Kirk-Othmer Encyclopedia of Chemical Technology.

AVIATION AND OTHER GAS TURBINE FUELS

The gas turbine power plant which has revolutionized aviation derives basically from the steam turbine adapted to a different working fluid. The difference is crucial with respect to fuel because steam can be generated by any heat source, whereas the gas turbine requires a fuel that efficiently produces a very hot gas stream and is also compatible with the turbine itself. The hot gas stream results from converting chemical energy in fuel directly and continuously by combustion in compressed air. It is expanded in a turbine to produce useful work in the form of jet thrust or shaft power.

The jet engine combines three basic steps (Fig. 1). Air is compressed in a series of stages, fuel is burned continuously and intensively in the compressed air, and the hot gas is then expanded through a turbine which extracts energy to run the compressor and the fan, and also to provide shaft power. The residual exhaust mixes with fan air and exits through a nozzle as a high velocity jet which provides forward thrust to the system. Whittle is credited with the vision in his 1930 patent to adapt the gas turbine concept to aircraft. He realized that at high speed and altitude this type of engine improved in efficiency and made jet propulsion competitive with propeller drive (1). His W-1 engine of 1937 has since proliferated into much more efficient aircraft power plants ranging in size from small auxiliary power units to the giant turbofans which propel wide-bodied airliners. In its most advanced form, the aviation gas turbine for supersonic aircraft, a second combustion step is added to the three basic steps of compression, combustion, and turbine work extraction. Additional fuel is burned in the turbine exhaust to increase the velocity of the jet from the nozzle and to gain more thrust.

The first application of the gas turbine principle to a ground system was in 1906 when waste heat from furnace gases was used to operate a turboblower which compressed air for a blast furnace. Developments in metallurgy and compressor design after World War I led, in 1937, to the first industrial gas turbine for generating electrical power (2). These developments also produced successful turbocompressors for increasing the air supply and power output of aircraft piston engines, a vital advantage for miliary aircraft during World War II.

Ground turbines carry out the same three basic steps of the jet engine, but residual energy of the turbine exhaust is extracted by a waste heat boiler or regenerator. Industrial turbines have heavy compressors, external combustion systems, and massive turbine sections. Lightweight design for aircraft required new high temperature metals and advanced concepts for cooling, compression, and combustion. Today these lightweight types have been adapted for many ground applications in gas compression, pumping, electrical power generation, and general-purpose utility units. Because the gas turbine is fundamentally a heat-conversion device, the combustor or gas generator is the heart of the engine. Combustion of fuel with a portion of compressed air is continuous. Early developers of gas turbines depended on the experience with oil-fired furnaces to design fuel nozzles and combustion chambers (3).

The first fuels burned in a turbine combustor were petroleum liquids, kerosene in Whittle's prototype jet engine and diesel fuel in the Brown-Boveri industrial turbine, selected because of their availability and convenience. After 50 years of experience the gas turbine has been adapted to a wide variety of combustible gases and liquids, including crude oil (4). Although such a wide-ranging appetite for fuels capable of releasing

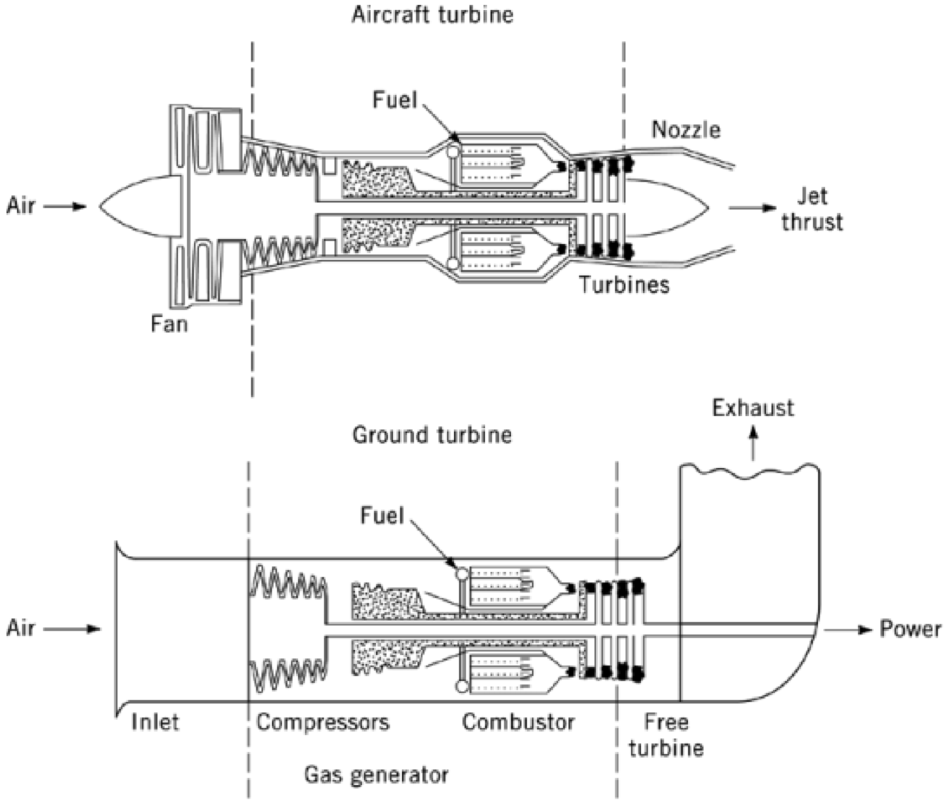

Fig. 1. Schematic of aircraft and ground gas turbines.

heat energy would appear to classify the gas turbine as fuel-insensitive, clearly defined limits on fuel properties have developed during a half century to optimize its performance. When gas turbine applications are classified according to fuels, as in Table 1, the aircraft propulsion unit is the most demanding, accepting only certain liquid distillates; the industrial turbines (low inlet temperatures) are the least demanding. For ground turbines a wide range of gases and liquids are suitable, although advanced units with turbine inlet temperature above 650°C are limited in accepting residual fuel components (2).

The special requirements of gas turbine fuels that have developed relate to the individual processes that take place in the engine itself and in the support systems for handling fuels. It is evident that aviation gas turbines place more severe demands on liquid fuels than ground turbines do, and that gaseous fuels are much easier to utilize since they only need to supply heat energy. Whittle chose a kerosene for turbine research in order to conserve gasoline for the impending war effort and because it had better low temperature properties than a diesel fuel. This decision tended to establish a dividing line between air and ground turbines; subsequent developments led to lighter fuels for jet engines and heavier fuels for industrial turbines. Aircraft have continued to fly on kerosene fuel or on a wide-cut blend of heavy naphtha and kerosene. Supersonic transports and advanced military vehicles are also operated on kerosene fuel. Most ground turbines utilize liquid fuel systems based on standard No. 2 diesel or on home burner fuel.

Table 1. Fuels Used in Gas Turbine Applications

		Ground power		
Fuel	Aircraft propulsion	Aircraft type	Advanced industrial	Heavy duty
hydrogen	[a]	X	X	
methane (natural gas)	[a]	X	X	
synthetic gas		X	X	
LPG		X	X	
light naphtha		X	X	
methanol (ie, nonhydrocarbons)		X	X	
gasoline	[b]			
wide-cut fuel	X	X	X	
kerosene	X	X	X	
No. 2 fuel oil (diesel)		X	X	X
other gas oils		X	X	X
residual fuel			[c]	X
crude oil				X

[a] Future application as cryogenic liquid

[b] Emergency fuel only.

[c] Limited by metal content of fuels.

1. Gas Turbine Products

1.1. Composition

Because the jet aircraft is a weight-limited vehicle, a high premium is assigned to hydrocarbon fuels with a maximum gravimetric heat content or hydrogen-to-carbon ratio. Paraffinic fuels have high mass-heat contents (about 45 MJ/kg or 10,800 kcal/kg) which decrease very slowly as chain length (mol wt) increases. However, because the density of these fuels is low the heat content on a volumetric basis is less than that of nonparaffinic fuels. Since fuels are measured and sold on a volumetric basis, the aircraft user obtains less energy for each cubic meter of the preferred paraffinic fuel but more energy per unit of mass. Ground turbine users are not concerned with weight limitations and instead seek maximum energy per unit of cost, which means that heavier fuels are more economical for ground application. Fuel properties are largely determined by the nature of the crude oil from which they are derived. This is illustrated by the typical density-paraffin content curve for the kerosene fractions (150–288°C) of different crudes (Fig. 2). Aromatics in this cut are of special concern because of their effects on combustion and elastomers. The mass spectrometric data in Table 2 illustrate that a wide range of single and multiring aromatics is possible even within a total aromatic concentration of 25%, the maximum permitted by most specifications.

1.2. Specifications

The global nature of jet aircraft operations has mandated that aviation fuel quality be closely controlled in every part of the world. Specifications tend to be industry standards issued by a consensus organization, like ASTM, or by a government body rather than by manufacturer's requirements. Table 3 lists some of the requirements for the principal grades of civil and military aviation turbine fuels in use throughout the world. Domestic and international airlines use fuel modeled on ASTM specification grades. Specifications issued by the British Ministry of Defense, the recommendations of the International Air Transport Association, and ASTM specifications are coordinated as a joint system checklist to control quality at many worldwide airports where jointly-operated fueling systems prevail. Specifications issued by Eastern European governments are

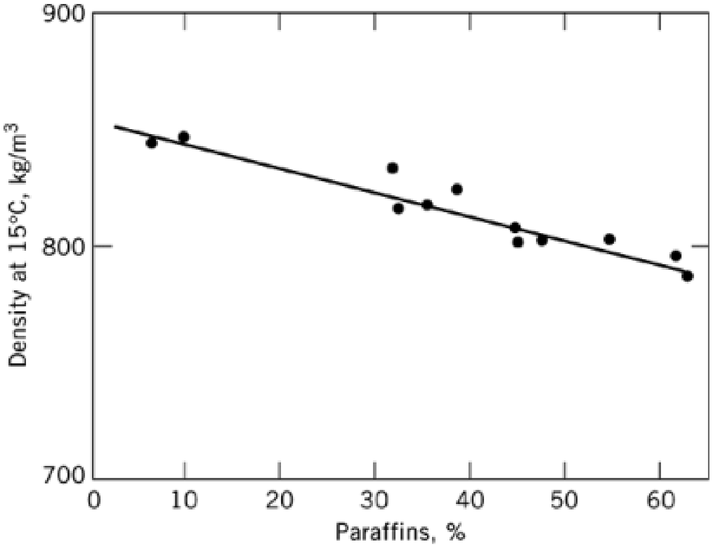

Fig. 2. Density vs paraffin content of gas turbine fuels (150–288°C fractions).

Table 2. Composition[a] of 150–288°C Kerosenes

Crude source	Middle East			North Africa	United States			South America				
saturates, wt %	78.8	82.4	80.3	83.1	85.5	81.0	76.8	81.7	78.8	76.8	76.1	74.5
paraffins	63.0	61.7	54.0	47.4	44.4	37.9	35.3	44.0	34.9	31.3	9.0	6.0
cycloparaffins, single ring	10.6	12.0	14.5	23.8	24.1	22.9	27.3	26.9	27.3	29.0	33.3	31.7
cycloparaffins, two-rings	4.7	7.6	8.7	9.8	12.0	17.9	11.3	9.6	12.8	12.6	24.9	28.1
cycloparaffins, 2 + rings	0.9	1.1	3.2	3.1	5.0	2.3	2.9	1.2	3.8	3.9	8.9	8.7
aromatics, wt %	18.4	16.3	18.2	14.7	14.0	17.7	21.9	17.0	19.9	22.0	23.7	25.5
single-ring	16.9	14.1	14.8	11.3	11.8	13.9	19.0	15.1	14.8	16.6	16.4	16.8
two-rings	1.4	2.0	3.0	3.2	2.1		2.6	1.9	4.7	5.1	3.6	7.7
2 + rings	0.1	0.1	0.2	0.2	0.1	3.8	0.3		0.5	0.4	0.7	1.0

[a] By mass spectrometric analysis.

similar to other world aircraft fuels but are not identical in all respects. International airlines that fly to Eastern European countries can utilize both types of fuels without difficulty. Except for severe arctic areas where Jet B fuel is used, essentially all civil aviation uses kerosene fuel. About half of the demand is Jet A fuel marketed in the United States, and half is Jet A1, the international fuel marketed outside the United States, similar to Jet A except for freezing point. A lower temperature limit of $-47°C$ for the (wax) freezing point of Jet A1 is required for long-duration international flights. The same fuel is labeled JP-8 by the U.S. Air Force and is used at most bases outside the United States to replace JP-4, the wide-cut fuel originally developed after World War II to ensure maximum availability. JP-4 is still the primary U.S. Air Force fuel used at bases and at certain NATO installations. The other military fuel of importance is JP-5, the high flash point kerosene used by the U.S. Navy to ensure handling safety aboard aircraft carriers. Although all three military fuels are used in supersonic aircraft, a special kerosene fuel called JP-7 developed for the Mach 3 SR-71 reconnaissance aircraft has been retired from service, like the SR-71 itself.

Liquid fuels for ground-based gas turbines are best defined today by ASTM Specification D2880. Table 4 lists the detailed requirements for five grades which cover the volatility range from naphtha to residual fuel.

Table 3. Selected Specification Properties of Civil and Military Aviation Gas Turbine Fuels

		ASTM D1655[a]		Mil-T-5624-N[a]		Mil-T-83133C[a]
Characteristic		Jet A kerosene A/L and	Jet B wide-cut Gen Avn	JP-4 wide-cut USAF	JP-5 kerosene USN	JP-8 kerosene USAF
composition						
aromatics, vol % max		25[b]	25[b]	25	25	25
sulfur, wt % max		0.3	0.3	0.4	0.4	0.3
volatility						
dist. ‖	10% rec'd	205			205	205
temp	50% rec'd		190	190		
max °C						
	end pt	300		270	300	300
flash pt, °C min		38			60	38
vapor pressure at 38°C, kPa max (psi)			21 (3)	14–21 (2–3)		
density at 15°C, kg/m^3		775–840	751–802	751–802	788–845	775–840
fluidity						
freezing pt, °C max		−40[c]	−50	−58	−46	−47
viscosity at −20°C, mm^2/s (=cSt) max		8.0			8.5	8.0
combustion						
heat content, MJ/kg, min[d]		42.8	42.8	42.8	42.6	42.8
smoke pt, mm, min		18[e]	18[e]	20	19	19
H_2 content, wt % min				13.5	13.4	13.4
stability						
test temp[f], °C min		245	245	260	260	260

[a] Full specification requires other tests.
[b] For aromatics above 20% (22% for Jet A1) users must be notified.
[c] International airlines use Jet A1 with −47°C freeze point.
[d] To convert MJ to kcal, multiply by 239.
[e] Plus naphthalenes 3 vol % max unless smoke point exceeds 25.
[f] Thermal stability test by D3241 to meet 3.3 kPa (25 mm Hg) pressure drop and Code 3 Deposit Rating.

The grades differ primarily in basic properties related to volatility; eg, distillation, flash point, and density of No. 1 GT and No. 2 GT fuels correspond to similar properties of kerosene and diesel fuel respectively. These properties are not limited for No. 0 GT fuel, which allows naphthas and wide-cut distillates. For heavier fuels, No. 3 GT and No. 4 GT, the properties that must be limited are viscosity and trace metals.

1.3. Manufacture

Aviation turbine fuels are primarily blended from straight-run distillates rather than cracked stocks because of specification limitations on olefins and aromatics. However, in refineries where heavy gas oil is hydrocracked, ie, a process that involves catalytic cracking in a hydrogen atmosphere, aviation fuels can include hydrocracked components since they are free of olefins, are low in sulfur, and are stable. Hydrocracking provides a means to extend availability of gasolines and distillates by converting most of the heavy ends in crudes to lighter products. Ground turbine fuels are equivalent to their fuel oil counterparts and are manufactured as dual-purpose products. No. 0 GT fuel is a light naphtha, the closest aviation counterpart of which is JP-4. No. 1 GT fuel is kerosene blended to Jet A or A1 quality and sold as dual-purpose kerosene (DPK). No. 2 GT corresponds to No. 2 diesel fuel or No. 2 heating oil and is usually blended from straight-run and cracked components since olefins and aromatics are not limiting. No. 3 GT and No. 4 GT fuels bracket the viscosity range of No. 4, 5, and 6 fuels and No. 4D diesel and are blended from gas, oils, and residua from pipestills and vacuum units with

Table 4. Specifications for Ground Gas Turbine Fuels

Property	0-GT[a] Naphtha	1-GT[a] Light distillate	2-GT[a] Medium distillate	3-GT[a] Heavy distillate	4-GT Heavy residual
90% distillation, °C		288 max	282–338		
density, kg/m^3, min		850	876		
flash pt, °C max		38	38	55	66
pour pt, °C max		−18	−6		
carbon residue, % max	0.15	0.15	0.35		
ash, wt % max	0.01	0.01	0.01	0.03	
viscosity at 40°C, mm^2/s (=cSt)		1.3–2.4	1.9–4.1		
viscosity at 50°C, mm^2/s (=cSt) max				638	638
water and sediment, vol % max	0.05	0.05	0.05	1.0	1.0

[a] Trace metal limits at point of delivery are established at 0.5 ppm by wt maximum for vanadium, sodium and potassium, calcium, and lead.

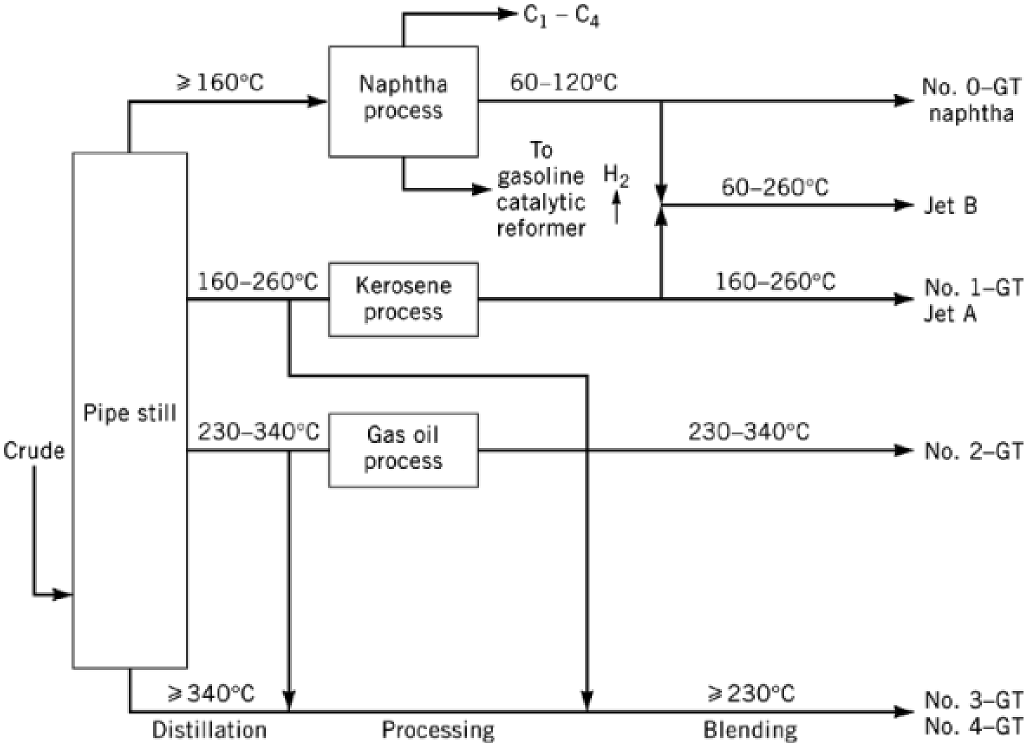

Fig. 3. Refinery process for gas turbine fuels. Processing may include hydrogen treating.

lighter distillates. A schematic of a typical refinery processing sequence appears in Figure 3. In this example the basic processes after distillation are catalytic reforming for gasoline and hydrogen processing of naphtha, kerosene, and gas oil using the hydrogen from reforming. A hydrocracking unit usually requires a separate source of hydrogen. The approximate boiling ranges of the sidestream cuts and of the finished gas turbine fuels are shown.

The distillation cut points must be closely controlled to yield a product that meets the requirements of flash point on one hand and freezing point on the other. In practical terms, a jet fuel requires a fraction of about

60°C initial boiling point and a final boiling point not exceeding 300°C. The lighter portion of this fraction contains gasoline components and meets the specification for JP-4. The heavier portion above 160°C must be tailored to either the Jet A or Jet A1 freezing point, but the final boiling point is dependent on crude composition. With higher aromatic crudes, undercutting is required to meet compositional limits or a test such as smoke point. Lower boiling components compensate for aromatic or freezing point limitations, but sometimes it is impossible to take advantage of them because a dual-purpose kerosene usually requires a higher flash point than jet fuel. The distilled fractions from the crude are apt to contain mercaptans or organic acids in excess of specification limits. A caustic wash is normally used to control acidity and to remove traces of hydrogen sulfide. Removal or conversion of odorous mercaptans is carried out in a sweetening process. The most widely used chemical treatment today, Merox sweetening, utilizes dissolved air to oxidize mercaptans to disulfides over a fixed-bed cobalt chelate catalyst (5). It has the advantage of simplicity and minimum waste disposal problems but does not lower the sulfur content. A modern version of the old doctor process, Bender sweetening, uses lead plumbite deposited on a fixed bed to carry out the mercaptan oxidation and the spent doctor regeneration processes simultaneously, but product quality is more difficult to control, and waste disposal problems are greater.

Most of the crudes available in greatest quantity today are high in sulfur, and yield products that must be desulfurized to meet specifications or environmental standards. The process most widely used is mild catalytic hydrogenation. Hydrofining uses a fixed-bed catalyst, usually cobalt molybdate on alumina, to convert all but ring sulfur compounds to H_2S, which is then removed (and recovered) from recycled gas. At reactor temperatures below 300°C only mercaptans react. This technique is called hydrosweetening. At reactor temperatures of 400–500°C extents of desulfurization are 80% or better and other reactive species, including some multiring sulfur compounds, are hydrogenated. The product of the hydrofiner is caustic washed to remove traces of dissolved H_2S and is then passed through sand or clay to blend tanks.

Hydrogen treating removes oxygen-containing species, such as phenols and naphthenic acids, that are found in some crudes. The former tend to perform as natural inhibitors of hydrocarbon oxidation by trapping peroxy radicals, while the latter act as natural lubricating agents. Recognition of this side effect of hydrogen treatment led refiners to add antioxidants to hydrotreated components; this procedure is now a specification requirement. Blending of two or more components is carried out to match as closely as practical the various specification constraints. At this point, additives are usually introduced, eg, an antioxidant to inhibit gum formation in storage or a metal deactivator to deactivate any dissolved metal ions (Table 5). Military fuels have made the addition of antiicing agents and corrosion inhibitors mandatory, the former because military aircraft fuel systems do not include fuel filter heaters to prevent ice formation, and the latter to reduce the tendency of fuels to pick up rust particles from pipelines and tanks. The Air Force also requires that antistatic additive be included in JP-4 to reduce the hazard of static generation and discharge in handling fuel and in operating aircraft with foam-filled tanks. It was discovered that the antiicing additives inhibit growth of microorganisms in aircraft and storage tanks and that certain corrosion inhibitors are excellent lubricity agents for prolonging the life of engine pumps.

With civil fuels, antiicing agents are not required since air transports are equipped with fuel-filter heaters to prevent ice formation. Corrosion inhibitors are not normally used in civil fuels since they tend to degrade the efficiency of filter-coalescers and would be removed in the clay filters that are commonly installed at receiving terminals and airports. However, antistatic additives are widely used in civil fuels, particularly Jet A1 at international airports. Antistatic additive is introduced into some Jet A to safeguard against static discharge in truck filling, but the widespread use of clay filters in the United States to clean up fuel before airport delivery makes refinery addition impractical. Table 5 also lists a boron-containing biocide used as a shock treatment additive to inhibit the tendency of organisms to form fungal mats in aircraft fuel tanks.

Table 5. Additives Used in Aviation Gas Turbine Fuels

Class of additive[a]	Chemical types	Purpose	Specification status[b] Civil	Military
antioxidant	alkyl phenylene diamines, hindered alkylphenols	improve oxidation stability–storage and high temperature	O	O
metal deactivator	disalicylidene alkyl diamine	remove metal ions that catalyze oxidation	O	O
antiicing	glycol ether	prevent low temperature filter icing		R
corrosion inhibitor	dimer acid, phosphate ester	reduce development of corrosion products, improve lubrication		R
antistatic	alkyl chromium salt and calcium sulfosuccinate, olefin–sulfur dioxides and polyamines	increase conductivity	OR	R
biocide	boron ester	inhibit organic growth in fuel tanks	A	

[a] See also Antioxidants; Antifreezes and deicing fluids; Antistatic agents; Corrosion and corrosion inhibitors; Industrial antimicrobial agents.

[b] O = optional, R = required, A = airline use in maintenance.

1.4. Distribution and Handling

Preserving the quality of gas turbine fuels between the refinery and the point of use is an important but difficult task. The difficulty arises because of the complicated distribution systems of multiproduct pipelines which move fuel and sometimes introduce contaminants. The importance is reflected by the sensitivity of gas turbine engines and fuel systems to water, corrosion products, metal salts, microorganisms, and other extraneous materials that can be introduced by the distribution system. Most products moved through pipelines contain additives (eg, detergents, deicers, antifouling dispersants, and rust inhibitors). Gasoline contains corrosion inhibitors, heating oil contains dispersants, and diesel fuel contains ignition promotors. Traces of these additives left on pipeline walls are picked up by nonadditive jet fuel, which makes it difficult for pipeline operators to deliver gas turbine fuel of the same quality as that introduced to the line.

The principal means of removing contaminants are tank settling and filtration. With aviation fuels it is common practice to install several stages of cartridge-type filter-coalescers between the storage tank and the aircraft delivery point. Figure 4 is a schematic of a typical airport fueling system which transfers fuel by underground hydrant lines. Filter elements of fiberglass covered with synthetic fabric are designed to coalesce water and to remove particulates at high flow rates. A hydrophobic barrier filter prevents coalesced water from passing with the fuel.

Tank settling as a means of contaminant removal is not very efficient with fuels having the viscosity of kerosene. It is common practice to design tanks with cone-down drains and floating suctions to facilitate water and solids removal.

Contamination control by filtration would be relatively easy if it were not for surface-active materials produced during fuel manufacture or picked up in distribution systems from pipe walls and tank bottoms. These surfactants stabilize water-in-oil emulsions, disarm filter elements, coat solid particles, and promote growth of organisms at fuel–water interfaces. When they reach the aircraft tanks, the surfactants tend to trap water containing dissolved salts and particulates, causing fungal growths, coating attack, and metal corrosion.

Gas turbine fuels can contain natural surfactants if the crude fraction is high in organic acids, eg, naphthenic (cycloparaffinic) acids of 200–400 mol wt. These acids readily form salts that are water-soluble and surface-active. Older treating processes for sulfur removal can leave sulfonate residues which are even more powerful surfactants. Refineries have installed processes for surfactant removal. Clay beds to adsorb these trace materials are widely used, and salt towers to reduce water levels also remove water-soluble surfactants.

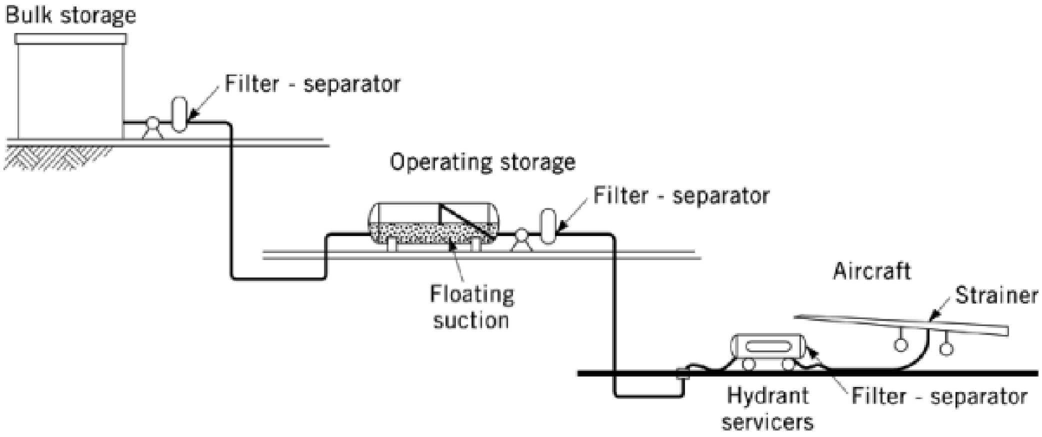

Fig. 4. Typical airport hydrant system.

In the field, clay filters designed as cartridges mounted in vertical vessels are also used extensively to remove surfactants picked up in fuel pipelines, in contaminated tankers, or in barges.

Specifications for gas turbine fuels prescribe test limits that must be met by the refiner who manufactures fuel; however, it is customary for fuel users to define quality control limits for fuel at the point of delivery or of custody transfer. These limits must be met by third parties who distribute and handle fuels on or near the airport. Tests on receipt at airport depots include appearance, distillation, flash point (or vapor pressure), density, freezing point, smoke point, corrosion, existing gum, water reaction, and water separation. Tests on delivery to the aircraft include appearance, particulates, membrane color, free water, and electrical conductivity.

The extensive processing and cleanup steps carried out on gas turbine fuels produce a purified liquid dielectric of high resistivity which is capable of retaining electrical charges long enough for buildup of large surface voltages. Because fuel is filtered at high flow rates through filter media of extensive surface area, the ionic species that adsorb on the filter surface generate a static charge. The current carried by fuel increases sharply as fuel flows through a filter and then decreases at a rate determined by the fuel conductivity. The charge remaining in the fuel at any given point is determined by the residence time available for charges to recombine. In a hose delivering fuel to an aircraft, only a few seconds are available for charge relaxation. The result is a possible hazard—a tank filled with charged fuel that under some circumstances can discharge its energy to ground in a spark capable of igniting fuel mists or vapors (6).

This aspect of fuel handling has received much attention because of a number of accidents that have resulted in tank explosions, most often in filling tank trucks but also in fueling aircraft. Several approaches have been taken to reduce the risk of static discharge. The most common method requires introduction of an additive to increase the electrical conductivity of the fuel, ie, to speed up charge relaxation to a fraction of a second. Charge generation can be decreased by using low charging screens instead of filters or by reducing flow rates. The conductivity additives used in fuel are readily removed in clay filters or are lost in pipeline movement and must be monitored by conductivity tests. The additives can also degrade water separation properties and lower filter efficiency. Nevertheless, the safety record since antistatic additives were introduced far outweighs the negative effects on other fuel properties.

Table 6. Net Heat Content of Gas Turbine Fuels

Fuel	Heat content, MJ/kg[a]
hydrogen	120
natural gas (methane)	50
light naphtha (0-GT)	44
wide-cut fuel (JP-4)	43
Jet A kerosene (1-GT)	43
No. 2-GT fuel	42
No. 3-GT fuel	41
No. 4-GT fuel	40
methanol	20

[a] To convert MJ to kcal, multiply by 239.

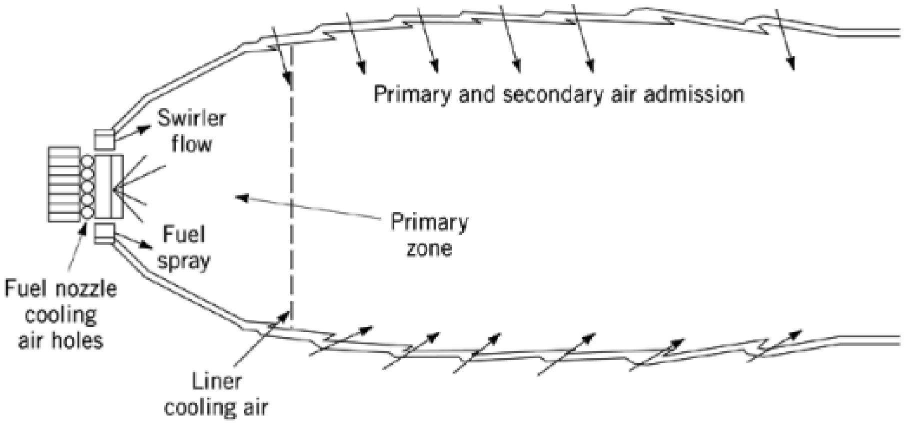

Fig. 5. Gas turbine combustion chamber.

2. Performance

2.1. Combustion

The primary reaction carried out in the gas turbine combustion chamber is oxidation of a fuel to release its heat content at constant pressure. Atomized fuel mixed with enough air to form a close-to-stoichiometric mixture is continuously fed into a primary zone. There its heat of formation is released at flame temperatures determined by the pressure. The heat content of the fuel is therefore a primary measure of the attainable efficiency of the overall system in terms of fuel consumed per unit of work output. Table 6 lists the net heat content of a number of typical gas turbine fuels. Net rather than gross heat content is a more significant measure because heat of vaporization of the water formed in combustion cannot be recovered in aircraft exhaust. The most desirable gas turbine fuels for use in aircraft, after hydrogen, are hydrocarbons. Fuels that are liquid at normal atmospheric pressure and temperature are the most practical and widely used aircraft fuels; kerosene, with a distillation range from 150 to 300°C, is the best compromise to combine maximum mass–heat content with other desirable properties. For ground turbines, a wide variety of gaseous and heavy fuels are acceptable.

Liquid fuel is injected through a pressure-atomizing or an air-blast nozzle. This spray is sheared by air streams into laminae and droplets that vaporize and burn. Because the atomization process is so important for subsequent mixing and burning, fuel-injector design is as critical as fuel properties. Figure 5 is a schematic of the processes occurring in a typical combustor.

Droplet size, particularly at high velocities, is controlled primarily by the relative velocity between liquid and air and in part by fuel viscosity and density (7). Surface tension has a minor effect. Minimum droplet size is achieved when the nozzle is designed to provide maximum physical contact between air and fuel. Hence primary air is introduced within the nozzle to provide both swirl and shearing forces. Vaporization time is characteristically related to the square of droplet diameter and is inversely proportional to pressure drop across the atomizer (7).

The vapor cloud of evaporated droplets burns like a diffusion flame in the turbulent state rather than as individual droplets. In the core of the spray, where droplets are evaporating, a rich mixture exists and soot formation occurs. Surrounding this core is a rich mixture zone where CO production is high and a flame front exists. Air entrainment completes the combustion, oxidizing CO to CO_2 and burning the soot. Soot burnup releases radiant energy and controls flame emissivity. The relatively slow rate of soot burning compared with the rate of oxidation of CO and unburned hydrocarbons leads to smoke formation. This model of a diffusion-controlled primary flame zone makes it possible to relate fuel chemistry to the behavior of fuels in combustors (7).

Aromatics readily form soot in the fuel-rich spray core as their hydrogens are stripped, leaving a carbon-rich benzenoid structure to condense into large molecular aggregates. Multi-ring aromatics form soot more readily than single-ring aromatics, and they exhibit greater smoking tendency and greater flame luminosity. At the other extreme, *n*-paraffins undergo little cyclization in the fuel-rich spray core, holding soot formation and flame radiation to a minimum. Other hydrocarbon structures exhibit smoke and radiation characteristics between the extremes of multiring aromatics and *n*-paraffins as illustrated by Figure 6, which shows the Luminometer number (LN) ratings of different types of hydrocarbons (8). High LN numbers are synonymous with minimum flame radiation and clean (soot-free) combustion. In mixed fuels, two-ring aromatics have been shown to have a tenfold greater effect in lowering LN rating than single-ring aromatics (9). Luminous flames in a gas turbine raise temperatures of the metal in the combustor liner and turbine inlet by the direct transmission by radiation of the heat energy in the flame core.

Air in the gas turbine combustor is carefully divided between primary and secondary uses. Primary air promotes the atomization process by adding swirl to the fuel exiting the nozzle; it must be limited to ensure that the flame core remains fuel-rich to avoid flame blow-out and to facilitate reignition. Most of the air in the gas turbine combustor is directed either toward secondary reactions beyond the primary flame core or toward dilution of the hot exhaust products so that a uniform temperature gas is presented to the turbine section. The secondary reactions involve intensely turbulent mixing under stoichiometric or fuel-lean mixtures to complete the combustion to CO_2 and burn up the soot particles formed in the fuel-rich core. A combustor design that causes proper mixing is critical for ensuring smoke-free exhaust products. Nevertheless, in any given combustor there is a relationship between smoke output and the hydrogen content of fuel, eg, as shown in Figure 7 (10).

A gas turbine used in aircraft must be capable of handling a wide span of fuel and air flows because the thrust output, or pressure, covers the range from idle to full-powered takeoff. To accommodate this degree of flexibility in the combustor, fuel nozzles are usually designed with two streams (primary and secondary flow) or with alternate rows of nozzles that turn on only when secondary flow (or full thrust power) is needed. It is more difficult to vary the air streams to match the different fuel flows and, as a consequence, a combustor optimized for cruise conditions (most of the aircraft's operation) operates less efficiently at idle and full thrust.

Unlike the aircraft turbine, the ground-based gas turbine operates continuously at the same power setting, usually 60–80% of maximum power output except when starting. Air and fuel flow patterns are constant and the combustor can be tuned to minimize smoke formation and high metal temperatures.

Exhaust emissions of CO, unburned hydrocarbons, and nitrogen oxides reflect combustion conditions rather than fuel properties. The only fuel component that degrades exhaust is sulfur; the SO_2 concentrations in emissions are directly proportional to the content of bound sulfur in the fuel. Sulfur concentrations in fuel are determined by crude type and desulfurization processes. Specifications for aircraft fuels impose limits of

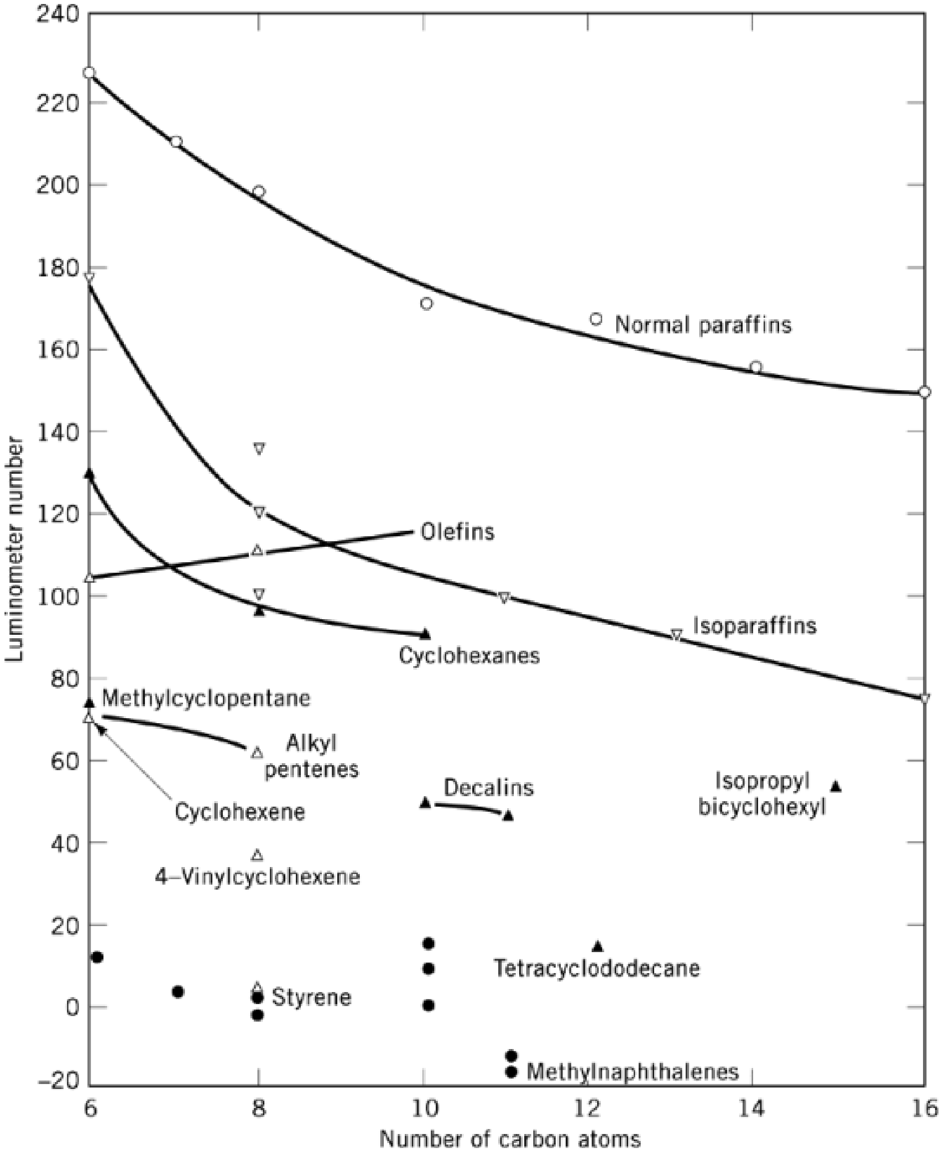

Fig. 6. Luminometer ratings of hydrocarbons (7), ○, *n*-paraffins; ▽, *i*-paraffins; ▲, cycloparaffins; △, olefins; ●, aromatics.

3000–4000 ppm total sulfur but the average is half of these values. Sulfur content in heavier fuels is determined by legal limits on stack emissions.

Control of nitrogen oxides in aircraft exhaust is of increasing concern because nitrogen oxides react with ozone in the protective layer of atmosphere which exists in the altitude region where supersonic aircraft operate. Research is under way to produce a new type of combustor which minimizes NO_x formation. It is an essential component of the advanced propulsion unit needed for a successful supersonic transport fleet.

Another class of pollutant in exhaust does serious damage to the turbine itself. In this case the damage is hot corrosion of the metal blades and vanes by alkali metal (primarily sodium) salts which remove blade

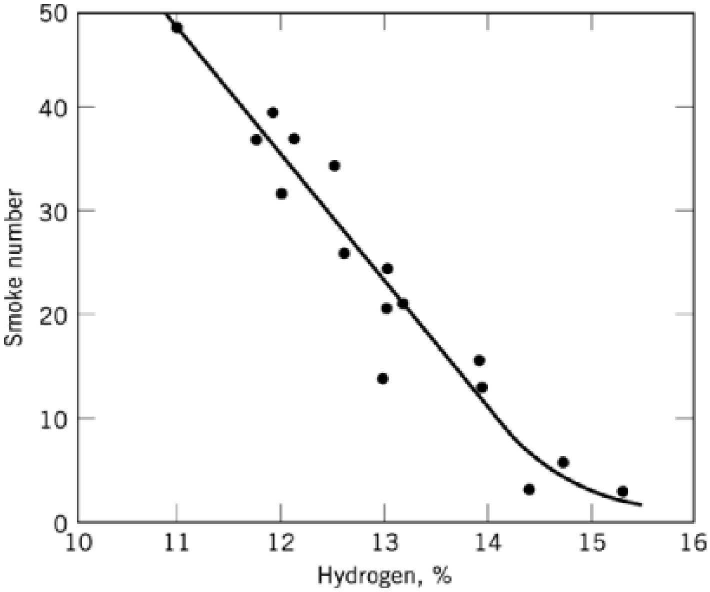

Fig. 7. Effect of hydrogen content of fuel on smoke number at cruise conditions (9).

coatings and promote intergranular corrosion. The source of the salts can be fuel (as metal salts dissolved or entrained in water) or the air that enters the gas turbine in huge quantities. Sulfur oxides in the exhaust react with alkali to form sulfates which produce a low melting flux on the oxide coatings. The problem is especially serious with gas turbines used in ground (or marine) locations because heavier fuels are apt to contain metal contaminants. For example, some crudes contain soluble vanadium which forms V_2O_5, leading to hot corrosion. Metal specification limits on gas turbine fuels are noted in Table 4 and are discussed fully in appendixes to ASTM D2880.

2.2. Stability

Aviation fuel is exposed to a wide range of thermal environments, and these greatly influence required fuel properties. In the tank of a long-range subsonic aircraft, fuel temperatures can drop so low that ice crystals, wax formation, or viscosity increase may affect the fuel system performance. On its way to the engine the fuel then absorbs heat from airframe or engine components and in fact is used as a coolant for engine lubricant. Current high thrust engines expose fuel in the main engine control, the pump, and the manifold to an intense thermal environment, and fuel temperatures steadily rise as flow reaches the nozzle. Fuel stability assumes primary importance since freedom from deposits within the fuel system is essential for both performance and life.

The fuel systems of ground-based turbines are far less critical, since coolants other than fuel can be used and fuel lines can be well insulated. The tendency for deposit formation in fuel is not a concern in ground systems.

Deposits sometimes block fuel nozzles and distort fuel spray patterns, leading to skewed temperature distribution with the possibility of burnout of turbine parts by a “hot streak” exhaust. These deposits are sometimes associated with metal-containing particulates, but in general are another manifestation of fuel instability.

Oxidation of hydrocarbons by the air dissolved in fuel is catalyzed by metals and leads to polymer formation, ie, varnish and sludge deposits, by a chain reaction mechanism involving free radicals. Since it is impossible to exclude air dissolved in fuel, oxidation stability is controlled by eliminating species prone to form free radicals and by introducing antioxidants (qv). An accelerated test, the Jet Fuel Thermal Oxidation Test (JFTOT), simulates the critical temperature regimes of the gas turbine engine fuel manifold and nozzles, ASTM D3241, and has been developed to measure the oxidation stability of aircraft gas turbine fuels. In the JFTOT test, deposits, formed in the heated test section in 2.5 h at a specified temperature, are assessed. This relative rating ranks fuels that would normally be expected to operate for thousands of hours in an engine without deposit formation. In those few instances when deposits have been observed in service, the fuel has been shown to fail JFTOT tests at the specification temperature.

The reactive species that initiate free-radical oxidation are present in trace amounts. Extensive studies (11) of the autoxidation mechanism have clearly established that the most reactive materials are thiols and disulfides, heterocyclic nitrogen compounds, diolefins, furans, and certain aromatic-olefin compounds. Because free-radical formation is accelerated by metal ions of copper, cobalt, and even iron (12), the presence of metals further complicates the control of oxidation. It is difficult to avoid some metals, particularly iron, in fuel systems.

It is possible to deactivate a metal ion by adding a compound such as disalicylidene alkyl diamine, which readily forms a chelate with most metal atoms to render them ineffective. Metal deactivator has been shown to reduce oxidation deposits dramatically in the JFTOT test and in single tube heat exchanger rigs. The role of metal deactivator in improving fuel stability is complex, since quantities beyond those needed to chelate metal atoms act as passivators of metal surfaces and as antioxidants (13).

Oxidation deposits in aircraft engines are related to the thermal stresses imposed by heat soakback, which results from the off/on cycles associated with many landings and takeoffs. In contrast, ground turbines tend to operate longer at constant flow and do not subject fuel to the same degree of thermal stress. Fuel stability testing has not been established as a quality requirement, although a carbon residue test (ASTM D524) provides a rough screening tool to protect against the tendency for carbonization in a fuel injection system.

2.3. Volatility

The volatility of aircraft gas turbine fuel is controlled primarily by the aircraft itself and by its operating environment. For example, limits of the vapor pressure of aviation gasoline were dictated by the vapor and liquid entrainment losses that could occur in a piston aircraft capable of climbing to an altitude of about 6000 m; the vapor pressure of the warm fuel exceeds atmospheric pressure at that altitude (48 kPa or 7 psi). Since early military jet aircraft could climb even higher (12,000 m) and faster, it was necessary to further limit the vapor pressure of military gas turbine fuels to 21 kPa (3 psi). Originally, the United States followed the British lead and selected a kerosene of very low vapor pressure for military jet engines. Because projected production of this fuel was limited, fuel availability was the eventual determining factor for the selection of the wide-cut gasoline type fuel JP-4 as the fuel for military jet aircraft. The volatility of kerosene fuel is measured not by its vapor pressure but by its temperature at the point where its vapors just prove to be flammable, ie, the flash point.

Commercial aviation utilizes low volatility kerosene defined by a flash point minimum of 38°C. The flammability temperature has been invoked as a safety factor for handling fuels aboard aircraft carriers; Navy JP-5 is a low volatility kerosene of minimum flash point of 60°C, similar to other Navy fuels.

The dependence of vapor pressure on temperature for the fuels most commonly used in gas turbines appears in Figure 8 (14). The points on the abscissa reflect the flash point temperatures used to define the volatility of higher molecular weight fuels. When vapor pressure itself is limited, as with JP-4 or Jet B, a test temperature of 38°C is specified.

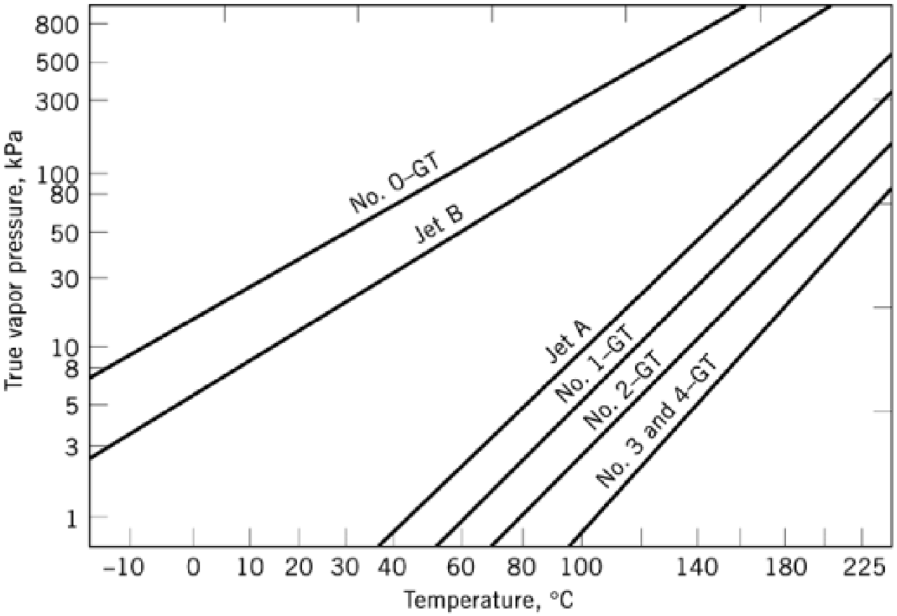

Fig. 8. Variation of vapor pressure with temperature for gas turbine fuels (14). To convert kPa to psi, divide by 6.9.

Ground turbine fuels are not subject to the constraints of an aircraft operating at reduced pressures of altitude. The temperature of fuel in ground tanks varies over a limited range, eg, 10–30°C, and the vapor pressure is defined by a safety-handling factor such as flash point temperature. Volatile fuels such as naphtha (No. 0-GT) are normally stored in a ground tank equipped with a vapor recovery system to minimize losses and meet local air quality codes on hydrocarbons.

A minimum volatility is frequently specified to assure adequate vaporization under low temperature conditions. It can be defined either by a vapor pressure measurement or by initial distillation temperature limits. Vaporization promotes engine start-up. Fuel vapor pressure assumes an important role particularly at low temperature. For example, if fuel has cooled to $-40^{\circ}\mathrm{C}$, as at arctic bases, the amount of vapor produced is well below the lean flammability limit. In this case a spark igniter must vaporize enough fuel droplets to initiate combustion. Start-up under the extreme temperature conditions of the arctic is a major constraint in converting the Air Force from volatile JP-4 to kerosene-type JP-8, the military counterpart of commercial Jet A1.

The lower volatility of JP-8 is a significant factor in the U.S. Air Force conversion from JP-4, since fires and explosions under both combat and ordinary handling conditions have been attributed to the use of JP-4. In examining the safety aspects of fuel usage in aircraft, a definitive study (15) of the accident record of commercial and military jet transports concluded that kerosene-type fuel is safer than wide-cut fuel with respect to survival in crashes, in-flight fires, and ground fueling accidents. However, the difference in the overall accident record is small because most accidents are not fuel-related.

2.4. Low Temperature Fuel Flow

The decrease in the temperature of fuel in the tank of an aircraft during a long duration flight produces a number of effects which can influence flight performance. Fuel viscosity increases, necessitating more pumping energy in the tank boost pump and in the engine pump. Fuel becomes saturated with water, and droplets of free water

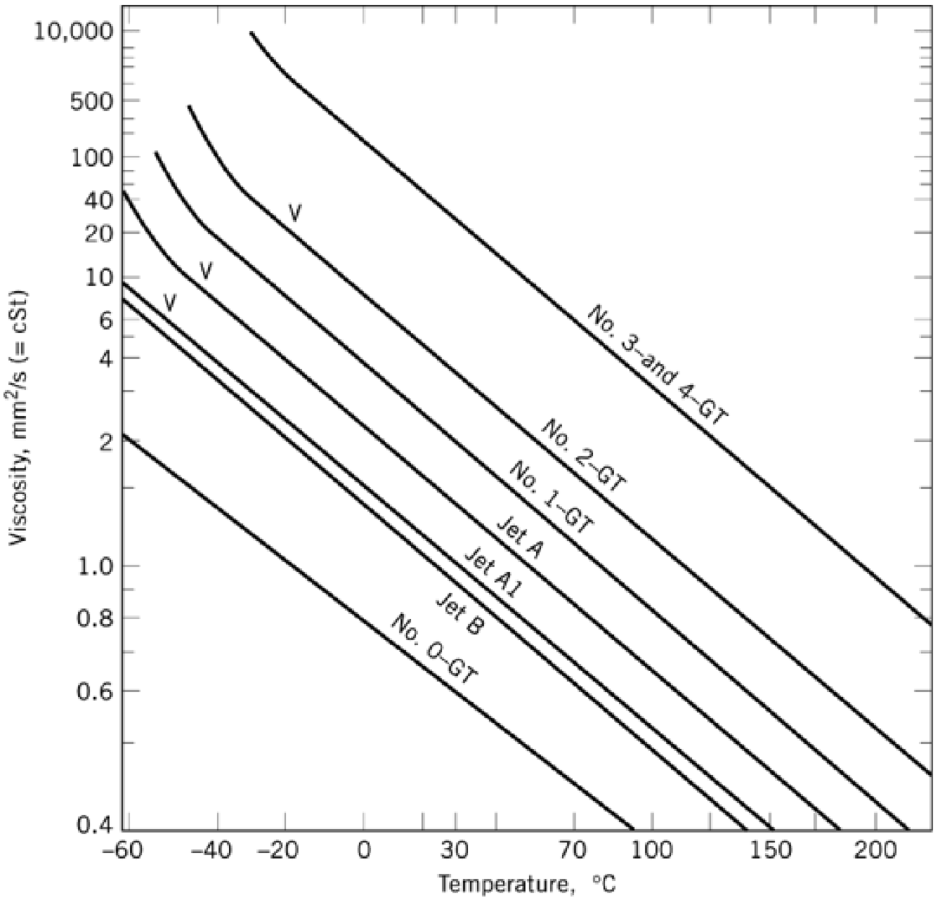

Fig. 9. Variation of viscosity with temperature of gas turbine fuels (14). V=specified limit for freezing (wax) point.

form and settle. Those carried with fuel may form ice on the cold filter which protects the fuel control. For this reason filter heaters are used in civil aircraft to avoid ice blockage and fuel starvation. Military aircraft avoid the complication of a filter heater and depend instead on an antiicing additive in the fuel to depress the freezing point of water. At still lower temperatures, crystals of wax form in fuel. The temperature at which these wax crystals disappear is called the freezing point and distinguishes Jet A1, used by long-range international airlines, from Jet A, used by domestic airlines for relatively short duration flights.

The increase in fuel viscosity with temperature decrease is shown for several fuels in Figure 9. The departure from linearity as temperatures approach the pour point illustrates the non-Newtonian behavior created by wax matrices. The freezing point appears before the curves depart from linearity. It is apparent that the low temperature properties of fuel are closely related to its distillation range as well as to hydrocarbon composition. Wide-cut fuels have lower viscosities and freezing points than kerosenes, whereas heavier fuels used in ground turbines exhibit much higher viscosities and freezing points.

Low temperature viscosities have an important influence on fuel atomization, and they affect engine starting. Cycloparaffinic and aromatic fuels reach unacceptably high viscosities at low temperatures. A kinematic viscosity of 35 mm^2/s (=cSt) represents the practical upper limit for pumps on aircraft, whereas much higher limits are acceptable for ground installations.

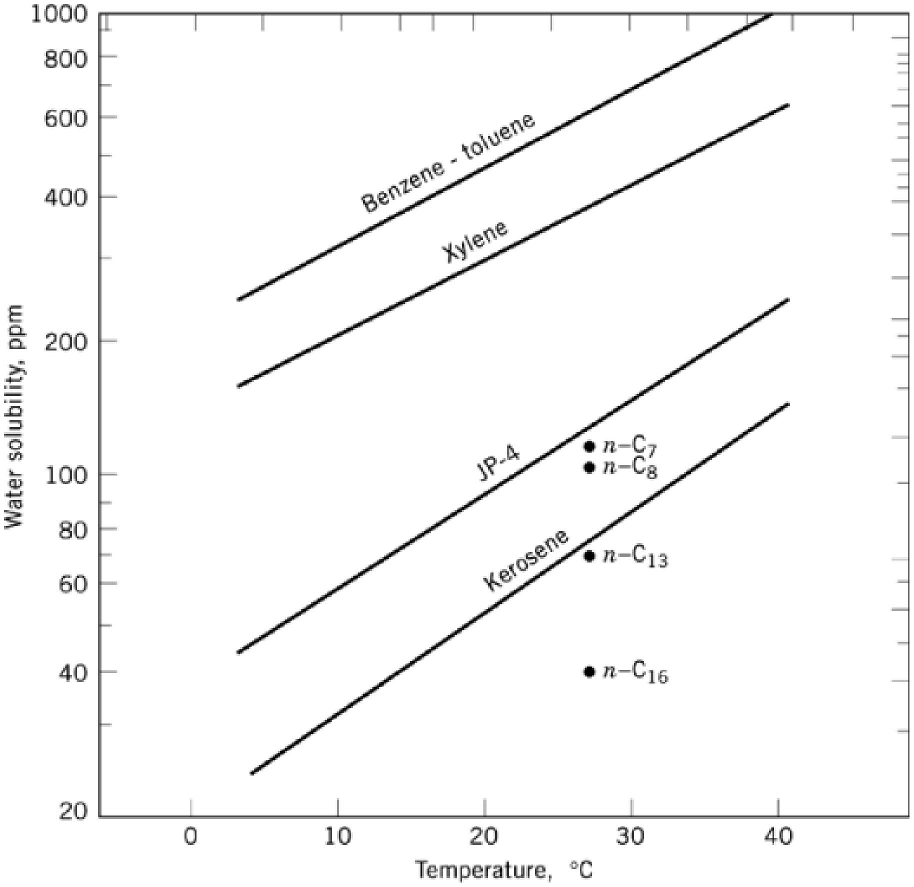

Fig. 10. Variation of water solubility of hydrocarbons with temperature.

2.5. Water in Fuel

The solubility of water in a hydrocarbon is related to the molecular structure of the hydrocarbon and to its temperature. Aromatics dissolve about five times more water than corresponding paraffins and, in turn, lower molecular weight paraffins dissolve more water than longer chain compounds. Figure 10 is a plot of water solubility for certain pure hydrocarbons and typical jet fuels. The water saturation values in fuel vary considerably because of composition effects. For example, wide-cut fuel normally dissolves more water than does kerosene, but because the latter may contain twice as many aromatics, the higher molecular weight fuel may in fact exhibit an equivalent water-saturation curve. At a temperature of 23°C, a Coordinating Research Council program on Jet A fuel showed a range of 56–120 ppm of soluble water (16).

The slope of the water solubility curves for fuels is about the same, and is constant over the 20–40°C temperature range. Each decrease of 1°C decreases water solubility about 3 ppm. The sensitivity of dissolved water to fuel temperature change is important. For example, the temperature of fuel generally drops as it is pumped into an airport underground hydrant system because subsurface temperatures are about 10°C lower than typical storage temperatures. This difference produces free water droplets, but these are removed by pumping fuel through a filter-coalescer and hydrophobic barrier before delivery into aircraft.

The amount of water actually dissolved in fuel at any given temperature is determined by equilibration with the water in the atmosphere above the fuel. If a tank is vented to the atmosphere, fuel may enter saturated with water but lose half its dissolved water when the relative humidity is 50%. Conversely, a tank of fuel in a humid environment rapidly picks up water. Many storage tanks contain floating roofs which effectively eliminate any opportunity for dissolved water to be removed as vapor. The tank in the aircraft behaves like a storage tank on the ground. In the upper atmosphere, the partial pressure of water is very low and fuel tends to dry out; dissolved water leaves fuel and exits from the vent. An aircraft descending through clouds picks up water and saturates its fuel. At the end of a flight, fuel in a tank is apt to be both cold and cloudy with free water.

A stable cloud of water in fuel usually means that a surfactant is present to form a stable water-in-oil emulsion. Smaller droplets resist natural coalescence processes. A surfactant that is potent as an emulsifying agent is apt to disarm the coalescing filters, allowing excess water to be delivered with fuel.

The effects of water in fuel inside a tank, particularly an aircraft tank, are important because of the demonstrated proclivity of free water to form undrainable pools where microorganisms can flourish. In ground storage tanks an attempt is made to exclude water bottoms by proper design and regular draining practices. This is more difficult in aircraft because pools of water freeze in flight and ice may not melt when fueling turnarounds are rapid. In a large storage tank, organisms (usually fungi and yeasts) develop at fuel–water interfaces, forming a cuff of growth which can plug filters. In the aircraft the growth usually takes place on tank surfaces, forming a fungal mat under which metabolic products such as organic acids penetrate polymeric coatings to attack the aluminum skin itself. The growth may also affect the capacitance gauge used to read liquid level.

It is common to curb growth of organisms by biocidal treatment. In storage tanks a water-soluble agent is used. Aircraft tanks are opened periodically for hand cleaning and subsequent treatment with a fuel-soluble boron-containing biocide. The antiicing additive used by the military to lower the freezing point of water, 2-methoxyethanol, happens also to inhibit growth of organisms effectively. Therefore, aircraft tank treatment to remove fungal mats is needed only for commercial transports.

Water plays a primary role in corrosion of the metal walls of tanks and pipes (17), and increases the tendency for high speed pumps to produce wear particles and to exhibit shortened life. Formation of corrosion products can be controlled by addition of corrosion inhibitors, a mandatory additive in military fuels. However, corrosion inhibitors may also degrade other fuel properties and adversely affect ground filtration equipment. Thus they are not generally acceptable in commercial fuels where rigorous attention is given to clean and dry fuels upon aircraft fueling.

2.6. Compatibility and Corrosion

Gas turbine fuels must be compatible with the elastomeric materials and metals used in fuel systems. Elastomers are used for O-rings, seals, and hoses as well as pump parts and tank coatings. Polymers tend to swell and to improve their sealing ability when in contact with aromatics, but degree of swell is a function of both elastomer-type and aromatic molecular weight. Rubbers can also be attacked by peroxides that form in fuels that are not properly inhibited (see Elastomers, synthetic; Rubber, natural).

Attack on metals can be a function of fuel components as well as of water and oxygen. Organic acids react with cadmium plating and zinc coatings. Traces of H_2S and free sulfur react with silver used in older piston pumps and with copper used in bearings and brass fittings. Specification limits by copper and silver strip corrosion tests are required for fuels to forestall these reactions.

Boundary lubrication of rubbing surfaces such as those found in high speed pumps and fuel controls has been found to be related to the presence in fuel of species capable of forming a chemisorbed film that reduces friction and wear (18). The lubricity of fuel is attributed to polar materials (19), multiring aromatics (19), and a thiohydroindane species (20). Oxygen-containing compounds, particularly long-chain acids, tend to adsorb on metal surfaces and act as lubricity agents. Corrosion inhibitors, which tend to form tenacious films on metal surfaces, are generally excellent lubricity agents. Refining processes to reduce sulfur, remove olefins, and control acidity tend to degrade a fuel's lubrication propensity. Corrosion inhibitors are mandatory in military fuels since they also improve the lubricity of fuels by extending the life of pumps and controls.

Both friction and wear measurements have been used to study boundary lubrication of fuel because sticking fuel controls and pump failures are primary field problems in gas turbine operation. An extensive research program of the Coordinating Research Council has produced a ball-on-cylinder lubricity test (BOCLE), standardized as ASTM D5001, which is used to qualify additives, to investigate fuels, and to assist pump manufacturers (21).

3. Economic Aspects

The exacting list of specification requirements for aviation gas turbine fuels and the constraints imposed by delivering clean fuel safely from refinery to aircraft are the factors that affect the economics. Compared with other distillates such as diesel and burner fuels, kerosene jet fuels are narrow-cut specialized products, and usually command a premium price over other distillates. The prices charged for jet fuels tend to escalate with the basic price of crude, a factor which seriously undermined airline profits during the Persian Gulf war as crude prices increased sharply.

Availability and cost of jet fuels are also affected by the interrelationships of the market for other petroleum products. An excellent example of these interrelationships was developed for the National Aeronautic and Space Administration (NASA) in a study on the affects of jet fuel property changes on producibility and cost in the United States, Canada, and Europe (22). For example, the western United States is a unique market compared with the rest of the country because demand for gasoline and jet fuel is high, but demand for burner and boiler fuels is low. This product distribution encourages high conversion refineries with particular emphasis on hydrocracking to make lighter products. At the same time, environmental concerns over urban air quality are pressuring refineries to market reformulated gasolines and low sulfur diesel fuels. Refining these products and also producing specification jet fuel has tended to limit availability and to increase the cost of aviation fuels in the western United States.

The majority of refineries operated by petroleum companies in different parts of the world to make local products, such as gasoline and burner fuels, also produce jet fuels. Even a small refinery with simple equipment can make suitable jet fuel if it has access to the right crude. However, the principal supply of both civil and military jet fuels is produced in large refineries. Many are located near major cities and airports and are frequently connected by pipeline directly to the airport. Modern airports have extensive storage and handling facilities operated by local authorities, petroleum companies or consortia, or the airlines themselves.

Worldwide demand for the jet fuels specified in Table 3 amounted to about 477,000 m^3/d (3 million barrels per day) in 1990. About one-half of this demand was kerosene Jet A sold in the United States. One-third represented kerosene Jet A1 for delivery to international airlines outside the United States; the balance comprised various military fuels used by air forces around the world.

4. Future Trends

4.1. Aircraft Fuels

Demand for aviation gas turbine fuels has been growing more rapidly than demand for other petroleum products since 1960, about 3–5% per year compared with 1% for all oil products. This strong demand reflects a current and predicted growth in worldwide air traffic of 4–7% annually until the end of the century. Total world oil demand will be up by 15% by the year 2000, but aviation fuel demand will increase by 50–125%. However, the fraction of the oil barrel devoted to aviation, now about 8%, will increase only slightly.

Changes in the crude supply outlook are, in fact, decreasing the potential yield of the straight-run kerosene fraction, needed not only for aviation, but also for blending into diesel and heating fuels. For example, Arabian Gulf crudes, the most abundant worldwide supply, yield less kerosene than the primary U.S. crude. This situation requires more conversion processes at refineries such as hydrocracking of gas oil, a process that yields high quality but more expensive aviation kerosene.

The vulnerability of the aviation market was exposed in the winter of 1973–1974 when the Arab oil embargo caused actual shortages of jet fuel (23). Coupled with the dramatic rise in crude and product prices, the supply crisis precipitated a new generation of fuel-efficient aircraft and a relaxation of specification limits, such as higher freezing points to $-47^{\circ}\mathrm{C}$ and higher aromatics to 25%. It has been estimated that 18% of the world's crudes produce a 150–250°C fraction containing more than 20% aromatics. Two of these, Heavy Arabian and North Slope, represent the important new sources of marginal jet fuel.

Operation of aircraft gas turbines on a wider cut than the 160–260°C fraction of crude to expand availability has been considered (24). Boiling range is limited at the low boiling end by flammability, ie, flash point, and at the high boiling end by low temperature needs, ie, freezing point. In the case of Jet A, a reduction of flash point from 38°C to 32°C would increase yield by 17%; an increase in Jet A1 freezing point to $-40^{\circ}\mathrm{C}$ would add about 25% to the kerosene pool.

Synthetic fuels derived from shale or coal will have to supplement domestic supplies from petroleum someday, and aircraft gas turbine fuels producible from these sources have been assessed. Shale-derived fuels can meet current specifications if steps are taken to reduce the nitrogen levels. However, extracting kerogen from shale rock and denitrogenating the jet fuel are energy-intensive steps compared with petroleum refining; it has been estimated that shale jet fuel could be produced at about 70% thermal efficiency compared with 95% efficiency for petroleum (25). Such a difference represents much higher cost for a shale product.

Synthetic jet fuel derived from coal is even more difficult and expensive, since the best of the conversion processes produces a fuel very high in aromatics. With hydrogenation, overall thermal efficiency is only 50%. Without additional hydrogenation, the gas turbine fuels would contain 60–70% aromatics.

Production of liquid jet fuel from processing of abundant natural gas is a more promising and cheaper source of high quality product than shale or coal.

4.2. Fuels for Advanced Aircraft

The area of greatest traffic growth is predicted to be the Pacific basin where distances are great and the greatest incentive exists for an advanced aircraft that could greatly reduce travel time. Research at NASA is proceeding on a high speed commercial transport (HSCT) that would satisfy this market by the year 2010. The aircraft would carry about 300 passengers nonstop over 8000 miles at three times the speed of sound, and would reduce travel time from 14 to 6 hours. To be economically and environmentally viable, the HSCT would have to produce less nitrogen oxides in exhaust, cause lower sonic boom, and operate on the same kerosene as subsonic aircraft.

The first commercial supersonic transport, the Concorde, operates on Jet A1 kerosene but produces unacceptable noise and exhaust emissions. Moreover, it is limited in capacity to 100 passengers and to about 3000 miles in range. At supersonic speed of Mach 2, the surfaces of the aircraft are heated by ram air. These surfaces can raise the temperature of fuel held in the tanks to 80°C. Since fuel is the coolant for airframe and engine subsystems, fuel to the engine can reach 150°C (26). An HSCT operated at Mach 3 would place much greater thermal stress on fuel. To minimize the formation of thermal oxidation deposits, it is likely that fuel delivered to the HSCT would have to be deoxygenated.

NASA is also considering a more advanced aircraft such as Mach 5 to cut Pacific travel time to about three hours, but in this case kerosene fuel is no longer acceptable, and liquefied natural gas or liquefied hydrogen would be needed to provide the necessary cooling and stability. However, a completely new fueling system would be required at every international airport to handle these cryogenic fluids.

In the speed regime of Mach 6 and beyond (hypersonicvehicles), hydrogen is the fuel of choice because of its high energy content and its combustion kinetics. For example, a first stage to orbit reusable booster for space vehicles would employ a supersonic combustor ramjet engine burning hydrogen, the only fuel capable of maintaining combustion in the shock wave. A booster that replaced 80% of the present weight of oxidizer would revolutionize space transportation by replacing the current space shuttle as a delivery vehicle.

Use of kerosene fuel rather than air as a coolant focuses attention on another fuel property, specific heat, which is a measure of its efficiency to absorb thermal energy. Heat capacity increases with temperature but decreases with density, which favors a low density paraffinic fuel from petroleum or natural gas sources.

Because of tank heating, fuel volatility is also more critical in supersonic aircraft. For example, the Concorde tank is pressurized to prevent vapor losses which could be significant at high altitude where fuel vapor pressure may equal atmospheric pressure. The tank can reach 6.9 kPa (1 psi) at the end of a flight. The need to deoxygenate fuel for thermal stability in the HSCT will doubtless require a similar pressurized system.

4.3. Ground Turbine Fuels

Unlike the outlook for aviation fuels, the demand for ground turbine fuels has stabilized because the ground turbine can be replaced by a more fuel-efficient engine for passenger cars and trucks. On the other hand, the ground turbine is unique in its ability to provide peak electrical power on a few seconds notice and to accept a variety of fuels as a prime mover in pipeline pumping and gas compression. The fuels described in Table 1 from gas to crude will continue to provide the energy source for ground turbines depending on location. Cogeneration plants which provide both electricity and heat simultaneously will undoubtedly continue to be a prime application of ground turbines to many complexes serving suburban and rural areas.

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W. G. DUKEK
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