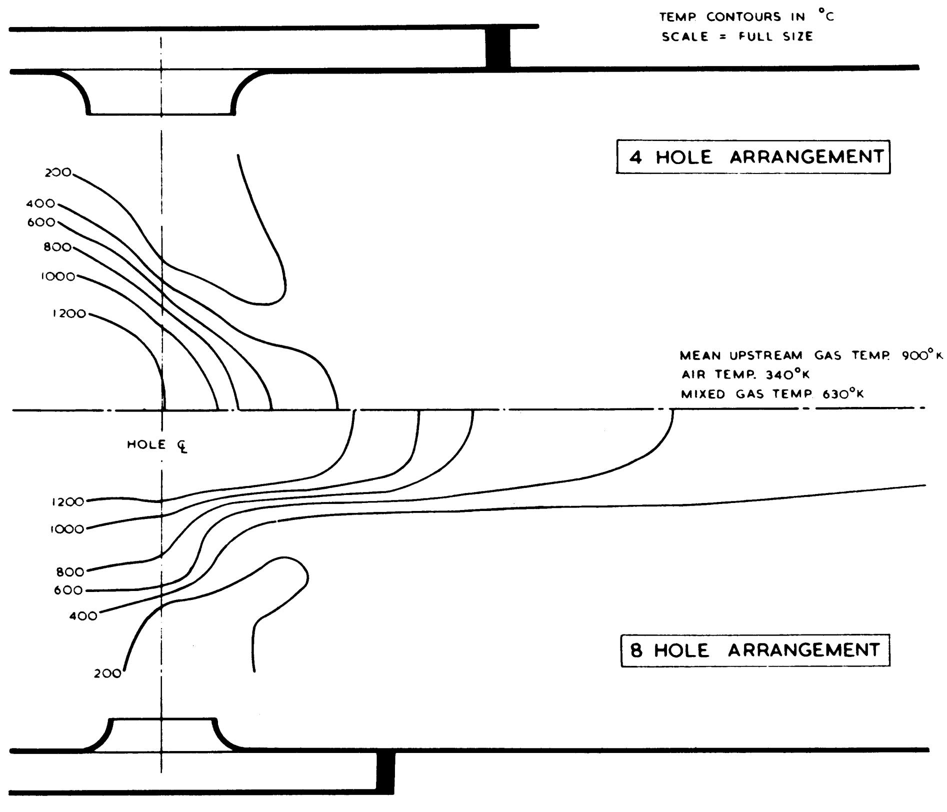


Fig. 18—Temperature contour diagram in mixing zone for mass ratio 1:1 with nonuniform upstream temperature profile

been generally found more effective, in the first place, to ensure adequate mixing by a system of four jets in preference to the use of six or eight jets.

Overall Flow Pattern - In the early development of gas turbine combustion chambers, very little was known about the air flow pattern. However, the need to create a high level of turbulence for improving combustion performance and for controlling the air flow, in order to effectively stabilize the flame within the combustion zone, soon led to the development of techniques for determining the air flow pattern.

Early attempts to investigate the internal flow pattern were made by observing the effect of the air flow on wool tuft probes sited inside the flame tube. By this method a general picture of the flow pattern was obtained, and to some extent confirmed, by velocity traverses. It was not until the development of the hydraulic analogy technique that the detailed flow pattern was fully appreciated.

In this technique, water is used to simulate air flow at approximately similar Reynolds number conditions in transparent perspex models of identical geometry to that of the actual combustion unit. The water is forced through the model by suitable means and a stream of fine air bubbles, injected into the water flow, provides a suitable tracer. The flow is then examined by a beam of light passing through a narrow slit which is adjustable relative to the chamber.

By means of this technique a comprehensive picture of the flow pattern inside the combustion chamber is obtained. A typical example of the pattern in a conventional type of pipe chamber is illustrated in Fig. 19.

The accepted practice in present-day development of new designs of combustion chamber is to eliminate flow pattern anomalies on a suitable perspex model before commencement of the more costly experiments on the chamber under combustion conditions.

Admittedly, the hydraulic analogy has certain limitations. The fact that it employs an incompressible fluid instead of a compressible one is not serious, since for the pressure differences prevailing in a typical chamber, the air can be regarded as behaving in a manner similar to that of an incompressible fluid. The hydraulic analogy falls short in that there is no method of introducing the equivalent of combustion and the consequent rise in temperature and increase in volume. Nevertheless, its advent has been of the greatest possible value and has enabled a much clearer picture to be obtained of the combustion conditions than was previously possible.

FLAME TUBE COOLING - One of the most important requirements of any present day combustion chamber, for other than expendable projects, is that it should operate with metal temperatures which will give extended life. Both excessive metal temperatures which reduce the physical strength of the chamber, and the temperature gradients or hot spots which induce stresses in the material are detrimental in obtaining a long life unit.

Heat Transfer Processes - In order to design and develop combustion chambers with acceptable metal temperatures, it is necessary to understand the basic heat transfer processes involved and their dependence on the operating conditions.

For the purpose of analysis the combustion chamber may be regarded as two concentric containers, with hot gas flow through the inner container or flame tube, and air flow through the annular space formed by the flame tube and surrounding casing. The flame tube receives heat from the hot gases inside it by convection and radiation, and loses heat by radiation to the outer casing and by convention to the surrounding annulus air. Under equilibrium conditions, the heat flow to the flame tube and away from it are equal, and byignoring conduction along the flame tube wall, a heat balance equation can be written.

The rate of heat transfer from the flame to the flame tube wall is dependent on the mean conditions of pressure, temperature and composition of the flame or hot gases, the geometry and luminosity of the flame, and the flame tube material and its surface condition and temperature.

Significance of Chamber Pressure, Air Inlet Temperature

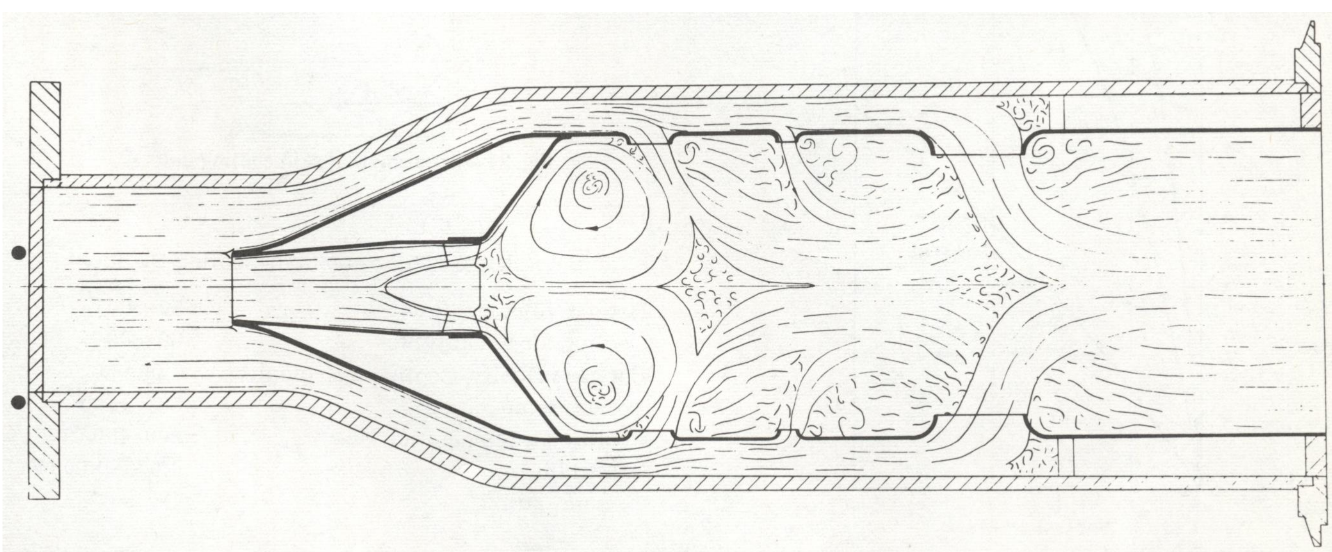


Fig. 19—Typical flow pattern in pipe chamber

and Type of Fuel - The primary effect of the chamber pressure is on the flame emissivity and hence on the internal radiation. Fig. 20 shows the variation of flame emissivity with pressure for different fuels in typical primary zone conditions. The flame emissivity increases with pressure according to an exponential law. Therefore an increase in pressure at high pressures has a smaller effect on the internal radiation than a similar increase at low pressures.

The air inlet temperature affects both the heating and cooling of the flame tube. An increase in air inlet temperature increases the flame temperature for a constant air to fuel ratio, and therefore the internal radiation is increased. In addition, the cooling of the flame tube is worsened, since the "sink" temperature has been increased.

For a given gas turbine engine, any increase in chamber pressure will usually be associated with an increase in both air inlet temperature and chamber air mass flow. Although the increase in air mass flow assists the convection cooling for the flame tube, this is outweighed by the pressure and temperature effects and an increase in flame tube temperature results.

In the military aero gas turbine engine, the highest combustion chamber metal temperatures are usually encountered at the greatest forward speed condition at sea level - a condition at which the pressure load stresses are also greatest.

The type of fuel burned and the presence of free carbon particles determine the degree of luminosity of the flame. One method of accounting for the luminous radiation from flames is by including an empirical luminosity factor in the well-known exponential expression for flame emissivity.

In the case of combustion of heavy fuels, such as residual oils or pulverized solid fuel, the presence of carbon particles at high temperature is highly significant, and the luminous radiation predominates, whereas the nonluminous radiation is much less important.

Film Cooling - In order to extend the operating life of combustion chambers, it is necessary to protect the flame tube walls against the scouring effect of the combustion gases. This is generally achieved by the injection of a film of cooling air, which acts as a buffer layer over the internal surface of the flame tube.

Since there is no rigid boundary between the cooling air and hot gases, mixing of the two streams occurs, and the cooling air stream gradually loses its identity. Thus the wall temperature increases with distance downstream, and it is necessary to introduce an additional film of air at some convenient point before the wall temperature becomes excessive.

Two types of practical skin cooling device in common use are the internal ring or splash and the corrugated spacer. For splash devices, cooling air is bled from the annulus through a ring of holes in the flame tube wall and directed along the inner surface by a "skirt," which is attached to the inside of the flame tube. In total head devices, a space is formed by overlapping two sections of the flame tube and introducing a corrugated spacer between them.

Tests on various experimental systems (a typical one is illustrated in Fig. 21) have been carried out over the range of conditions given in Table 4.

The results for an insulated duct when the cooling air was injected through an unobstructed gap have been correlated (Fig. 22) in the form of cooling efficiency, η, versus a function X.

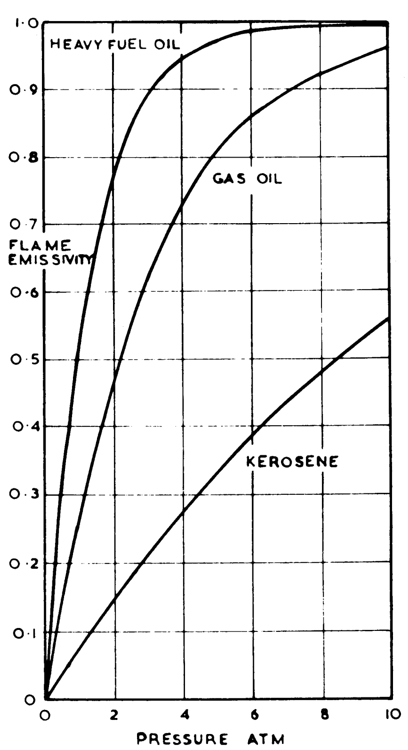


Fig. 20—Flame emissivity for typical primary zones

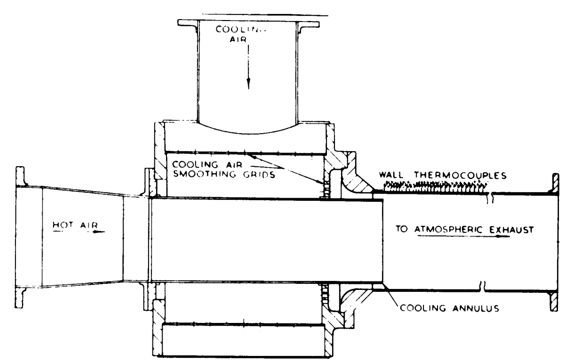


Fig. 21—Experimental skin cooling unit

Table 4 - Range of Tests on Skin Cooling Devices

Hot gas velocity, fps	50-300
Cooling air velocity, fps	50-300
Hot gas velocity/Cooling air velocity	0.05-3.0
Hot gas temperature, K	500-1100
Cooling air temperature, K	300-450
Gap width, in.	0.075-0.200
Pressure, atm	1-7

where: $$\eta = \frac{T_g - T_w}{T_g - T_a}$$

X = Function of the ratios of the Reynolds, Prandlt, and Schmidt numbers of the hot gas and cooling air

T_g = Temperature of gas

T_a = Temperature of air

T_w = Temperature of wall

Results by other workers (8 and 9) using various forms of fundamental apparatus, have been found to agree fairly well with the type of correlation employed above.

A comparison between calculated and observed metal temperatures for a typical flame tube, making use of the preceding correlation, is given in Fig. 23. It will be seen that the agreement is generally good.

INTRODUCTION OF THE FUEL - The fuel can be introduced into the combustion chamber either premixed with air or in liquid form for vaporization within the chamber, or thirdly, as is most usual, by means of an atomizer. In the latter case, the atomization is usually by means of a pressure jet, though the rotating cup and the air blast atomizer are alternatives. In by far the majority of cases, a pressure jet atomizer is used.

It can be shown that, provided the viscous losses in the swirl chamber and orifice are negligible, a swirl atomizer will have a fixed coefficient of discharge. Thus the configuration of the spray will remain independent of the pressure. An atomizer can therefore be described in terms of its spray cone angle and its flow number, which is defined as a ratio $F/\sqrt{P}$, where F is the flow in gph and P is the effective atomizing pressure in psi.

The basic characteristics of Simplex, Duplex, and Spill atomizers have been adequately described elsewhere (10).

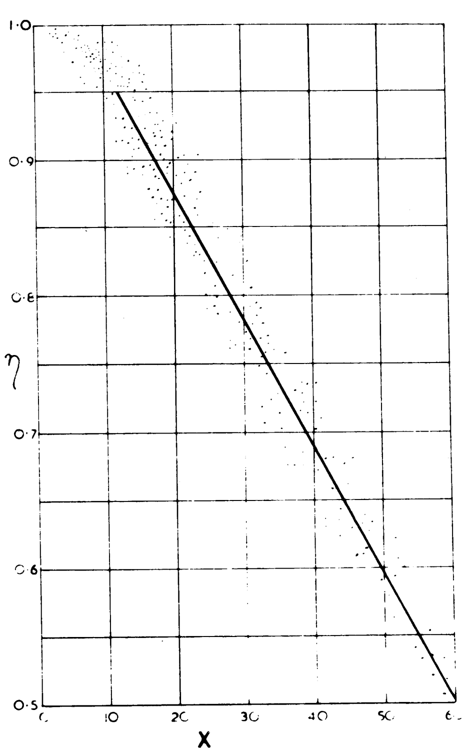
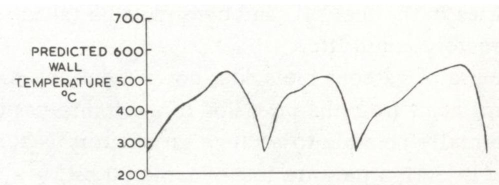


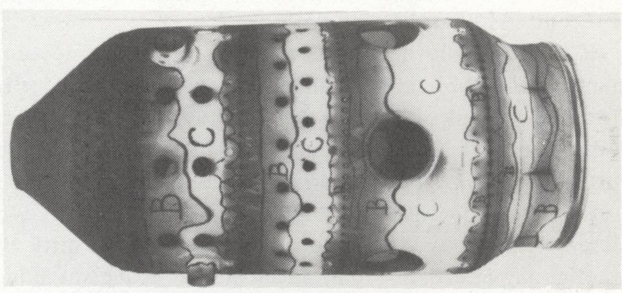
Fig. 22—Cooling efficiency versus correlating function for various systems



HIGH PRESSURE TEST CONDITIONS

Air mass flow	lb/sec	15.08
Air inlet temp.	deg K	541
Air inlet press.	psia	103
Air/fuel ratio	-	55/1

Fig. 23 A



TEMPERATURE CODE
ON FLAME TUBE, C

A	< 410
B	410 - 490
C	490 - 575

Fig. 23 B

Fig. 23—Comparison of predicted and measured wall temperatures

Table 5 - Viscosities of Liquid Fuels

Fuel	Gas Oil	Medium Diesel	Marine Diesel	Light Fuel Oil	Medium Fuel Oil	Heavy Fuel Oil
Viscoisty, centistokes @ 100 F	2.46	3.12	5.2	55	330	940

The prime importance of operating costs on industrial units has resulted in the use of residual oils, crude oil, and natural gas for fuels, in addition to the more normal range of gas oils. Typical viscosities for liquid fuels used on industrial gas turbines are given Table 5.

As a general rule, acceptable pressure jet atomization giving a droplet size (Sauter mean diameter, SMD) not greater than 120 microns can be obtained if the viscosity does not exceed 15 centistokes; fuels with higher, viscosities must be preheated. For example, using a normal heavy fuel oil (3500 sec Redwood No. 1 at 100F, or 940 centistokes at 100F), it is necessary to heat the fuel to 100 F before it can be pumped; it is necessary to preheat to 250-270 F to obtain an SMD of 60-80 microns. With such a fuel it would be normal to have a two-stage fuel heating system with initial heating before the low pressure pump, and final heating either before or after the high pressure pump. Excessive pump wear has been experienced with residual fuels caused by abrasive impurities in the fuel oil, and care must be taken to ensure a satisfactory pump life.

The use of gaseous fuels does not present any particular problems apart from the provision of a suitable gas injector. It is normally possible to arrange satisfactory gas injection with an injection pressure loss of some 20 psi.

Requirements arise on industrial engines for normal operation burning natural gas, but with provision for standby operation with liquid fuel. In this connection a composite gas-liquid fuel combustion head has been used that enables the fuel to be changed over from gas to liquid, or vice versa, in a matter of seconds without shutting down.

IGNITION - In the early stages of gas turbine development, considerable use was made of trains of sparks for ignition. The sparks, each of a few millijoules energy content and occurring at a frequency of about 400 per sec, were emitted by a plug positioned in the combustion wall.

High Tension and High Energy Ignition Systems - With increased altitudes of operation, and hence greater difficulty in relighting after flame-out, development produced the high energy system (Fig. 24) in which the electric energy is stored over a period of around 1 sec in a capacitor and then released over a period of about 100 μsec. In this system, 12 joules of stored energy is dissipated at a power level of at least 100 kw during the peak period of the spark discharge. Unfortunately, when dealing with such power in equipment small both in size and weight, it is difficult to avoid great loss, and in fact the latest figures show only 7% useful heat energy appearing at the igniter plug face.

However, this is still a power several hundred times, greater than the original high tension spark provided, and Fig. 25 (showing the relation between spark energy, gas speed, gas pressure, and at a particular fuel droplet size) suggests that there is probably little benefit in further increases of spark power. Further advancement lies in controlling air velocities and providing suitable air and fuel mixtures. This might well result in readoption of the torch igniter type of combination spark plug and fuel spray, incorporating high energy plugs.

Other methods of ignition such as hydrogen peroxide and kerosene burners, chemical flares, low voltage arcs, and the like have all been tried, but for the gas turbine engine, the electric high energy system remains first choice.

Torch Igniters - Torch igniters were developed an an alternative, more reliable means of ignition and were used

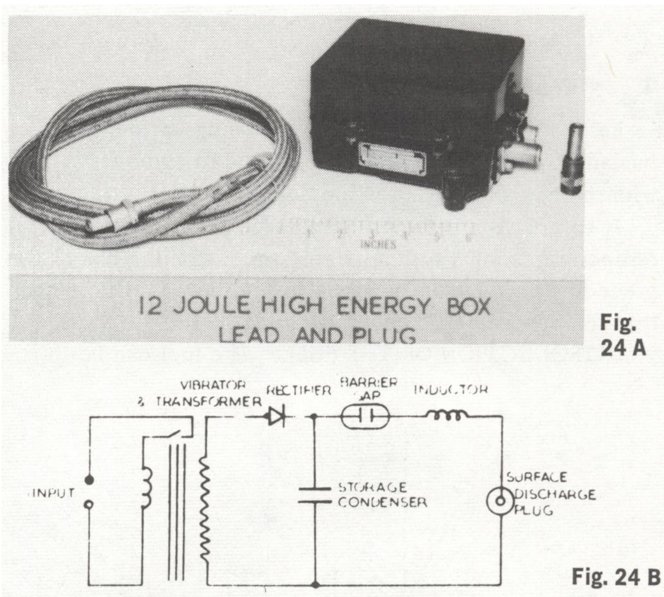


Fig. 24—High energy ignition system

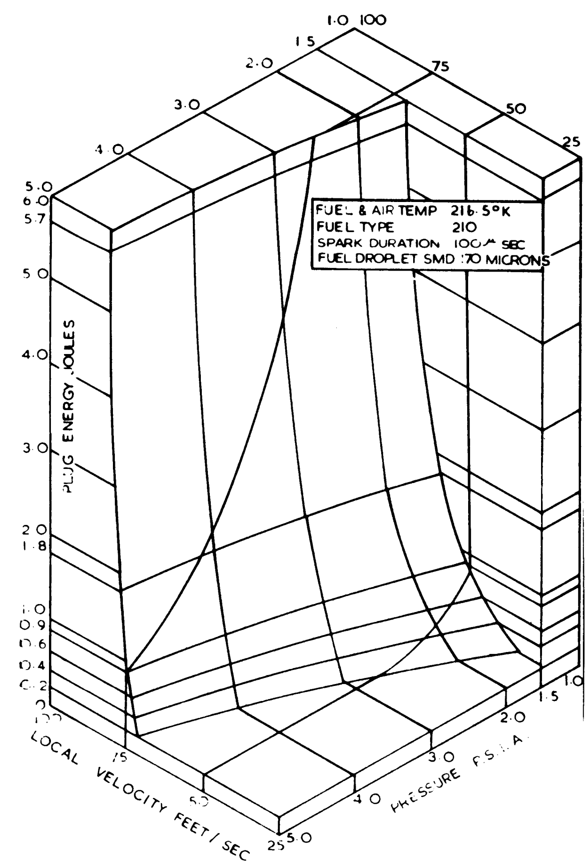


Fig. 25—Limits of ignition for high energy spark

initially on aero combustion systems but more recently have been used almost exclusively on industrial units.

The torch igniter is essentially a small combustion system on its own. Fuel is supplied to the Simplex atomizer (Fig. 26) and ignition is by high tension or high energy plug. The air for combustion is supplied from the annulus between the flame tube and outer casing. As the name implies, these igniters provide a torch flame across the primary zone of the combustion chamber. They are especially suitable for obtaining light-up under particularly arduous conditions, expecially when using the heavier fuel oils.

Mechanical Design

THE PROBLEM - The problems arising in designing to fulfill the technical and mechanical requirements tabulated in the second section are legion and often complex. Let it be said at the outset that a satisfactory design can be evolved only by integrating the combined experience and knowledge of the research, development, performance, heat transfer, metallurgical, chemical, production, and other specialist engineers. The designers' task is to seek and understand the advice of the specialists, to asses this advice, in total, and then to evolve an economically sound design that is compatible with the overall engine requirement and which strikes a compromise between what will usually be found to be conflicting factors.

The loading on a flame tube arises from various sources, which can be classified as follows:

1. Flame temperatures in the order of 1600-1800 C.
2. Cyclic temperature variations.
3. Metal operating temperatures of 500-700 C with peaks up to 900C.
4. Metal temperature gradients up to 300 C per inch.

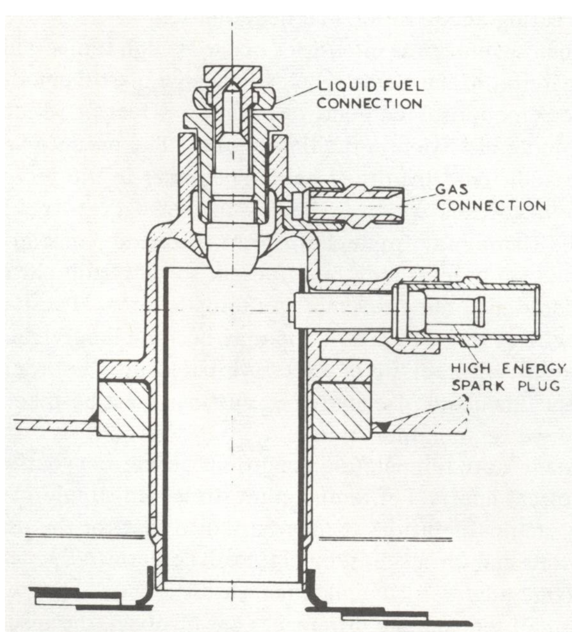


Fig. 26—Industrial torch igniter

5. Exciting frequencies, either mechanical or aerodynamic, over a very wide frequency range and at varying amplitudes.
6. Acceleration loadings up to 15g.
7. Collapsing pressure differentials across the flame tube wall normally of 1-5 psi, but up to (say) 25 psi for high compression ratio engines and high flight Mach number aircraft applications.

The simultaneous subjection of a sheet metal structure to the above loadings inevitably results in one or more of the following modes of failure:

1. Cracks.
2. Fretting.
3. Structural failure.
4. Distortion and buckling.
5. Overheating.
6. High temperature corrosion.

A simple definition of the problem, then, is to prevent these failures occurring within the predicted life of the equipment while at the same time fulfilling the requirements given in the second section of this paper.

STRESS CONSIDERATIONS - The following three items are the main prerequisites for a stress analysis, and it will be seen that these are not easily definable.

1. Reliable data regarding the conditions of operation; the unknowns are the relative magnitudes of thermal and vibratory effects and the nature and magnitude of dynamic loads.
2. Reliable data regarding the materials of a structure; most of the data published by the material manufacturers are for bar materials, and further testing has been required to establish the properties of sheet materials over a range of temperatures.
3. Proving tests: experience from previous engine running, combustion rig test, and the simulated bench testing of part of the structure.

On the basis of such data, and guided by past experience, a design may be evolved by consideration of the proof, fatigue, and creep stresses arising from the loads imposed in service. In the subsequent analysis, the various loading sources are discussed individually, but it must be remembered that in service these are all operative at the same time. Consequently, design consideration on any one aspect must always be assessed in conjunction with related loadings, and these considerations are then particularly valuable as a guide to action rather than to an exact formulation of the final stress conditions.

Pressure Loads - Two types of pressure loads must be considered:

1. Circumferential - The walls of combustion chambers are subjected to a pressure differential that can become relatively large in high compression ratio engines at low level, high flight speed operation.

This is important with respect to the outer flame tube of annular chambers, where the wall thickness does not increase proportionately with the diameter and consequently the circumferential compression gives rise to the possibility of elastic instability.

In general, critical pressures depend on the length to diameter ratio, the thickness to diameter ratio, the degree of support afforded by end attachments, manufacturing eccentricities, discontinuities, metal temperatures, Young's modulus, and the stiffness introduced locally by skin-cooling devices.

The resistance of the design to collapse is effectively contributed to by the latter item, namely, the skin-cooling design. In the case of, for example, corrugated spacer constructions, the stiffening effect is largely dependent on the width of the corrugated spacer and on the rigidity of the spacer.

A complete theoretical assessment is complex and testing has revealed that collapse is due to yielding at local eccentricities rather than to straightforward elastic instability as predicted by the small deflection theory. However, it is possible to substantiate relatively simple theoretical approaches by practical testing and to introduce empirical factors to solve practical problems. The formula used can be that of Von Mises for cylindrical shells subject to modifications, to account for stiffening due to the skin cooling devices, and others. Good agreement is found when the developed theory is compared with experiments carried out on flame tubes, as described in the next section, and metal thicknesses exceeding 0.050 in. are seldom required.

2. Longitudinal - The static pressure within the flame tube, being lower than the static pressure within the air annulus, gives rise to direct longitudinal forces that act on component parts of the flame tube and in turn on the flame tube mountings and support pins.

For example, the forces on the flame tube flare are in a downstream direction, whereas the forces on the discharge duct are in an upstream direction; the summation of these various forces dictates the loads to be carried by the support attachments. Design suspension methods for accommodating these loads are well established.

Mention should also be made of acceleration loading requirements for aero applications. The requirement is usually accommodated within the range 10-15 g three-directional loadings, and these forces can be contained without resorting to excessively large mountings.

Bearing pressure intensities on suspension pins are normally restricted to values of 250-500 psi, and the fretting effect is reduced by surface treatments.

Dynamic Loads - Vibrational stresses can originate from pressure pulsations in the compressor air delivery, variations in burning rate, acoustic oscillations, and engine vibrations, but the flame tube possesses a whole range of natural frequencies in its various parts, and it is not possible, in the first instance, to ensure that all will be safe from excitation by the fundamental engine vibrations or its harmonics.

Much consideration has been given to the general factors that influence fatigue resistance, such as cold working, residual stresses, stress concentations, temperature, size effects, microstructure, and corrosion, and such considerations play a considerable part in the choice of material. Failure of the flame tube from vibrational effects is shown exclusively in frettage or mechanical fatigue cracks that usually originate in the regions of stress concentrations such as the weld attachments and around the vicinity of injection holes.

Undoubtedly the most rewarding way of combating fatigue failures is by scheduling the testing of parts or whole structures under simulated operating conditions. Although correlation of the test results with actual engine experience is not simple or direct, it is possible, with interpretative understanding, to establish an order of merit and a bench to engine life relationship that will be borne out in practice.

One of the common vibrational failures is fatigue cracks in the vicinity of holes, and tests described in Ref. 11 have been undertaken to determine the endurance limit of reinforced sample specimens under simple push-pull conditions at constant temperature, as well as the effect of various types of hole edge finish on fatigue life.

This experience has indicated that from an all-round point of view, a plunged hole is the most satisfactory solution if coupled with the advantages gained by increased coefficients of discharge and better penetration of air flow through the hole.

With regard to the vibrational effects on the internal cooling skirts, it has been shown that those that are riveted may have a superior life to the welded type. It is thought that this effect may be contributed to by the damping forces arising with the rivet attachment, as compared with, on the other hand, stress concentrations at the weld nugget of the welded skirts.

Thermal Loads - The operational duties for both aircraft and industrial chambers subject the flame tube to a range of elevated temperatures and to cyclic temperature variations during acceleration and deceleration.

When severe stress intensities occur at high temperature, the material of the flame tube can undergo plastic deformation or creep displacement, or both the effect of which is to promote distortion in the flame tube. The pressure loads cause additional localized bending stresses in the vicinity of the distortion, which is thereby further aggravated.

The flame may impinge upon the distorted part and the combustion process may be affected, so that such parts of the flame tube run at even higher temperatures. The flame tube will continue to distort and may become unserviceable as a result of cracking or excessive buckling. In order to prevent this chain of events, precaustions must be taken to minimize temperature stresses.

Steady state temperature conditions permit conventional theoretical analyses of temperature stresses in simple cases. From such calculations it may be shown that for the usual materials and for a skin temperature differential ΔT C across the flame tube wall, the maximum stress is 300 ΔT psi. Since only small temperature differences are involved, the induced stress is of a relatively low magnitude. However, at a localized hot spot where high temperature gradients exist, the stress may be of considerable magnitude; assuming a uniform gradient, the stress can be shown to be approximately 150 ΔT psi where ΔT denotes the difference in temperature between the center and periphery. Temperature stresses so calculated are, however, not always realized in practice because of deformations that occur in the sheet metal.

The effect of nonuniform temperature distribution is quite marked in the vicinity of the corrugated spacers where the admission of cooling air results in a hot-cold tie-up. Investigations have shown that the stresses due to this type of loading are greatly in excess of those arising from other causes. Analysis shows that the induced stresses depend mainly on spot weld pitch to flame tube diameter ratio, flame tube diameter to wall thickness ratio, and the temperature differentials.

MATERIAL SELECTION - The desirable properties that a material must possess for flame tube application may be listed as follows:

1. Creep strength.
2. Mechanical fatigue strength.
3. Thermal fatigue strength.
4. Corrosion resistance.
5. Ease of fabrication.

Selection by Physical Properties - In the British gas turbine industry, Nimonic 75 (80% Ni, 20% Cr) is still the "standard" flame tube material, where temperatures can be limited to 700 C. For higher temperatures and for the larger diameter chamber, Nimonic 90 (a nickel-based age-hardening alloy) has been introduced, although this alloy is more difficult to fabricate and does not posses the excellent ductility qualities of Nimonic 75.

Much of the published data regarding material properties are for bar material, and extensive work has been undertaken in the Lucas Materials Laboratory in establishing corresponding data for sheet material.

It has been found that sheet has a creep life that is not so good as bar material; the major factor responsible for this, in the case of Nimonic 75, is the much smaller grain size resulting from the different manufacturing processes.

Although the creep ductility of Nimonic 75 at service temperatures is perfectly adequate, this is not so of the age-hardening, nickel-based alloys, which suffer from what is known as a ductility trough in the range from 650-800 C. Different heat treatments are necessary to give maximum creep life as opposed to maximum creep ductility. One of the most desirable characteristics that attains creep ducitility is a very fine grain size; therefore it is recommended that heat treatments at 1150 C should be avoided, since there is a danger of grain growth and consequent loss of ductility, which cannot be regained by subsequent heat treatment.

With regard to mechanical fatigue, sheet alloys retain their notch sensitivity to elevated temperatures; consequently the usual precautions to avoid stress raisers must be taken. Pitting resulting from corrosion will reduce the fatigue properties, and this may be particularly severe when burning heavy fuels.

Surface Treatment - The protection of metal surfaces may be required in combustion chamber design, and a number of processes can be helpful. Surface treatments may be required for several reasons: to improve resistance to wear or fretting, to reduce material costs by using coated low grade materials, and to prevent corrosion.

Certain parts of the combustion chamber (including locating rings, suspension pins, and interconnectors, and in fact all components that are subjected to vibrational impact or which have a sliding duty) need protection against wear. Several methods have been employed in practice, and hard chromium plate is extensively used, with a total thickness of 0.001-0.003 in., depending upon the application.

It is well known that seizure of screw threads using conventional materials occurs during the cooling down process from high temperature. For this reason, the choice of material should always be such that the bolt has a higher expansion rate than the nut, thus allowing the bolt to shrink away from the nut during cooling. For very high temperature operation, our experience has shown that a suitable combination of nut and bolt material is, for example, Nimonic 75 and 18/8 Stainless Steel, respectively. It has also been found beneficial to design screw threads with a 0.002 in. reduction in the basic effective diameter for male threads. Furthermore, although lubricants are not used during the assembly of screw threads, it is recommended that graphite or iodine-impregnated oils be used before any nut or bolt is unscrewed. Surface treatments such as silver plating and nitriding have been found beneficial, but chromium plating in the majority of cases has not been so effective.

Metal spraying techniques, such as aluminum spraying followed by heat treatment at 800 C, give a particularly good surface protection of mild steel for casings subjected to atmospheric corrosion.

Material costs are becoming increasingly important, particularly in the case of the small industrial engine. The possibilities of aluminized or chromized steels and the 18/8 type stainless steels should be also considered in cases where metal temperatures can be minimized by improved cooling technique.

High Temperature Corrosion - Corrosion is an important consideration with some industrial engines utilizing residual fuel oils containing up to about 4% sulfur, which on combustion forms SO_2, SO_3, and under some conditions, H_2S. Such gases, particularly H_2S, which is the most virulent, attack metal surfaces directly at the high temperatures. However, H_2S is likely to be present only in the primary zone or in local over-rich pockets, whereas SO_2 and SO_3 attack is more likely to occur downstream of the primary zone. In addition, certain constituents of the fuel ash, notably sodium and vanadium complexes, can fuse and be deposited at temperatures as low as 600 C. Such deposits flux the protective oxide layer of the metal and cause rapid corrosion or permit rapid oxidation.

The problem can be combated by ensuring an effective barrier of air and by maintaining metal temperatures at a level of around 600 C, since above this temperature, chemical attack becomes increasingly rapid.

STRUCTURAL BENCH TESTS - A failure in a structure must be regarded as the product of all stresses acting in the vicinity of that point. Although it is possible to bench-test part or whole structures in which the stresses of greatest magnitude (thermal stresses) are simulated, it is not generally possible, nor is it economically attractive, to superimpose simultaneously the complementary pressure and dynamic stresses.

A technique of proving structures has therefore been evolved in which a comprehensive program of cyclic thermal and vibration testing is allied to stress studies in such a way that the type of engine failure resulting from service is simulated.

Where possible, the engine temperature gradients are simulated (in the case of thermal tests) on dummy test specimens that are fitted with thermocouples. If excessive test times to failure are experienced, then the test may be accelerated by increasing the temperature gradients.

The thermal shock aspect of this technique has been successfully applied in the case of skin cooling, corrugated, spacer spot welds; the results have borne out the stress predictions already described under "Thermal Loads." Test sections incorporating such spacers have been tested on thermal and vibration rigs to conditions equal to, and also more severe than those that would be met in service. The results of these tests confirm the theoretical prediction referred to earlier.

The great value of work such as described above has been in replacing expensive development of combustion equipment on the engine by relatively cheap bench testing. In general the improvement of life and reliability of structural parts by simulated tests of the kind described has proved to be extremely valuable in leading to new design concepts and parameters.

In support of the theoretical predictions referred to previously in discussing thermal load on the collapsing pressure of large flame tubes, tests have been carried out on a wide range of experimental chambers by means of specially made flexible rubber bags that were inserted between an outer casing and the flame tube under test. The bags were then inflated with water, and the pressure was increased until collapse of the flame tube occurred. The stress distributions present were measured by suitably located rosettes of strain gages, for general interest, and the critical collapsing pressure was corrected for temperature effects.

Development Testing As An Aid to Design

When studying any given design problem, the results of development work on past designs of a similar type are taken into consideration. Development testing therefore fulfills two important functions, the provision of such a background of knowledge, and the solution of problems specific to the actual chamber.

Ideally, the development facilities should allow the combustion equipment to be tested over the full range of engine conditions and should also allow detailed investigation of particular parts of the combustion chamber, including the flame and other regions of particular interest. In the case of gas turbine combustion chambers, there is therefore a need for test equipment to reproduce conditions from subatmospheric to high pressures, while at the same time keeping the demands on the air supply within reasonable bounds.

Among the test rigs used, therefore, there must be provision for air supplies at high pressures, at atmospheric pressure, and at quite low subatmospheric pressures, the latter being commonly obtained either by exhaust blowers or ejectors.

Another type of rig of considerable importance is the flow visualization rig for studies on flow pattern detail. This rig need not necessarily use the same fluid medium, and water is a familiar alternative.

Because of the restrictions in available air supply or the need to limit the cost of the work when testing very large combustion chambers, it is sometimes necessary to use scale models or portions of the full sized combustion chamber or, again, to test at conditions of reduced Reynolds number and so on.

As far as possible it is desirable that the conditions of operation of the chamber on the engine should be precisely duplicated. Thus the exact shape and size of the ducts by which the air reaches the chamber, and through which the gases leave it, should be identical, as should be the velocity and pressure distribution of the incoming air. Steps must also be taken to ensure that the pressure of the air and the temperatures of the air and the fuel are appropriate for the particular running conditions; it may be necessary, therefore, to use preheaters or cooling apparatus in order to ensure this.

Adequate attention to all the above points involves the provision of a wide variety of instrumentation, including standard means of measuring pressures, temperatures, flows, and other characteristics, as well as more sophisticated instrumentation for determining distribution of temperature and velocity, local flame tube metal temperatures, gas compositions, and similar factors.

The development procedure required as a general rule is such as to reveal quickly any unforeseen troubles that may arise in operating the particular combustion chamber, and to suggest the means of correcting these. At this stage, an initial calibration is carried out and a study of the resulting performance points out the lines along which development improvements must be made. This is followed by any necessary endurance testing and a final calibration, after which prototypes are submitted for engine test.

Future Trends

A trend toward the use of higher combustion chamber pressures will certainly make itself felt in the future as the new generation of supersonic aircraft comes into being and maximum chamber pressures of 200-300 psia will be involved. In the case of military aircraft, this will come from high flight

Mach numbers at or near sea level, whereas on civil aircraft, high compression ratios will be used in the interests of low specific fuel consumption.

The corresponding trend toward higher combustion chamber inlet temperatures is quite different for those of the aircraft and industrial cases. With aircraft, it is a combined result of higher compression ratios and high flight Mach numbers, predominatly the latter. Maximum values of up to 700 K or even more are contemplated, depending on the exact maximum flight Mach number considered and quite apart from the exacerbated problems of flame tube metal cooling which then arise; this would be closely associated with increases of turbine inlet temperature. These temperature effects will be of particular importance in the case of the outer flame tube of annular equipment that will be simultaneously subjected to high collapsing loads.

A concomitant problem on aircraft will be the tendency for higher fuel temperatures to be required, particularly where the fuel is used as a heat sink. Thus problems of thermal stability of the fuel and fuel injection into the chamber will have to be solved.

The use of vertical thrust engines for VTO and similar applications will obviously increase in the future, and the problem of large installed thrusts for small weight will become increasingly pressing. The desirability of installing such engines in a relatively thin aircraft wing will favor the development of very short combustion chamber designs and will have an important bearing on the use of lightweight materials and new fabricating methods.

In industrial gas turbines, the use of increased inlet temperature will come from efforts to improve cycle efficiency by higher compression ratios or heat exchange or both. These developments will also be associated with the use of heavier fuels, with their higher flame emissivities and more corrosives constituents.

In all the developments mentioned above, it will be of paramount importance not to lose sight of the need for long life of the combustion equipment, and technical advances that enable higher temperatures to be used at the expense of life are unlikely to be acceptable. With both flame tube and turbine, the toleration of these increased temperatures and allied pressure effects may come from a combination of better cooling techniques, with improvements in available materials. It will in any case be imperative to improve the uniformity of distribution of metal temperatures, to allow the use of higher mean values. An essential contributory factor will be the improvement of compressor delivery conditions or the incorporation of velocity profile correcting devices of the type described in this paper. Devices of the latter kind would, of course, be used as structural members, integrating the outer and inner diffuser casings.

In the case of industrial engines, it may be necessary to eventually depart from the concept of a completely air cooled, all metal, flame tube or to consider a relaxation of certain combustion chamber performance characteristics in order to ensure dependability, or both may be required.

With regard to materials, improvements in the ductility of the precipitation-hardening, nickel-base materials, particularly in the region of the edges of welded zones, would provide an immediate dividend. But it is necessary to face up to more complicated heat treatments (to develop the required mechanical properties) and also to increased fabrication problems (welding, machining, deep drawing, pressing) as compared with the simpler single phase alloys such as Nimonic 75. Light alloys such as titanium, will become more widely used, particularly for VTO applications. The development of ceramic coatings to resist high temperatures and high temperature gradients without flaking must also be considered, as well as the advent of techniques to deal with cast alloys that have the required properties.

Many advances in welding technology are anticipated, and new techniques such as electron beam welding are likely to bring about new trends in fabrication. New processes such as spark erosion or electrochemical drilling and further advances in forming processes, such as explosion forming, magnetic forming, spinning, and flow turning, are likely to become much more commonly used.

Requirements and factors such as those briefly touched upon above will all play a part in the coming decade and will provide to the combustion designer an opportunity and stimulating challenge.

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