Twenty-Seventh Symposium (International) on Combustion/The Combustion Institute, 1998/pp. 1793–1807

POWER GENERATION AND AEROPROPULSION GAS TURBINES: FROM COMBUSTION SCIENCE TO COMBUSTION TECHNOLOGY

SANJAY M. CORREA

GE Corporate Research & Development Center
Schenectady, NY 12301

In the 50 years since its introduction, the gas-turbine engine has become an essential component of our global society. One need only look at the nearest airport to realize its dominance of air transportation. It has also become a significant element of the power-generation industry. In the last decade, power-generating combined-cycle powerplants have increased in thermal efficiency to about 60%, while NO_x emissions have been reduced by an order of magnitude, to below 9 ppm (dry, at 15% O_2) in some cases. This paper reviews the ongoing transition from science to the needed technologies: new modes of combustion have been introduced in gas turbines, including lean premixed combustion, reheat and axially staged combustion, catalytic combustion, and rich-lean combustion; high-efficiency low-emissions performance is being extended to nonpremium fuels such as coal gas and crude oil; new materials such as superalloys, thermal barrier coatings, and ceramics have been incorporated into designs; and improved theories greatly dependent on advanced laser-based diagnostics of flame structure have led to design tools of increasing scope. Future challenges—such as viable propulsion for supersonic transports, powerplants fueled by renewable resources, and extension of gas turbines to micropower applications—can be met only through further progress in the underlying aerothermal and materials sciences.

Introduction

Sir Frank Whittle commented that the greatest technical problem in the early development of the jet engine was reliable combustion at an intensity at least 20 times greater than had been achieved before in any machine [1]. Combustors in modern engines operate with even higher intensities, on the order of 1 GW/m^3, yet it is not unusual for heavy-duty gas turbines (GTs) to operate for more than 1 year and for aeropropulsion GTs to remain in service for as many as 20,000 flights without significant maintenance. This review addresses GT combustion technologies—developed from a range of sciences and at an accelerating pace over the last decade—and presents some challenges for the future.

The review is organized into a summary of the two principal types of GTs, a discussion of NO_x formation and GT cooling techniques because they are strongly interdependent, a discussion of lean premixed combustion of natural gas that has provided the basis for very low NO_x and has been the focus of several emerging technologies, a discussion of non-premixed combustion primarily of liquid fuels including crude oil, and a summary of capability and future expectations of combustion modeling. A more detailed analysis of the flame structure and the scales of turbulence–chemistry interactions in various modes of GT combustion is already available in the literature [2].

The combustion system of a GT takes a transonic stream of air from the compressor, slows it down to recover static pressure, and provides a specified temperature rise (Fig. 1). Some systems must operate on different types of fuel. Constraints include the shapes of the radial and circumferential temperature profiles delivered to the turbine (which affect turbine life), the pressure drop across the combustion system (which affects thermal efficiency), the range over which the combustor can be turned down without flame extinction, the ability to relight at high altitudes, the levels of combustion pressure oscillations, metal temperatures, and emissions [3]. It is important to note that the thermal efficiency of a GT-based powerplant is determined by the pressure ratio and the turbine Rotor Inlet Temperature (RIT), not by the flame temperature. If temperatures in the flame exceed the RIT, for example, in a non-premixed flame, NO_x will increase without an increase in efficiency.

Combustion processes (and fertilizer production) fix atmospheric nitrogen and are key players in the global nitrogen cycle [4]. Photochemical smog, acid rain, and depletion of the ozone layer have made combustion-generated NO_x a matter of public policy and a pacing item in combustion technology [5]. The recent Kyoto conference on global warming may lead to further regulations on emissions of greenhouse gases [6].

Power-Generating Gas Turbines

Starting in the early 1980s, global events including

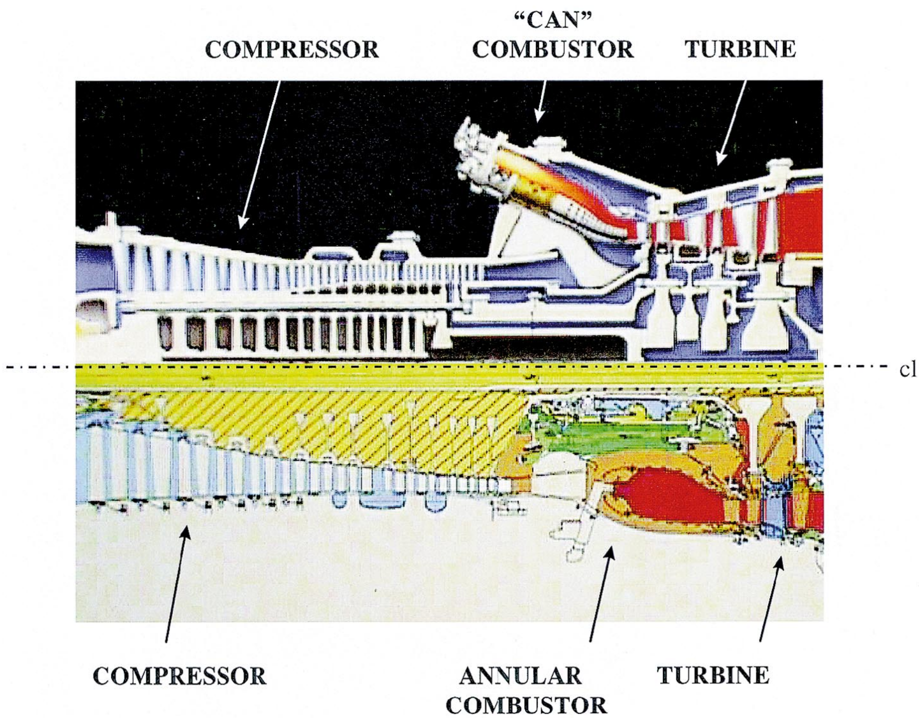

FIG. 1. Cross sections of heavy-duty (upper half) and aeropropulsion (lower half, enlarged ca. 5×) gas turbines.

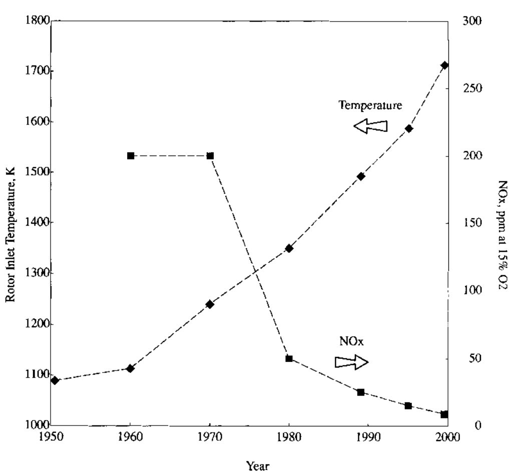

FIG. 2. Trends in heavy-duty gas turbines.

(1) a rapid increase in the need for efficient generation of electricity, driven by worldwide economic development,
(2) an increased environmental consciousness regarding pollutants such as SO_x and NO_x [5],
(3) concerns regarding CO_2, which has been linked to global warming [6,7], and
(4) a continuing abundance of natural gas [8]

have led to the development of large combined-cycle power plants. These consist of GTs—up to 350 MW in size—whose hot exhaust is used to raise steam for steam turbines. Natural gas and distillate oil are the predominant fuels. By introducing lean premixed combustion in gas-fired engines, NO_x emissions have been reduced from unabated levels of over 200 ppm to below 25 ppm (by volume, dry, corrected to 15% O_2). RITs have increased to current values of about 1600 K, enabling (combined cycle) thermal efficiencies of 55–60% (Fig. 2). High efficiency amounts to less fuel cost as well as less CO_2 per unit of electricity. GTs also offer low cost per installed kilowatt of power-generating capacity and short construction times relative to conventional power plants. As a result, about 80% of the 300 GW of electrical power expected to be added in the United States in the period 1995–2015 will be based on simple- or combined-cycle GTs. Similar trends are expected in other parts of the world. Another factor in some regions is replacement of the first generation of nuclear power plants (which were generating 17% of electricity worldwide at the end of 1997).

Large heavy-duty power-generating GTs have annular or "can" combustion systems, the latter being more accessible for maintenance (Fig. 1). Long combustor cans with residence times of 10–20 ms have been needed to complete the combustion of heavier fuels. Silo or off-board combustors are not used in modern engines, primarily because RITs are so high that the transition piece from the silo to the turbine would require substantial cooling.

Aeropropulsion Gas Turbines

A modern aeropropulsion GT engine has an annular combustion system, with pressure ratios approaching 40, combustor inlet temperatures approaching 1000 K, RITs of 1800 K or higher at take-off power (1500 K or less in cruise), kerosene-based fuels (with military variants), residence times of 1–3 ms, operational altitudes that reach 20 km, and speeds that may be above Mach 2. The power:weight ratio of an aircraft engine is 10–20 times greater than that of a power-generating unit. There is no realistic substitute for GTs for civilian and military aeropropulsion, including turboshaft engines for helicopters and small aircraft, turbofans for large aircraft, and after-burning turbojets and turbofans for combat aircraft.

Some aircraft engines are repackaged for stationary power generation or land and marine propulsion, in which case the fan in the front is removed and a power turbine is added. Such engines range in size from less than 1 MW up to about 50 MW, with larger engines under development.

NO_x Formation and Air Management

NO_x emissions are reduced by reducing the fuel:air ratio in the flame, while providing the required RIT. The challenges to achieving low NO_x therefore include higher RITs as well as noncombustion use of air discharged from the compressor, such as cooling of combustor and turbine components. Dramatic reductions in NO_x emissions from GTs have been made possible by advances in the sciences underlying flame stability, control, and materials, and in cooling technologies.

NO_x Formation in Gas Turbines

NO_x is defined by regulations as the sum of nitric oxide (NO) and nitrogen dioxide (NO_2), but in most circumstances, it is NO that is formed in the combustor with conversion to NO_2 occurring downstream. Elucidation of the various combustion routes to NO_x is one of the principal contributions of science to combustion technology [9].

"Thermal" NO_x is the dominant route to NO_x in non-premixed combustors [10], because stoichiometric interfaces between fuel and air lead to high temperatures; recall that the air is preheated by the compression process. The forward rate of the nitrogen-fixing reaction $N_2 + O = NO + N$, accelerated by high temperatures and superequilibrium levels of O atoms [11], can exceed 5000 ppm/ms [2]. Non-premixed flames in modern GT cycles would make in excess of 200 ppm of NO_x via the thermal NO_x route. If water or steam is injected into the flame zone, the peak temperatures drop and NO_x can be reduced. This technology is referred to as "wet control" of NO_x. Emissions data from a typical engine (Fig. 3) show that reduction of NO_x to below 50 ppm requires water:fuel ratios on the order of 1 and is eventually limited by an unacceptable increase in CO. Combustion dynamics may also increase and accelerate wear. In practice, the ratio is usually 0.8–1.2.

In the prompt NO_x mechanism, atmospheric nitrogen is fixed by hydrocarbon fragments in the flame zone, $CH + N_2 = HCN + N$ [12]. This mechanism can contribute on the rich side of non-premixed flame structures; however, since the combustor exit gas is lean overall (given the temperature limits of materials used in turbine airfoils), neither thermal nor prompt NO_x needs to be a controlling factor.

NO_x can also be formed via $N_2 + O + M = N_2O + M$, followed by further oxidation of N_2O to NO [13]. Sensitivity calculations of laminar flames at various equivalence ratios and pressures have shown that this mechanism is dominant in lean premixed combustion under GT conditions [14,15]. These findings were supported by lean high-pressure combustion experiments conducted in a perforated plate burner [16]. N_2O itself is not a significant emission in lean premixed combustion being less than 1% of NO_x, that is, comparable to the 0.3 ppm (by vol) background level in the atmosphere [4,17].

NO_x can be formed in large quantities from fuel-bound nitrogen (FBN). This is not an issue with fuels such as natural gas or light distillates but can be very significant if the fuel is derived from FBN-laden sources such as coal or heavy distillates.

NO_2 is not usually formed in GTs, but NO may be converted to NO_2 in the exhaust gas. This process is promoted by the presence of CO and temperatures in the range that maintains HO_2 [18], via the elementary steps

$$CO + OH = CO_2 + H$$

$$H + O_2 + M = HO_2 + M$$

$$NO + HO_2 = NO_2 + OH$$

such that, overall

$$NO + CO + O_2 + M = NO_2 + CO_2 + M$$

Conversion of NO to NO_2 could occur within the combustor at interfaces where dilution air is introduced downstream of the flame [19] and in the boundaries of relatively cool pockets of fuel in which

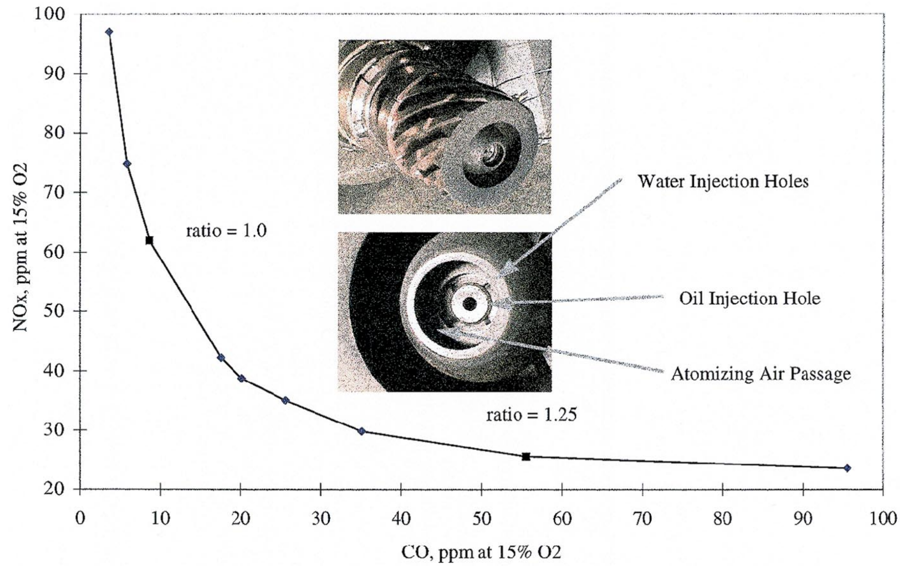

FIG. 3. NO_x and CO emissions with wet control parameterized by water:fuel mass flow ratio. Insets show a typical fuel nozzle.

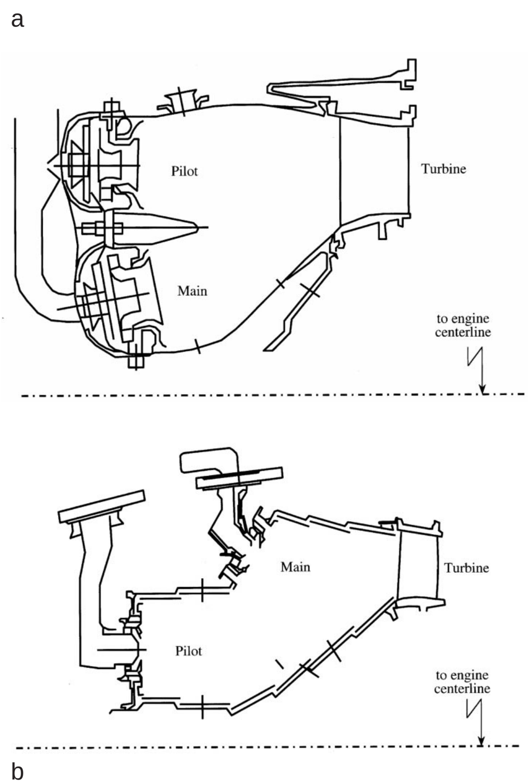

FIG. 4. Staged combustors. (a) Radial staging (courtesy of General Electric). (b) Axial staging (courtesy of Pratt and Whitney) [21].

pyrolysis is occurring but combustion is not complete—an abnormal situation that may occur if fuel escapes the flame zone [20].

Air Management: Staging and Cooling

Staging enables the flame to be operated near the lean limit at high load while still capable of being turned down without extinction. In fuel staging, the fuel injectors are turned off singly or in groups as the load is reduced, which keeps the remaining injectors within flammability limits. This approach is used in stationary and some aeropropulsion GTs. Figure 4a illustrates a double-annular or radially staged combustor in a commercial aircraft engine: The outer annulus provides ignition and relight margin, while the inner annulus is operated at a leaner setting than otherwise possible. Staging may also be accomplished axially (Fig. 4b), with piloting provided by the upstream stage [21], or circumferentially. More complex embodiments of fuel staging can be found in stationary GTs. Air staging is a technique in which valves are used to redirect compressor air from the upstream portion of the combustor at high load to the downstream portion at low load, thereby maintaining a constant fuel:air ratio as the fuel flow is reduced. This approach was used in older stationary GTs and in some smaller engines but raises issues of mechanical reliability and packaging in modern GTs. Advanced sensors, programmable control systems, and an ever-increasing understanding of flame stabilization at GT conditions have facilitated the deployment of staged combustion.

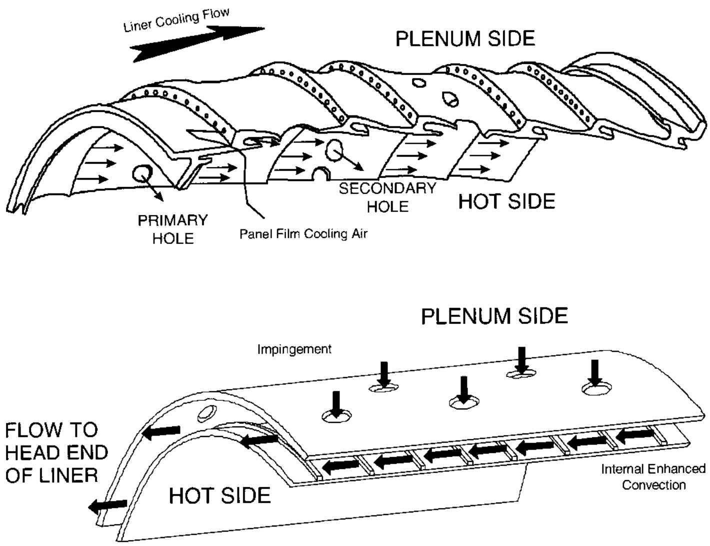

FIG. 5. Film-cooled and convectively cooled combustor liners.

The most common approach to cooling combustor walls (liners) is to direct only part of the compressor discharge air into the flame and to use some air to cool the walls by means of a film (Fig. 5). Additional diversion of air, to primary and secondary dilution airholes, allows (1) operation above the lean extinction limit and (2) postflame tailoring of the temperature profile. As a consequence, the flame runs hotter than it needs to for the same RIT and thermal efficiency.

Modern heavy-duty combustor liners have neither film-cooling nor dilution holes; they are typically cooled by "backside" convective heat transfer to the airflow that then enters premixer tubes. Figure 5 also shows a variant in which the liner is a double-walled structure within which the cooling air is contained [22]. Spent cooling air is recovered in the head end of the combustor for premixing purposes, thereby lowering the stoichiometry of the flame. Other approaches are effusion or transpiration cooling [23], tiling the liner with shingles, and so on. The fraction of compressor discharge air participating in the flame in a heavy-duty GT has increased from about 30% in old engines to about 80% in modern engines.

Another technology, relevant to combined-cycle power generation, is closed-loop steam cooling of turbine airfoils and combustor components [24]. Steam cooling frees up significant amounts of air for premixing with fuel.

Advances in materials have complemented the foregoing advances in cooling technology. Metals used for combustor components have evolved from stainless steel to precipitation-hardened Ni- and Co-based superalloys originally developed for turbine airfoils. By virtue of their high strength at high temperature, these materials permit cooling of combustors with less air and so have become an integral part of high-efficiency low-emissions designs. Thermal barrier coatings (TBCs) of yttria-stabilized zirconia on the hot side of the liners further reduce the demand for cooling air.

Materials science has also addressed ceramics for GT components, because the benefit can be as high as two percentage points in thermal efficiency. Significant progress has been reported recently [25]. For example, ceramic combustors have been demonstrated for about 1000 h in small GTs. The issues to be addressed include design properties, cost, and durability but fall outside the scope of this review.

Lean Premixed Combustion

Lean premixed combustion (LPC) of natural gas has reduced NO_x emissions from heavy-duty GTs from unabated levels of over 200 ppm to below 25 ppm (by vol, dry, corrected to 15% O_2) [26–35]. This technology has now seen an estimated 5 million h of commercial operation on natural gas at RITs of 1375 K and above, including over 1 million h at temperatures above 1550 K. Engines with RITs of 1700 K are under development.

Aircraft engines have not yet incorporated LPC because combustor inlet temperatures are usually higher and aviation fuel autoignites at a lower temperature than the corresponding parameters in natural gas fueled heavy-duty engines. Programs such as the High-Speed Civil Transport are, however, investigating lean premixed combustion to meet NO_x regulations for future supersonic transports [36].

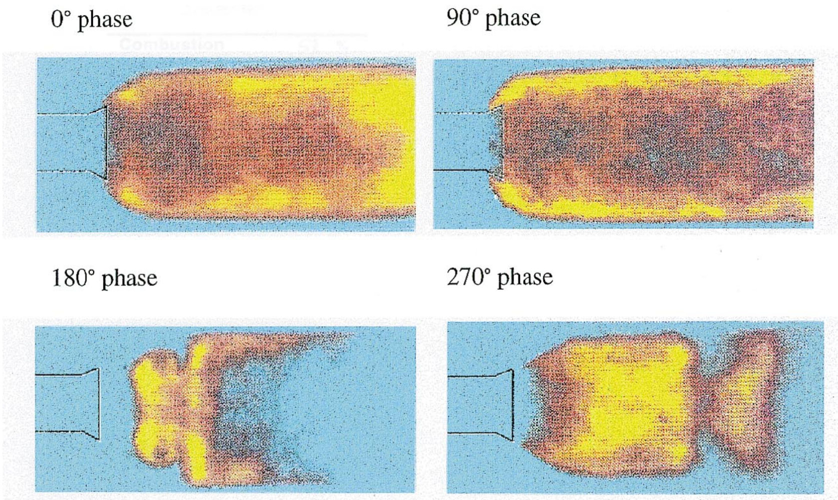

FIG. 6. A lean premixed flame undergoing one cycle of pressure oscillation in the longitudinal mode.

Premixing and Autoignition

Premixers in a lean premixed GT combustion system reside between the discharge of the compressor and the inlet to the combustor. The premixers mix fuel and air to as near uniformity as possible without risking autoignition or flashback. Injector geometries must be chosen to eliminate aerodynamic mechanisms for flashback, such as propagation up boundary layers and flame stabilization in the wakes of injectors [37]. Typical GT pressures and compressor discharge temperatures increase the propensity for autoignition. Although data are available for the autoignition of perfectly premixed (lower) hydrocarbons and air at various stoichiometries, the reported ignition delay times often are longer (more optimistic) than indicated by GT experience. Ignition delay times are affected by factors including the presence of other fuel species and the nonuniformity of fuel:air ratios:

1. Natural gas usually contains appreciable amounts of other hydrocarbons. Spadaccini and Colket [38] developed a correlation for the effect of other hydrocarbons on the ignition delay time of binary mixtures with methane.
2. The initial unmixedness in the near field of a fuel injector in a premixer reduces the autoignition delay time [39] by as much as a factor of 2 below values measured in initially homogeneous chemical systems such as shock tubes [40].

Premixed combustion systems can be vulnerable to contaminants in the fuel. For example, natural gas varies widely over the world: it may contain large amounts (e.g., 25%) of diluents such as CO_2 or N_2, and trace amounts of higher hydrocarbons (beyond hexane). Although the latter do not affect the heating value of the fuel, they can lead to autoignition at much lower temperatures than would be expected in mixtures of the lower hydrocarbons [41].

Combustion Dynamics and Control

Combustion pressure oscillations—often referred to as combustion dynamics—can be generated during lean premixed combustion. The fuel delivery system, the compressor discharge plenum, the premixers, and the combustor down into the sonic region of the turbine act as coupled acoustic cavities with characteristic resonances. The dependence of heat release on (1) unsteady large-scale structures in the flow and (2) variations in fuel:air ratio may lead to self-sustaining oscillations via the Rayleigh mechanism [42]: Unsteady heat release in phase with the unsteady pressure field will lead to limit cycles whose amplitudes are determined by damping in the system and losses at acoustic boundaries. Figure 6 illustrates the first submechanism, by which a lean premixed flame is undergoing one cycle of 1.1 atm (peak-to-peak) pressure oscillation at 150 Hz in the longitudinal mode. The 7-cm (dia.) burner was operating at 6 atm and 5 ppm NO_x, indicative of a well-premixed system. In this case, the fuel and air were premixed at an acoustically isolated location; vortex shedding couples with the pressure field through the large-scale unsteadiness in heat release. The second submechanism is more often observed in GTs: Acoustic waves propagating upstream into premixing ducts can cause unsteady pressure drops across the fuel injectors, unsteady fuel flow, unsteady fuel–air ratios, and unsteady heat release.

Combustion dynamics are most often suppressed by passive means, such as fuel staging (which senses unacceptably high amplitudes of pressure oscillation, moves the heat release zone to another spatial location, and so disrupts the Rayleigh mechanism) or damping (such as screech liners used in afterburners of military engines). More recently, active control has been under intense development in laboratories around the world [43–45].

In active control, the fuel flow rate is modulated in time to disrupt the phase relationship between heat release and the pressure field. This is a very promising approach that has been demonstrated in many laboratories, usually at the level of single burners [46–52]. Among the capabilities to be developed before implementation in GTs are:

1. sensors capable of operating under GT conditions.
2. mode identification in acoustically complex systems.
3. actuators capable of frequency response as required for both gas and liquid fuels, and capable of on the order of 10^{10} cycles (500 Hz for 1 year) without failure.

Computational fluid dynamics (CFD) is not capable of predicting combustion dynamics for the general case of a GT combustor. Progress has been made in some cases, for example, for longitudinal modes in relatively simple burners with simple acoustic boundary conditions [53].

Some segments of the chemical industry generate process gases with useful heating value as by-products. It can be economically advantageous to burn this fuel in GTs. Issues that can arise are (1) high H_2 content, which increases the propensity for autoignition and flashback into the premixing system, given the high flame speed of H_2-air flames; and (2) variations in injector pressure drop, if the heating value of the gaseous fuel deviates significantly from the original intent. To provide the same heat rate into the turbine, the volumetric flow rate of fuel also has to change. This alters the pressure drop at the exit orifices of the fuel injectors in the premixer, which can affect the pressure-coupling between the fuel delivery system and the combustion process. Changes in this coupling can affect the amplitude of pressure oscillations in the system.

Employing fuel-staging to achieve flame stability can lead to high CO at low power. CO is produced by pyrolysis of the fuel and is oxidized by $CO + OH = CO_2 + H$, with timescales that can couple with the turbulence. As a result, CO emissions can depend on the combustor geometry [54], unlike NO_x, which is very similar in very different types of lean premixed turbulent flames (e.g., Fig. 19 in Ref. [2]).

Axial Staging and Reheat Combustion

There are situations in GTs where combustion is carried out in "vitiated" air, that is, the products of a prior overall-lean combustion process. Examples are

1. afterburners in military engines, where additional fuel is sprayed into a duct following the last turbine stage and the products are expanded through a nozzle to produce additional thrust.
2. axially staged combustion, used in some aeropropulsion [21] and heavy-duty [27] GTs.
3. the *reheat cycle,* here defined as a thermodynamic cycle in which the turbine is split axially with an additional combustor in between. This cycle can offer higher specific work and (combined cycle) thermal efficiency at a lower RIT than a conventional Brayton cycle [55].

In afterburners and in reheat combustion, but not in axially staged combustion as defined previously, the temperature of the vitiated air entering the second burner is lowered by an amount corresponding to the work extracted by the turbine stage(s).

Combustion in hot vitiated air is interesting for several reasons. Autoignition issues are exacerbated by the high temperature but ameliorated by the reduced oxygen content. In a reheat GT, for example, the second burner might have to operate in a stream at 1250 K with 12% oxygen, by vol. Ignition delay times are about 5 ms and so do not necessarily preclude LPC, but aerodynamically sophisticated fuel injectors may be required [56].

Experiments have been conducted using an axially staged combustion system consisting of a premixed fuel injector followed by a non-premixed fuel injector [57]. Conditions at the exit of the first stage were held fixed at 6 atm and 1450 K, while the second stage was exercised across a temperature range. NO_x at the exit of the second burner increases with temperature, but NO_x corrected to 15% oxygen increases less rapidly because additional oxygen is consumed in the second burner (Fig. 7). Supporting calculations have shown that the low NO_x can be attributed to the (partial) premixing that occurs prior to the (lifted) flame, a reduction in the level of superequilibrium O atoms, and an overall decrease in residence time at high temperature. In other words, an axially staged system can deliver higher RITs at lower NO_x levels than a conventional system.

Catalytic Combustion

Catalytic combustion offers the potential of stabilizing a premixed flame at equivalence ratios below the lean blowout limit of a conventional burner [58] and has been widely demonstrated at GT conditions in subscale rigs [59–63]. Depending on the catalyst, a preburner may be required for light-off. Recent full-scale tests in a heavy-duty combustor can have demonstrated 3–4 ppm NO_x, 2 ppm CO, and negligible combustion pressure oscillations [64].

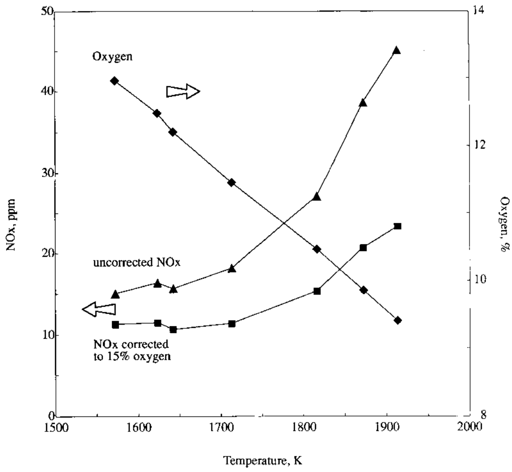

FIG. 7. NO_x and residual oxygen as functions of the temperature at the exit of the second stage in an axially staged combustor [57].

Before use in GTs, catalytic combustion technology must demonstrate the following:

1. Operation at higher RITs than demonstrated to date, because lean premixed systems with sub–9 ppm NO_x are already operational in modern GTs.
2. Elimination of the preburner by assuring light-off across the load range (i.e., across a range of catalyst inlet temperatures); otherwise, the preburner itself can be a significant source of NO_x.
3. Fuel flexibility—most of the development to date has been conducted with natural gas.
4. Operation at high fuel:air ratios, without overheating the downstream end of the catalyst in the event that the homogeneous (gas) phase flame is too close to the catalyst; in some designs, fuel above a certain level is injected downstream of the catalyst and burns in the homogeneous phase.
5. Elimination of thermal instabilities: loss of catalytic activity in a nonuniform manner across the face of the catalyst can lead to cold spots, reduced pressure drop along those "stream tubes," corresponding preferential increases in airflow that exacerbate the issue, and consequently a pattern of alternating hot and cold spots on the catalyst [65].
6. Durability of materials, including mechanical characteristics and chemical activity.

Non-premixed Combustion

Non-premixed combustion is employed in aircraft engines because LPC has not yet been qualified for aeropropulsion conditions and fuels, and in that subset of stationary engines where NO_x is not regulated or wet control is adequate to meet standards.

Rich-Quench-Lean Combustion

Gas turbines can burn gases derived from coal and from biomass [66,67]. These energy sources can be important in regions that do not have natural gas or distillate oil. Properly renewed biomass can be CO_2 neutral to the environment and may become an important fuel, initially for smaller GTs. Issues include the need to remove ash, the need to remove sulfur from the gas to protect turbine components and eliminate SO_x emissions, and the need to prevent FBN species in the gas from contributing to NO_x emissions.

Rich-quench-lean (RQL) combustion has been successful for FBN-containing gas. For example, an RQL combustor including advanced cooling and fabrication technology has been operated off a 900 kg/h pilot-scale coal-gasification plant [68]. The gas had a nominal heating value of 4370 kJ/kg and included 4600 ppm by vol of ammonia (the FBN). The double-walled liner avoided film cooling, and so the entire rich stage operated at the intended equivalence ratio of 1.25 [22]. The pressure and inlet temperature were 10 atm and 640 K, respectively. With 40% of the air going to the head end, conversion of FBN to NO_x was about 5% at 1600 K (Fig. 8); the apparent scatter in the data is caused by variations in the gasification plant. The optimal split of air shifts toward the lean stage at lower combustor exit temperatures. Also shown are the results of a perfectly stirred plug-flow reactor model, indicating good representation of the detailed chemistry and so facilitating future designs.

RQL combustion systems are being considered for the suppression of thermal NO_x in the high-speed civil transport [36].

Distillate: No. 2 Oil (Diesel) and Jet Fuel

Distillate oil is free of ash and includes naphtha, diesel, and kerosene. These fuels require atomization and evaporation across the load range, generally accomplished by pressure-atomizing or air-blast fuel injectors [3]. Heavier fuel oils may require auxiliary high-pressure air to assist atomization and to assure complete combustion and absence of visible smoke in the exhaust. Better atomization can also reduce the radiant heat load on the combustor liner. Macrolaminate fuel injectors, fabricated by methods similar to those used for integrated circuits, offer a new degree of flexibility to the combustor designer [69]. Spray injectors have traditionally been designed by semiempirical rules [3], but new mathematical models are being developed for CFD-based tools [70]. An important consideration is that GT fuel sprays may be operating in the supercritical regime [71].

Smoke can be an issue in GTs operating on liquid fuel and historically has been reduced by empirical

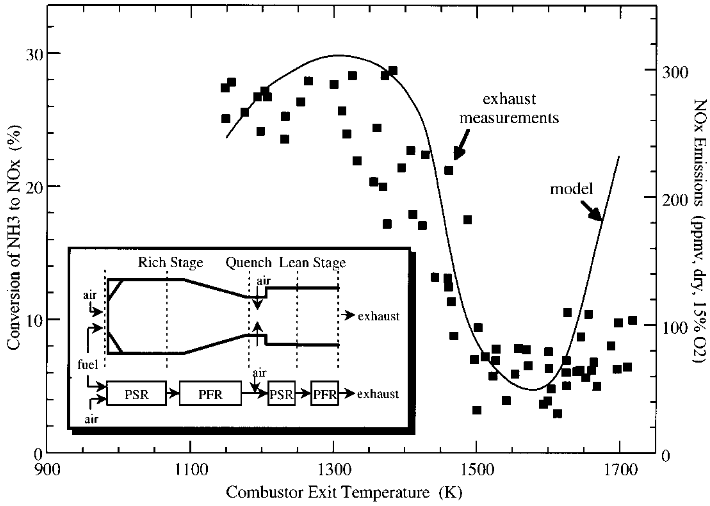

FIG. 8. NO_x emissions from an RQL combustor operating on high FBN fuel [68].

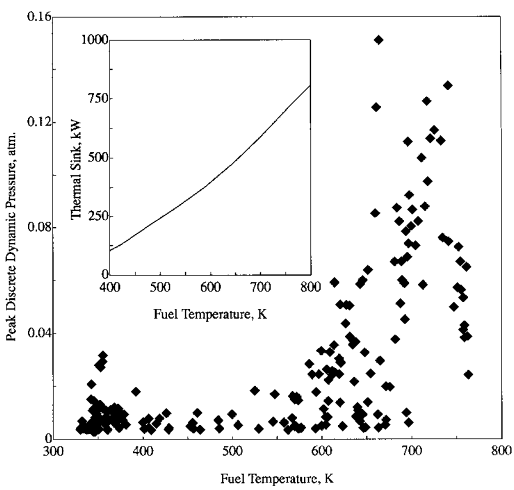

FIG. 9. The amplitude of pressure oscillations in a single-cup sector of an aircraft engine as a function of the fuel temperature. The inset shows the thermal sink capacity based on the fuel flow in the engine.

methods. For example, a review written in the 1970s found that more than 400 combustor modifications and more than 100 engine tests were required to develop a smokeless version of an already existing aircraft engine [72]. Scientific understanding has grown in recent years [73], however, and a start has been made on integrating the kinetic mechanisms developed in such research with CFD-based models of the type used to design GT combustors [74].

Combustion of heated aviation fuel is of interest, because the fuel flowing into the combustor may be used as a sink for heat generated by the electronics, the propulsion system, or the airframe (if flight speeds are high enough for the latter to be an issue). The thermal stability of fuel has been studied extensively [75]. The fuel may be hot enough to exceed the critical point, affect the fuel injection process, and increase combustor pressure oscillations. An example of this is shown in Fig. 9, using data from a single-cup sector of an annular combustor operating at 13 atm and 750 K inlet air temperature (high-subsonic conditions). The thermal sink capacity can be significant, approaching 1 MW, at high fuel temperatures.

Gumming or coking may occur in the premixer, the combustor, and the fuel system. This issue can be exacerbated by staging because fuel may reside in manifolds for long periods of time at high (compressor discharge) temperatures. Recent work has addressed the deposition of solids from liquid fuel including the effects of residence time, vertical versus horizontal orientation of the surface, temperature of the surface, and composition of the surface, for example, various metals and coatings [76,77]. Fundamental data such as these provide the basis for solving deposition problems in oil-fired engines.

Crude Oil

Heavy-duty GTs have accumulated about 10 million h on crude oil, generally at RITs of 1300 K or less [78–80]. Crude oil may contain metals in amounts up to 100 ppm or even more. Maximum allowable limits are usually specified for vanadium (V), sodium (Na), potassium (K), lead (Pb), and calcium (Ca). Exceeding the limits for Pb or Ca will increase maintenance costs. Exceeding the limits for Na, K, or V will significantly reduce life. For example, the limit for vanadium in untreated fuel is typically 0.5 ppm. If left in the fuel and burned, an ash containing vanadium pentoxide would be formed, would melt because of its low melting point, and would corrode combustor and turbine components. A level of 1 ppm of V without treatment can reduce the life of components in the "hot section" by as much as a factor of 5. By adding oil- or water-soluble magnesium (Mg) compounds, typically in a 3:1 Mg:V weight ratio, vanadium is captured as compounds whose melting point is higher (1465 K), and the ash resulting from combustion is not corrosive to the hot section. At the operating temperatures of advanced GTs, however, the magnesium–vanadium ash compounds form deposits that adhere to and build up on combustor and turbine components and dramatically reduce both performance and parts life. Hence, fuels of this type cannot be used directly in advanced GTs. Gasification is an acceptable option but entails large capital expense.

Laser Diagnostics and Combustion Models

Science has contributed to GT combustion technology in two ways. The first, largely empirical, is the discovery of phenomena that can be exploited without fully understanding their causative mechanisms. Semiempirical correlations can often be developed that permit design in some restricted range of parameters. The second, which requires a deeper level of understanding, is to provide predictive capabilities based on first principles. Much progress has been made, for example, chemical kinetic schemes are routinely used to estimate many of the pollutants discussed earlier. On the other hand, the development of combustion models such that they increase in scope and become accurate enough to be used as design tools—as whimsically forecast by Bilger [81]—remains an area of great but only partly fulfilled promise.

The physical situation is complex even in the relatively simple case of gas-fueled flames. Because the bulk-averaged axial velocity in the combustor is at least an order of magnitude greater than the flame speed, the flame must be stabilized in recirculation zones such as those produced by strong swirl or by sudden expansions. Turbulence–chemistry interactions under these conditions are of great interest [82,83]. Given that there is a spectrum of turbulence timescales and a partly overlapping spectrum of chemical timescales (reactions of interest can range from relatively slow NO_x formation to relatively fast pyrolysis), Damkohler numbers can span several orders of magnitude [2,82]; such systems undergo interactions between turbulent mixing processes and chemical reactions in the flamelet regime [84] and simultaneously in the "distributed reaction zone" regime [85]. For example, experiments have shown that NO_x is not a function of the turbulence structure in lean premixed combustion [2], which helps to explain why perfectly stirred reactor (PSR) models can calculate NO_x quite accurately. Such is not the case, however, for CO or unburned hydrocarbons.

Nonintrusive laser diagnostics have accelerated development by (1) providing composition and temperature data in relatively simple flames, which motivate theoretical developments, and (2) providing similar albeit restricted data on the more complex flames in practical combustors [86], which are used to assess models.

Many of the accepted characteristics of turbulent combustion were discovered by laser-based diagnostics [87]. A very incomplete list would include the role of large-scale structures in the turbulent mixing of parallel fuel and air streams [88]; the broadening of NO_x formation zones by superequilibrium levels of O and OH [11,89]; the measurement of temperature and major species jointly with minor species such as OH, which is particularly helpful to modeling [90,91]; images of the microstructure of turbulent mixing processes [92]; and the structure of spray flames [93]. In the future, it will be very useful to have nonintrusive diagnostics for high-pressure highly luminous and more turbulent flow fields. In particular, mixing rates need to be significantly higher than in laboratory burners so that turbulence–chemistry interactions can be studied in the regimes of practical significance. Measurements should include species at ppm levels, such as CO and various unburned hydrocarbons. To this end, advanced diagnostics such as coherent anti-Stokes Raman scattering (CARS) thermometry have been demonstrated in a model gas-turbine combustor [94].

Design tools range from empirical rules to unsteady three-dimensional CFD-based models. The former are used widely but usually are valid only in a narrow range [3,95]. CFD has, in principle, a wider range of validity but so far can address only a few design parameters. Pressure-corrected algorithms based on the averaged Navier–Stokes equations with two-equation turbulence closure are popular, because they converge quite reliably even in the complex three-dimensional geometry of fuel-injectors, swirl cups, film-cooling slots, dilution holes, and so on [96,97]. A typical CFD-based design tool [98] would use the averaged Navier–Stokes equations with a turbulence submodel and a PDF approach for turbulence–chemistry closure [99,100], a particle-tracking type of spray model, reduced mechanisms for the chemical kinetics of interest (the range of which is continually broadening) [101,102], and a model for radiation [103]. To illustrate the utility of a typical calculation, Fig. 10 shows a (12°) periodically repeating sector of a typical annular combustor with (30) fuel injectors spaced evenly around its circumference. The velocity and temperature fields reveal internal details resulting from the interaction of

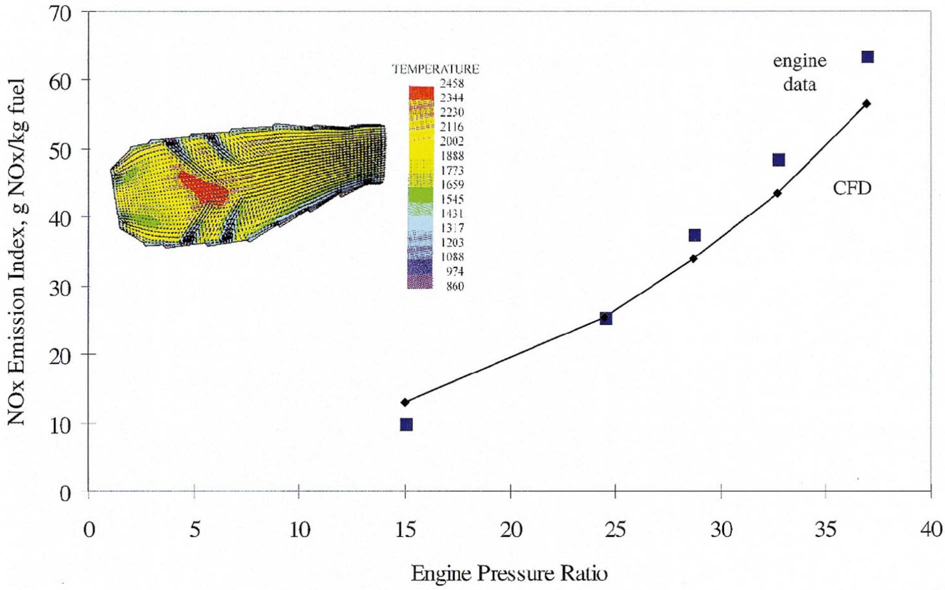

FIG. 10. Side view of velocity and temperature fields (K) and total NO_x emissions from CFD calculations of an annular combustor.

the swirling fuel-rich primary-zone flow with the dilution jets. In most cases, good agreement with engine data is obtained on NO_x—modeled using the thermal mechanism with PDF closure—and on the mean temperature profiles at the combustor exit.

Future models must incorporate more complex chemical kinetics so as to address extinction phenomena and pollutant species besides NO_x (e.g., CO, various unburned hydrocarbons, smoke), as well as unsteady phenomena including combustion dynamics.

Some theories include arbitrarily complex chemistry by means of *a priori* "library" calculations. Models based on the assumption that the microstructure of the turbulent flame may be represented by PSRs have been developed [104] and integrated with the PDF method [105]. Flamelet-based CFD is used widely [84], but neither PSR nor flamelet-based models give entirely satisfactory results. Better turbulence models, more efficient algorithms for complex chemical kinetic schemes [106], and a better matching with emerging computer architectures such as parallel computing—already used successfully for multistage axial compressors [107]—will be needed.

The inclusion of unsteady phenomena may require approaches such as the discrete vortex method [108] or large eddy simulation [109]. These will need to account for the complex three-dimensional geometries of interest and the complex nature of the acoustic path in the GT combustion system.

Future Challenges

Gas turbines have developed rapidly since their introduction in the 1940s. Table 1 shows the status of the underlying combustion technology. Escalating environmental and economic pressures will dictate continuing reduction of NO_x while increasing RITs to and beyond 1700 K, in heavy-duty GTs fueled with natural gas and distillates; operation of heavy-duty GTs with low NO_x emissions on crude oil, coal gas, biomass gas, and waste gas, again while increasing RIT from presently allowed limits (1300–1375 K); and flight-worthy lean premixed, lean direct injection, and/or rich-quench-lean combustion systems.

GTs will also be scaled down as microturbines (50–500 kW) for distributed power generation [110,111]. To be cost-effective with the diesel engine in this application, the GT might have only one stage in each of the compressor and the turbine. This sets a very low pressure ratio, typically less than 5. To increase efficiency, exhaust heat is recovered by means of a heat exchanger that leads to the challenges associated with high combustor inlet temperatures (autoignition, flashback, coking, and so on).

It is interesting to note that the process of combustion limits the ultimate thermal efficiency of the gas turbine. The large thermodynamic potential driving fuel and air to water vapor and carbon dioxide leads to large irreversibility losses. About 25% of the available work in the fuel is lost in the course

TABLE 1
Combustion technologies for gas-turbine engines

Technology	Pros	Cons
Non-premixed combustion	• widest experience • excellent operability	• unacceptable NO_x for stationary GTs
Water or steam injection	• proven in commercial service • extends non-premixed combustion to lower NO_x	• limited by CO increase • cost (diluent, thermal efficiency) • life (increased dynamics, wear) • not practical for aircraft
Premixed combustion	• approximately 5 million h in heavy-duty GTs since 1990 • 5–25 ppm NO_x, depending on turbine rotor inlet temperature	• not yet practical for aircraft: under development for the high-speed civil transport
Axially staged combustion	• in commercial service in aircraft and heavy-duty GTs	• cooling of second-stage fuel injectors
Catalytic combustion	• potential to stabilize very lean flames • demonstrated under heavy-duty GT conditions	• unproven fuel flexibility • unproven durability • not practical for aircraft
RQL combustion	• demonstrated reduction of NO_x from FBN sources under heavy-duty GT conditions	• not yet practical for aircraft: under development for the high-speed civil transport for reduction of thermal NO_x
Catalytic ammonia-based deNO_x (in exhaust stack)	• proven in commercial service • extends non-premixed combustion to low NO_x operations	• cost (ammonia usage) • emissions (ammonia "slip") • safety (transportation, storage) • not practical for aircraft

of adiabatic combustion, which sets an upper thermal efficiency limit of 70–75% [112].

For the foreseeable future, there appears to be no alternative to the gas-turbine engine for aeropropulsion and as the best use of premium fossil fuels (at least) for large-scale power generation—with a continuing need for scientific and technological support.

Acknowledgments

My sincere gratitude goes to many teachers and colleagues who have shared their keen insight with me over the years, in particular, Profs. Marty Sichel, Bill Kauffman, Steve Pope, Jim Whitelaw, and Bob Bilger, and Drs. Berkley Davis and Hukam Mongia of GE. Dr. Julian Tishkoff of the USAF-OSR has provided long-standing financial support. Drs. Tony Dean, Rob Cambell, Alan Feitelberg, Greg Waldherr, and Anil Tolpadi provided most of the figures.

REFERENCES

1. Whittle, Sir Frank, *Gas Turbine Aero-Thermodynamics,* Pergamon Press, New York, 1981.
2. Correa, S. M., *Combust. Sci. Technol.* 87 (1–6):329–362 (1992).
3. Lefebvre, A. H., *Gas Turbine Combustion,* Hemisphere, New York, 1983.
4. Smil, V., *Sci. Am.* 76–81 (July 1997).
5. Bowman, C. T., in *Twenty-Fourth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, 1996, pp. 859–878.
6. Third Conference of the Parties to the U.N. Framework on Climate Change, Kyoto, Japan, December 1–10, 1997.
7. Prather, M. J. and Logan, J. A., in *Twenty-Fifth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, 1994, pp. 1513–1527.
8. Woods, T. J. and Holtberg, P. D., "Long-Term Trends in U.S. Gas Supply and Prices," GRI report 97/0009, July 1997.
9. Miller, J. A. and Bowman, C. T., *Prog. Energy Combust. Sci.* 15:287–388 (1989).
10. Zeldovich, Ya. B., Sadovnikov, P. Ya., and Frank-Kamentskii, D. A., *Oxidation of Nitrogen in Combustion,* Academy of Sciences of the USSR, 1947.
11. Drake, M. C., Correa, S. M., Pitz, R. W., Fenimore, C. P., and Shyy, W., *Combust. Flame* 69:347–365 (1987).
12. Fenimore, C. P., in *Thirteenth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, 1971, pp. 373–380.
13. Malte, P. C. and Pratt, D. T., in *Fifteenth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, 1974, pp. 1061–1070.
14. Correa, S. M. and Smooke, M. D., in *Twenty-Third*

Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, 1990, pp. 289–295.
15. Drake, M. C. and Blint, R. J., *Combust. Flame* 76:151–167 (1989).
16. Leonard, G. L. and Correa, S. M., ASME/PD Vol. 30, (S. N. Singh, ed.), pp. 69–74, 1990.
17. Spoelstra, H., "N_2O Emissions from Combustion Processes," International Climate Change Research Conference, Maastricht, The Netherlands, December 6–9, 1994.
18. Feitelberg, A. S. and Correa, S. M., "The Role of Carbon Monoxide in NO_2 Plume Formation," GE report MR 4240-01-203, 1996.
19. Sano, T., *Combust. Sci. Technol.* 38:129–144 (1985).
20. Hori, M., Matsunaga, N., Malte, P. C., and Marinov, N. M., in *Twenty-Fourth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, 1992, pp. 909–916.
21. Koff, B. L., "Aircraft Gas-Turbine Emissions Challenge," *Symposium on the Aeroengine and the Environment,* Berlin, Germany, June 17, 1992.
22. Jackson, M. R., Ritter, A. M., Abuaf, N., Lacey, N., Lacey, M. A., Feitelberg, A. S., and Lang, P., ASME paper 96-GT-219, 1996.
23. Verdouw, A. J., Detroit Diesel Allison report EDR 9039, 1976.
24. Corman, J. C. and Paul, T. C., "Power Systems for the 21st Century: "H" Gas Turbine Combined Cycles," Power Gen. Europe '95, Amsterdam, The Netherlands, May 1995.
25. Richerson, D. W., *Mech. Eng.* p 80–83 (Sept. 1997).
26. Davis, L. B., ASME paper 96-GT-27, 1996.
27. Antos, R. J., "Westinghouse Combustion Development: 1996 Technology Update," Power Gen '95, Anaheim, CA, December 5–7, 1995.
28. Puri, R., Stansel, D. M., Smith, D. A., and Razdan, M. K., ASME paper 95-GT-406, 1995.
29. Rocha, G., Saadatmand, M., and Bolander, G., ASME paper 95-GT-411, 1995.
30. Snyder, T. S., Rosfjord, T. J., McVey, J. B., Hu, A. S., and Schlein, B. C., ASME paper 94-GT-234, 1994.
31. Bahlmann, F. C. and Visser, B. M., ASME paper 94-GT-405, 1994.
32. Etheridge, C. J., ASME paper 94-GT-255, 1994.
33. Mezzedimi, V., Bonciani, L., Ceccherini, G., and Modi, R., "Development of a Dry Low NO_x Combustion System," Canadian Gas Association Symposium on Industrial Application of Gas-Turbines, Banff, Canada, October 13–15, 1993.
34. Leonard, G. L. and Stegmaier, J., ASME paper 93-GT-288, 1993.
35. Semerjian, H. and Vranos, A., in *Sixteenth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, 1976, pp. 169–179.
36. Kandebo, S. W., *Aviation Week & Space Technology,* October 13, 1997, p. 74.
37. Plee, S. L. and Mellor, A. M., *Combust. Flame* 32:193–203 (1978).
38. Spadaccini, L. J. and Colket, M. B., *Prog. Energy Combust. Sci.* 20:431–460 (1994).
39. Correa, S. M. and Dean, A. J., in *Twenty-Fifth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, 1994, pp. 1293–1299.
40. Ciezki, H. K. and Adomeit, G., *Combust. Flame* 93:421–433 (1993).
41. Bowman, M. J., "Effect of Liquid Contaminants on the Autoignition of Natural Gas," in preparation, GE Class 1 report, 1998.
42. Rayleigh, Lord J. W. S., *The Theory of Sound,* Dover, New York, 1945.
43. Candel, S. M., in *Twenty-Fourth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, 1992, pp. 1277–1296.
44. McManus, K., Poinsot, T., and Candel, S., *Prog. Energy Combust. Sci.* 19:1–29 (1993).
45. Schadow, K., Yang, V., Culick, F., Rosfjord, T., Sturgess, G., and Zinn, B., AGARD report 820, September 1997.
46. Richards, G. A., Gemmen, R. S., and Yip, M. J., *Trans. ASME* 119:776–782 (1997).
47. Neumeier, Y., Nabi, A., Arbel, A., Vertzberger, M., and Zinn, B. T., *J. Prop. Power* 13(6):705–713 (1997).
48. Leipertz, A., Obertacke, R., and Wintrich, F., in *Twenty-Sixth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, 1996, pp. 2869–2876.
49. Hantschk, C., Herman, J., and Vortmeyer, D., in *Twenty-Sixth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, 1996, pp. 2835–2842.
50. Davis, N. T. and Samuelsen, G. S., in *Twenty-Sixth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, 1996, pp. 2819–2826.
51. Sivasegaram, S., Tsai, R. F., and Whitelaw, J. H., *Combust. Sci. Technol.* 105:67–83 (1995).
52. Brouwer, J., Ault, B. A., Bobrow, J. E., and Samuelsen, G. S., in *Twenty-Third Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, 1991, pp. 1087–1092.
53. Bloxsidge, G. J., Dowling, A. P., and Langhorne, P. J., *J. Fluid Mech.* 193:445–473 (1988).
54. Correa, S. M., *J. Prop. Power* 8(6):1144–1151 (1992).
55. Sontag, R. E. and Van Wylen, G. J., *Introduction to Thermodynamics: Classical and Statistical,* Wiley, New York, 1971.
56. Joos, F., Althaus, R., Brunner, P., Eroglu, A., Paikert, B., and Syed, K., Power Gen Asia '95, Singapore, September 27–29, 1995.
57. Waldherr, G. A. and Roos, M. R., "Reheat Combustion Simulations," GE-CRD MSL report, March 1996.
58. Pfefferle, L. D. and Pfefferle, W. C., *Cataly. Rev. Sci. Eng.* 29(2&3):219–267 (1987).
59. Dalla Betta, R. A., Schlatter, J. C., Chow, M., Yee, D. K., and Shoji, T., "Catalytic Combustion Technology to Achieve Ultra Low NO_x Emissions: Catalyst

Design and Performance Characteristics," *Second International Workshop on Catalytic Combustion,* Tokyo, Japan, April 18–20, 1994.
60. Cowell, L. H. and Larkin, M. P., ASME paper 94-GT-254, 1994.
61. Griffin, T., Weisenstein, W., Schlegel, A., Buser, S., Benz, P., Bockhorn, H., and Mauss, F., "Investigation of the NO_x Advantage of Catalytic Combustion," *Second International Workshop on Catalytic Combustion,* Tokyo, Japan, April 18–20, 1994.
62. Scherer, V. and Griffin, T., ASME paper 94-JPGC-GT-1, 1994.
63. Schlegel, A., Buser, S., Benz, P., Bockhorn, H., and Mauss, F., in *Twenty-Fifth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, 1994, pp. 1019–1026.
64. Schlatter, J. C., Dalla Betta, R. A., Nickolas, S. G., Cutrone, M. B., Beebe, K. W., and Tsuchiya, T., ASME paper 97-GT-57, 1997.
65. Correa, S. M., *Combust. Flame* 102:205–208 (1995).
66. Anson, D., "Gas Turbine Fuels from Coal and Biomass," *ASME Turbo Expo '97,* Orlando, FL, June 2–5, 1997.
67. Yan, J., Alvfors, P., Eidenstein, L., and Svedberg, G., *Mech. Eng.* 94–96 (October 1997).
68. Feitelberg, A. S. and Lacey, M. A., ASME paper 97-GT-127, 1997.
69. Benjamin, M. A. and Crocker, D. S., AIAA paper 96-3165, 1996.
70. Faeth, G. M., in *Twenty-Sixth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, 1996, pp. 1593–1612.
71. Givler, S. D. and Abraham, J., *Prog. Energy Combust. Sci.* 22:1–28 (1996).
72. Osgerby, I. T., *AIAA J.* 12:743–754 (1974).
73. Kennedy, I. M., *Prog. Energy Combust. Sci.* 23:95–132 (1997).
74. Fairweather, M., Jones, W. P., Ledin, H. S., and Linstedt, R. P., in *Twenty-Fourth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, 1992, pp. 1067–1074.
75. Hazlett, R. N., "Thermal Oxidation Stability of Aviation Turbine Fuels," ASTM Monograph 1, 1991.
76. Brandauer, M., Schulz, A., and Wittig, S., ASME paper 95-GT-49, 1995.
77. Dean, A. J., Bradt, J. E., and Ackerman, J. F., ASME paper 96-GT-46, 1996.
78. Clark, J. S. and DeCorso, S. M., eds., "Stationary Gas-Turbine Alternative Fuels," American Society for Testing and Materials, Special Technical Publication 809, 1983.
79. Freeman, A. and Kaufman, E., "Considerations When Burning Ash-Bearing Fuels in Heavy-Duty Gas-Turbines," GE Power Systems report 3764, Schenectady, NY, May 1993.
80. Johnson, K. W., ASME paper 96-GT-7, 1996.
81. Bilger, R. W., *Combust. Sci. Technol.* 98:223–228 (1994).
82. Correa, S. M., *Comp. Sys. Eng.* 5(2):135–145 (1994).
83. Kobayashi, H., Tamura, T., Maruta, K., Nioka, T., and Williams, F. A., in *Twenty-Sixth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, 1996, pp. 389–396.
84. Peters, N., in *Twenty-First Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, 1986, pp. 1231–1250.
85. Bilger, R. W., in *Twenty-Second Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, 1988, pp. 475–488.
86. Gulati, A., *J. Prop. Power* 10:169–175 (1994).
87. Wolfrum, J., "Lasers in Combustion: Diagnostics and Control," Hottel Lecture, in *Twenty-Seventh (International) Symposium on Combustion,* Boulder, CO, August 2–7, 1998.
88. Dimotakis, P. E., "Turbulent Shear Layer Mixing with Fast Chemical Reactions," GALCIT report FM87-1, 1987.
89. Barlow, R. S., Fiechtner, G. J., and Chen, J.-Y., in *Twenty-Sixth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, 1996, pp. 2199–2206.
90. Nandula, S. P., Pitz, R. W., Barlow, R. S., and Fiechtner, G. J., AIAA paper 96-0937, 1996.
91. Masri, A. R., Dibble, R. W., and Barlow, R. S., *Prog. Energy Combust. Sci.* 22:307–362 (1996).
92. Bilger, R. W., Yip, B., Long, M. B., and Masri, A. R., *Combust. Sci. Technol.* 72:137–155 (1990).
93. Bachalo, W. D., in *Twenty-Fifth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, 1994, pp. 333–344.
94. Zhu, J. Y., Tsuruda, T., Sowa, W., and Samuelsen, G. S., *J. Eng. Gas-Turbines Power* 115:515–521 (1993).
95. Rizk, N. K. and Mongia, H. C., *J. Eng. Gas-Turbines Power* 115:612–619 (1993).
96. Mongia, H. C., Reynolds, R. S., Bruce, T. W., and Coleman, E., "Combustor Design Criteria Validation," USARTL-TR-78-55, 1979.
97. Correa, S. M. and Shyy, W., *Prog. Energy Combust. Sci.* 13(5):249–292 (1987).
98. Tolpadi, A. K., Correa, S. M., Burrus, D. L., and Mongia, H. C., *J. Prop. Power* 13:218–225 (1997).
99. Pope, S. B., *Prog. Energy Combust. Sci.* 11:119–192 (1985).
100. Pope, S. B., in *Twenty-Third Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, 1990, pp. 591–612.
101. M. D. Smooke, ed., "Reduced Kinetic Mechanisms and Asymptotic Approximations for Methane-Air Flames," Springer-Verlag, Berlin, 1990.
102. N. Peters and B. Rogg, eds., "Reduced Kinetic Mechanisms for Applications in Combustion Systems," Springer-Verlag, Berlin, 1993.
103. Lockwood, F. C. and Shah, N. G., in *Eighteenth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, 1981, pp. 1405–1414.
104. Magnussen, B. F., Hjertager, B. H., Olsen, J. G., and

Bhaduri, D., in *Seventeenth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, 1978, pp. 1383–1393.

105. Hu, I. Z. and Correa, S. M., in *Twenty-Sixth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, 1996, pp. 307–313.
106. Pope, S. B., *Combust. Theory Mod.* 1:41–63 (1997).
107. Fischberg, C. J., Rhie, C. M., Zacharias, R. M., Bradley, P. C., and DesSurealt, T. M., "Using Hundreds of Workstations for Production Running of Parallel CFD Applications," Parallel CFD '95, Pasadena, CA, June 1995.
108. Najm, H. M. and Ghoniem, A. F., *Combust. Sci. Technol.* 94:259–278 (1993).
109. McMurtry, P. A., Menon, S., and Kerstein, A., in *Twenty-Fourth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, 1992, pp. 271–278.
110. Ashley, S., *Mech. Eng.* 78–81 (October 1997).
111. Scott, W. G., *Power Eng.* 46–50 (September 1997).
112. Vakil, H. B., "Thermodynamics Analysis of Gas-Turbine Cycles with Chemical Analysis," Second World Congress of Chemical Engineering, Montreal, Canada, October 4–9, 1981.

COMMENTS

Ann Karagozian, University of California–Los Angeles, USA. Would you comment on the effects that restrictions recommended by the recent Kyoto Conference on CO_2 emissions might have on future developments in gas turbine engines, both for stationary power plants and aeropropulsion systems?

Author's Reply. Concerns regarding the effect of carbon dioxide on global warming will affect the development of gas turbines, but the levels and timing of regulations are not clear at present.

a. By virtue of having the highest available thermal efficiency (in combined-cycle mode), power-generation gas-turbines offer the most energy per unit mass of CO_2 when compared with other viable large-scale power plants (except nuclear power). In the short term, the focus will be on incremental efficiency gains by means of higher pressure ratios and higher rotor inlet temperatures. In the longer term, (1) hydrocarbon fuels such as natural gas may be reformed to hydrogen and CO_2, with the hydrogen being consumed in the gas turbine and the CO_2 being sequestered for purposes such as reinjection in gas wells, and (2) hydrogen may be developed from non-fossil sources. Combustion and turbine material technologies would have to be developed for these fuels. Smaller power-generation gas turbines may be reoptimized for biomass or for integration with fuel cells as topping cycles.
b. The options are relatively limited in the aeropropulsion segment. Trends to higher cycle efficiency will continue, requiring higher pressure ratios and rotor inlet temperatures in the core gas turbine as well as developments in the fan and compressor systems. Fuel options that emerge for stationary gas turbines may not be feasible for aeropropulsion. For example, it is not presently possible to envision commercially viable hydrogen-powered aircraft or airborne CO_2 sequestration technologies.

•

Alessandro Gomez, Yale University, USA. In the design and optimization of the combustor of gas turbines, both experimental work and numerical modeling play an important and complimentary role. Clearly, in the not too distant past, the process was largely empirical, and CFD played no role. How different is the situation nowadays? Could you perhaps justify (man-hour or similar other parameters) the relative importance of experimental activity and numerical modeling?

Author's Reply. Computational Fluid Dynamics (CFD) plays an important role in the conceptual design phase of a gas-turbine combustor, particularly in the case of a new design. As the design process progresses, CFD is useful for refining mean temperature fields and thermal NO_x but not (as yet) other emissions, extinction limits, or the amplitude of pressure oscillations. Costly and time-consuming tests at full scale and full pressure are still required. CFD of wider scope would enhance productivity.