

1
2
3
4 **Recent Development in Studies of Alternative Jet Fuel Combustion:**
5
6
7 **Progress, Challenges, and Opportunities**
8
9

10 Chi Zhang¹, Xin Hui^{1,2}, Yuzhen Lin¹, and Chih-Jen Sung²
11
12

13 ¹National Key Laboratory of Science and Technology on Aero-Engine Aero-thermodynamics
14 School of Energy and Power Engineering
15 Beihang University
16 Beijing 100191, P. R. China
17
18

19 ²Department of Mechanical Engineering
20 University of Connecticut
21 Storrs, CT 06269, USA
22
23
24

25 **Abstract**
26

27 With the growing air transport demand and concerns about its environmental impacts, alternative
28 jet fuels derived from non-conventional sources have become an important strategy for achieving
29 a sustainable and green aviation. In the past ten years, governments around the world along with
30 aviation industry have invested significant efforts into exploring all sorts of alternative jet fuels
31 that can be used to power aircraft engines. Among all the alternative jet fuels explored, the
32 aviation sector has agreed that hydrocarbon-based ‘drop-in’ replacement fuels, which are fully
33 interchangeable and compatible with current conventional jet fuels, would be the best choice in
34 the near future, as they can be used without any modifications to today’s aircraft or fuel
35 infrastructure. This paper reviews the current state of development of ‘drop-in’ alternative jet
36 fuels including various Fisher-Tropsch synthetic jet fuels and bio-jet fuels. Recent advances in
37 research activities on alternative jet fuels, including fuel property evaluations, combustor
38 component tests, engine tests, and flight tests, are highlighted. Furthermore, basic research needs
39 for understanding the combustion characteristics of alternative jet fuels are underlined and
40 discussed by reviewing recent fundamental combustion studies on ignition, extinction, flame
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61

1
2
3
4 propagation, emissions, and species evolution of various conventional and alternative jet fuels.
5

6
7 Recognizing that the use of ‘simpler’ surrogate fuels to emulate the behavior of ‘complex’
8
9 alternative jet fuels is of fundamental and practical importance for the development of physics-
10
11 based models to enable quantitative emissions and performance predictions using combustion
12
13 modeling, recent studies on surrogate formulation for alternative jet fuels are also reviewed and
14
15 discussed. This review concludes with a brief discussion of future research directions.
16
17
18
19
20
21

22 **Keywords:** Alternative jet fuels; Synthetic jet fuels; Bio-jet fuels; Aviation emissions;
23
24 Combustion characteristics; Jet fuel surrogates
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4 **Nomenclature**
5

6
7 ASTM American Standard for Testing and Materials
8
9 ATJ Alcohol To Jet
10
11 BPD Boiling Point Distribution
12
13 BTL Biomass To Liquid
14
15 CAAFI Commercial Aviation Alternative Fuels Initiative
16
17 CBTL Coal/Biomass To Liquid
18
19 CCS Carbon Capture and Sequestration
20
21 CHRJ Camelina-based HRJ
22
23 CTL Coal To Liquid
24
25 DCN Derived Cetane Number
26
27 FSJF Fully Synthetic Jet Fuel
28
29 FT Fisher-Tropsch
30
31 GTL Gas To Liquid
32
33 GHG Greenhouse Gases
34
35 HEFA Hydroprocessed Esters and Fatty Acids
36
37 HRJ Hydroprocessed Renewable Jet
38
39 IPK iso-Paraffinic Kerosene
40
41 LBO Lean Blowout
42
43 LTO Landing and Take-off
44
45 NTC Negative Temperature Coefficient
46
47 OEM Original Equipment Manufacturer
48
49 PM Particulate Matter
50
51 SMD Sauter Mean Diameter
52
53 SPK Synthetic Paraffinic Kerosene
54
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

SSJF	Semi-Synthetic Jet Fuel
THRJ	Tallow-based HRJ
TSI	Threshold Sooting Index
UHC	Unburned Hydrocarbon

1
2
3
4 **1. Introduction**
5

6
7 1.1 Background
8

9 Global energy demand will continue to increase in the next decade as the world has been reeling
10 from the financial crisis and economic recession. In the transportation sector, air transport has
11 been growing faster than any other transport mode in the recent years and is likely to continue
12 growing rapidly in the future. Today, global aviation consumes about 5 million barrels of oil per
13 day, accounting for about 5.8% of total oil consumption in the world [1]. The world jet fuel
14 demand is projected to grow by 38% from 2008 to 2025 at a mean growth rate of 1.9% per year
15 [2]. Air transport sector is currently the leading sector with significant growth in demand for oil,
16 while the key driver for global jet fuel demand is led by emerging economies, such as China and
17 India. The ever-increasing energy demand coupled with the finite fossil fuel reserve has put a
18 great challenge on our society. The aviation industry and governments around the world have
19 been developing rational strategies through non-conventional alternative jet fuels to
20 accommodate the challenge.
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37

38 The increasing aviation activity has elicited growing concern with regard to its impacts on
39 environment and public health. Aircraft produces the same type of emissions as other ground
40 transportation vehicles, including carbon monoxide (CO), carbon dioxide (CO₂), water vapor
41 (H₂O), nitrogen oxides (NO_x), sulfur oxides (SO_x), unburned hydrocarbons (UHC), and
42 particulate matters (PM). Depending on whether they occur near the ground or at altitude,
43 aircraft emissions can be considered as local air quality pollutants or greenhouse gases (GHG),
44 the latter are believed to be the primary cause for global climate change [3]. Aviation sector is
45 relatively a small contributor to air pollutants compared to other sectors, it is estimated to
46 account for 2–3% of total CO₂ emissions and less than 3% of the transportation NO_x emissions
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4 [4]. However, given the fast growth of aviation, its emissions are likely to represent a greater
5
6 share of transport sources in the future. It has also been shown that high-altitude emissions near
7
8 or in the stratosphere, where airliners frequently fly, can have significantly more impacts on the
9
10 climate change compared to the ground-level emissions [5]. Aware of the challenges, the
11
12 aviation community has invested much effort to tackle the issue. In 2009, International Air
13
14 Transport Association (IATA) announced a three-step commitment for industry to achieve
15
16 carbon-neutral growth: (1) 1.5% average annual improvement in fuel efficiency from 2010 to
17
18 2020; (2) carbon-neutral growth from 2020 onwards; (3) 50% reduction in carbon emissions by
19
20 2050 as compared to the 2005 level [6]. More stringent standards and regulations on emissions
21
22 are expected to push the industry towards a more sustainable and greener aviation.
23
24
25
26
27

28
29 In view of the above, society has been challenged to balance conflicting energy and
30
31 environmental demands by decarbonizing our energy chain and finding clean and viable sources
32
33 of fuel. Concerns about rising fuel price, energy supply, energy security, emissions, and climate
34
35 change have called for a fresh look at the development and use of alternative jet fuels, which
36
37 hold great potential for reducing aircraft emissions while expanding domestic energy sources. In
38
39 the past decade, many alternative jet fuels, including synthetic fuels, bio-fuels, alcohol fuels,
40
41 liquid hydrogen, liquid methane, etc., have been proposed and explored for aviation use. Aircraft
42
43 original equipment manufacturers (OEMs) have been working closely with researchers to
44
45 investigate the practicality of these alternative jet fuels in the near, mid, and far-term aircraft.
46
47 Recently, the aviation community has agreed that ‘drop-in’ fuels are the most feasible choice for
48
49 alternative jet fuels in the near future. A ‘drop-in’ jet fuel is a substitute for conventional jet fuel
50
51 that is completely interchangeable and compatible with conventional jet fuel, and hence does not
52
53 require any modifications to the current aircraft engine or fuel distribution system. The Federal
54
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4 Aviation Administration (FAA) has been working to enable the U.S. use of one billion gallons
5
6 per year of alternative ‘drop-in’ fuels by 2018 [7]. Other countries as well as airlines have also
7
8 been making enormous efforts for the development and commercialization of alternative ‘drop-in’
9
10 jet fuels. Therefore, the present paper focuses on the recent development and studies of
11
12 alternative ‘drop-in’ jet fuels. It has to be pointed that alternative jet fuels discussed in this
13
14 review are only referred to the hydrocarbon-based ‘drop in’ fuels, which have a similar energy
15
16 content as the conventional jet fuels and can be either blended with or used as a total replacement
17
18 of conventional jet fuels. Other alternative jet fuels such as liquid methane, liquid hydrogen,
19
20 syngas, biogas, and oxygenated fuels are beyond the scope of the present paper.
21
22
23
24
25
26

27 1.2 Conventional and alternative jet fuels

28
29 Nowadays, the most used jet fuels are the kerosene-type fuels derived from petroleum. In U.S.,
30
31 Jet A is used in the commercial flights, while JP-8 is its counterpart for military use; JP-8 is
32
33 similar to Jet A, but contains extra additives for corrosion and static protections. Jet A-1, which
34
35 is widely used outside U.S., has similar composition as Jet A. The major difference between Jet
36
37 A and Jet A-1 is that Jet A-1 has a lower freezing point (-47°C), thereby making it more suitable
38
39 for intercontinental flights. Some countries may have their own jet fuel grading. For example,
40
41 Russia uses TS-1 and RT fuels for civil and military uses, respectively, while China uses RP-3
42
43 fuel for both civil and military use. Though there are some differences, TS-1, RT, and RP-3 are
44
45 considered to be on a par with the western Jet A and Jet A-1 [8].
46
47
48
49
50

51 Compared to conventional jet fuels, alternative jet fuels can be derived from a variety of
52
53 sources such as coal, oil shale, tar sand, plants, and animal fats. The compositions of alternative
54
55 jet fuels can differ significantly based on their feedstocks and production process. [Today, the two](#)
56
57
58
59
60
61
62
63
64
65

1
2
3
4 main industrial routes to alternative fuels in aviation are through (1) synthetic process of nature
5 gas or coal (synthetic jet fuels) and (2) hydrotreating process of lipids (bio-jet fuels) [9].
6
7

8
9 Synthetic jet fuels are derived from fossil feedstocks such as coal, natural gas, and other
10 hydrocarbons. Typically, the feedstocks are first gasified to produce a mixture of hydrogen and
11 carbon monoxide known as synthesis gas. The synthesis gas is further converted into liquid
12 hydrocarbons through Fisher-Tropsch (FT) process. The FT process is often termed as indirect
13 liquefaction and fuels are often referred to as coal-to-liquid (CTL) and natural gas-to-liquid
14 (GTL). However, some FT fuels that are derived from biomass (i.e. BTL – biomass-to-liquid) or
15 coal/biomass (i.e. CBTL – coal/biomass-to-liquid) are not considered as ‘synthetic’, in the sense
16 that they are not fossil-derived. Hence, BTL and CBTL fuels are generally referred to as non-
17 synthetic FT fuels, while the synthetic FT fuels are commonly termed as synthetic paraffinic
18 kerosene (SPK).
19
20
21
22
23
24
25
26
27
28
29
30
31
32

33 There are many positive qualities associated with FT fuels. The most notable advantage is
34 that they burn cleaner in aircraft engines. FT fuels generally produces approximately 2.4% less
35 carbon dioxide, 50%–90% less particulate matter, and 100% less sulphur than conventional
36 petroleum-based jet fuels [10]. FT fuels also have excellent low temperature properties and
37 superior thermal stability that can improve high altitude operation and low temperature starting
38 [10]. However, there are also some challenges and issues for using FT fuels. Although burning
39 FT fuels produce less carbon emissions, the total life-cycle carbon emissions of synthetic FT
40 fuels can be twice those of conventional jet fuels, if without involving any carbon capture and
41 sequestration (CCS) technology during fuel production [11]. To reduce the life-cycle carbon
42 emissions of FT fuels, FT plants need to further implement the necessary CCS technology, which,
43 however, could significantly increase the fuel production cost [12]. Another issue with FT fuels
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4 is the potential failure of engine seals due to the lack of aromatic hydrocarbons. Aromatics have
5
6 the desirous effect of causing engine seals to swell and prevent leakage [13]. To solve this
7
8 problem, the fully-synthetic jet fuels (FSJF) are required to contain a minimum amount of
9
10 aromatics to prevent seal failure. It is noted that there is no such requirement for the semi-
11
12 synthetic jet fuels (SSJF) since they are always blended with conventional jet fuels that already
13
14 contain aromatics.
15
16
17

18
19 Bio-jet fuels are derived from biological matter (biomass) such as agricultural crops, trees,
20
21 wood, plants, fibers, and animal wastes. Today, most bio-jet fuels are produced from plant oils
22
23 (e.g., algae, camelina, jatropha, etc.) and animal fats (e.g., beef tallow) through hydroprocessing,
24
25 a process that removes the chemically-bound oxygen and produces proper molecular weight
26
27 components for jet fuels. Thus, these bio-derived fuels are often termed as hydroprocessed
28
29 renewable jet (HRJ) or hydroprocessed esters and fatty acids (HEFA) fuels. One major
30
31 advantage of HRJ fuels is that their feedstocks are renewable, which can reduce the energy
32
33 reliance on the finite fossil fuel resources. In addition, unlike FT fuels, HRJ fuels can potentially
34
35 be carbon neutral in a sense that the carbon emitted by burning a HRJ fuel can be offset by the
36
37 carbon absorbed during the growing process of its feedstock. Though complete carbon neutrality
38
39 can still be challenging in practice, HRJ fuels hold great potentials for reducing carbon emissions.
40
41
42
43
44

45
46 Figure 1 plots and compares the life-cycle GHG emissions for several FT, HRJ, and
47
48 conventional jet fuels based on the data from PARTNER – Partnership for Air Transportation
49
50 Noise and Emissions Reduction [11]. It can be seen that the life-cycle GHG emissions level of
51
52 the FT CTL without CCS is ~123% more than that of the baseline conventional jet fuel, while
53
54 the FT CTL with CCS and FT GTL fuels have similar levels, which are about 11–15% higher
55
56 than the conventional jet fuel. In addition, all the HRJ fuels shown in Fig. 1 have substantial
57
58
59
60
61
62
63
64
65

1
2
3
4 lower GHG emissions than the conventional and FT jet fuels. Therefore, bio-jet (HRJ) fuels are
5
6 widely considered by the aviation industry to be one of the primary means to reduce its carbon
7
8 footprint. Recently, Lokesh et al. [14] has predicted the “cradle-grave” carbon intensities of
9
10 several bio-jet fuels using a life cycle GHG model. Their results revealed that bio-jet fuels
11
12 derived from camelina, micro-algae, and jatropha deliver 70%, 58%, and 64% of life cycle
13
14 emissions savings, respectively, relative to Jet A-1. However, bio-jet fuels have some drawbacks
15
16 that include low energy density, poor high-temperature thermal stability, storage instability, etc.
17
18 For these reasons, bio-jet fuels need to be developed with technology that can address those
19
20 issues and be able to tailor the resulting fuel for aircraft applications.
21
22
23
24
25

26 In general, the development and deployment of alternative jet fuels should depend on their
27
28 sustainability that needs to be carefully assessed both economically and environmentally. The
29
30 economical sustainability of alternative jet fuels needs to consider the costs of fuels, the
31
32 implementation of new technologies, and the associated infrastructure changes, while the
33
34 environmental sustainability mainly focuses on the issues of GHG emissions, air quality, land
35
36 use, and water quality. In order to be sustainable, an alternative fuel has to be cost-competitive
37
38 and maintain an ecological balance by avoiding depletion of nature resources. Though synthetic
39
40 FT fuels are currently widely used, using natural gas and coal as their feedstocks has limited
41
42 their capability for carbon reduction. However, the advantages of CTL and GTL fuels, including
43
44 abundant reserves for feedstocks, low fuel price, domestic production, etc., still make them very
45
46 attractive alternative jet fuels, especially in the coal-rich countries (e.g., U.S. and China) and the
47
48 gas-rich countries (e.g., Russia). On the other hand, although non-synthetic FT fuels and bio-jet
49
50 fuels that are derived from biomass have better carbon emission benefits compared to synthetic
51
52 FT fuels, there have been concerns about their competition for farmland with food [15]. Since
53
54
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4 the growing demand for biofuels can eventually put a strain on the balance between fuel uses and
5
6 food uses, the industry needs to focus on the new-generation, sustainable biofuels that are
7
8 derived from non-food crops. At the same time, the development of a new industry for bio-jet
9
10 fuels has its risks and challenges, as the availability of bio-jet fuels in future depends on the
11
12 large-scale production of biomass feedstocks, production technology and cost, world oil price,
13
14 and emissions regulation. As the aviation community is striving to move toward to a sustainable
15
16 and green aviation, the industry needs to ensure that the alternative fuels into which it invests
17
18 will provide the hoped-for benefits (environmental, economic, etc.). More detailed discussions
19
20 on the sustainability of alternative jet fuels can be found from a wide range of studies (e.g., [16-
21
22 21]).
23
24
25
26
27
28

29 1.3 Strategies and global efforts for alternative jet fuels

30
31 To achieve a sustainable and green aviation through alternative jet fuels, actions have been taken
32
33 by governments and international aviation community. Early in 2003, the U.S. Department of
34
35 Defense has launched Clean Fuels Initiative that includes two programs: Total Energy
36
37 Development (TED) Program and Joint Battlefield Use Future Fuel (J-BUFF) Program. TED
38
39 was aimed to catalyze commercial production of fuels from alternative energy resources, while J-
40
41 BUFF was designed to develop specifications for alternative jet fuels that enable a single fuel for
42
43 the entire battle space [22]. In 2013, the U.S. Air Force (USAF) released its Energy Strategic
44
45 Plan [23], in which USAF was committed to increase use of cost-competitive drop-in alternative
46
47 aviation fuel blends for non-contingency operations to 50% of total consumption by 2025.
48
49
50
51
52
53

54 In civil aviation, the Commercial Aviation Alternative Fuels Initiative (CAAFI) was formed
55
56 in 2006 under the co-sponsorship of Aerospace Industries Association, Airports Council
57
58 International-North America, Airlines for America, and U.S. Federal Aviation Administration
59
60
61
62
63
64
65

1
2
3
4 (FAA). The CAAFI also consists of approximately 300 non-sponsor members and is a coalition
5
6 of airlines, aircraft OMEs, energy producers, researchers, international participants, and
7
8 government agencies. The CAAFI functions as a clearing house to facilitate the exchange of
9
10 information and coordination of private-sector and government initiatives for the development
11
12 and commercialization of alternative jet fuels [24]. In 2008, the European Union (EU) has
13
14 launched a program of Alternative Fuels and Biofuels for Aircraft Development (ALFA-BIRD)
15
16 that was aimed at developing the whole chain for alternative jet fuels. In 2011, this R&D
17
18 program has adopted Sasol FSJF[®], a well characterized and certified fuel, as the reference fuel
19
20 and tested several other alternative jet fuels. The test results were used to prepare the
21
22 environmental and economic impact assessment that forms the basis for the elaboration of the
23
24 future strategy for alternative jet fuels [25].
25
26
27
28
29
30

31 In 2009, twenty European and international organizations have launched a three year
32
33 project, named as Sustainable Way for Alternative Fuels and Energy for Aviation (SWAFEA), to
34
35 investigate the feasibility and impact of the use of alternative jet fuels. The final report of
36
37 SWAFEA [26] was submitted to the European Commission to provide guidance to policy
38
39 makers on aviation sustainability issues. This report pointed out the major economic issue for
40
41 bio-jet fuels is their lack of competitiveness with conventional jet fuels, at least in the first
42
43 decade of deployment; new technologies are required for more efficient processing pathways
44
45 with higher yields and reduced costs. It was also suggested that the Commission explores the
46
47 possibility of including bio-jet fuels in the EU Renewable Energy Directive, which sets a binding
48
49 target of 20% share of total energy consumption from renewable sources and a 10% share of
50
51 energy from renewable sources in transport by 2020 [27].
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4 Being the fastest country in the growth of jet fuel demand, China has also launched its own
5
6 alternative jet fuel initiative known as National Industrial Collaborative Innovation Alliance of
7
8 Alternative Aviation Fuels in 2012. The initiative is a collaboration of several research institutes
9
10 aiming for the development of alternative jet fuels as well as relevant certification processes and
11
12 standards. In the same year, China Air Force and fuel producers have also started a program for
13
14 the development of coal-derived jet fuels for both military and commercial use.
15
16
17

18
19 Other countries around the world have also started various initiatives and programs to boost
20
21 the development and application of alternative jet fuels. More information and news with regard
22
23 to alternative jet fuels can be found on the CAAFI website [28].
24
25
26

27 1.4 Overview

28
29 In a broad view of literature, many studies have already been devoted to the review of alternative
30
31 jet fuels. For example, Gupta et al. [29] reviewed different kinds of bio-fuels for gas turbine
32
33 applications. Law [30] reviewed the state of research on developing fuel options for next-
34
35 generation chemical propulsion for aviation uses. Liu et al. [31] provided a technical review on
36
37 the production processes of jet fuels including conventional/unconventional oiled-based process,
38
39 FT process, and hydrotreating process. Chuck and Donnelly [32] discussed the compatibility of
40
41 potential bio-derived fuels with Jet A-1. Kallio et al. [33] reviewed the existing technologies for
42
43 renewable alternative jet fuel production. Hari et al. [34] reviewed the production routes for bio-
44
45 jet fuels, including thermochemical process, hydroprocessing, biochemical process, and others.
46
47 Murphy et al. [35] reviewed the biomass production for sustainable alternative jet fuels in
48
49 Queensland, while Cremonez et al. [36] reviewed the current scenarios and prospects of bio-jet
50
51 fuels in Brazil. Blakey et al. [37] provided a comprehensive review on the development of ‘drop-
52
53 in’ alternative jet fuels including fuel production pathways, life-cycle analysis, economic
54
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4 availability, flight tests, and engines tests on various combustion characteristics. In the present
5
6 paper, we extend the work of Blakey et al. [37] with more recent progress in the development of
7
8 ‘drop-in’ alternative fuels with focus on fuel properties and performance in various testing
9
10 processes. In addition, we summarize fundamental studies on combustion characteristics of
11
12 alternative jet fuels including fuel ignition, flame propagation, extinction, emissions, and
13
14 combustion speciation. Finally, recent development on surrogate formation for alternative jet fuels
15
16 is also highlighted, followed by a brief discussion of future fuel development and research
17
18 directions.
19
20
21
22
23
24
25

26 **2. Alternative Jet Fuel Evaluations**

27 2.1. Path to alternative jet fuel readiness

28
29 To facilitate the development and deployment of alternative jet fuels, the CAAFI has developed
30
31 a path to fuel readiness, also referred to as CAAFI communication tools [38]. The tools include
32
33 fuel readiness level (FRL), FRL exit criteria, feedstock readiness level (FSRL), guidance for
34
35 selling alternative jet fuels to airlines, and environmental progression. Moreover, the tools are
36
37 designed to aid in the communication of both the necessary steps to be taken and the progress of
38
39 alternative jet fuel projects.
40
41
42
43
44

45 In the process of alternative jet fuel development, FRL is commonly used to classify and
46
47 track the progress on research, certification, and demonstration activities at different milestones,
48
49 i.e. R&D (FRL 1–5), Certification (FRL 6–7), and Business and Economics (FRL 8–9). In this
50
51 chapter, we first introduce the jet fuel specification, and then focus on the property evaluations of
52
53 alternative jet fuels in the R&D stage, followed by the combustor component, engine, and flight
54
55 tests in the Certification stage. While the Business and Economics stage is outside the scope of
56
57
58
59
60
61
62
63
64
65

1
2
3
4 this review, interested readers can refer to Refs. [39-41] for more information and discussions on
5
6 this stage.
7

8 9 2.2. Jet fuel specification

10
11 Fuel specification is a list of standards by which the producers and users can identify and control
12
13 the properties of fuel necessary for adequate and reliable performance. Two organizations have
14
15 taken the leading roles in setting and maintaining specifications for jet fuels, namely the
16
17 American Society for Testing and Material (ASTM) and the United Kingdom Ministry of
18
19 Defense.
20
21

22
23 ASTM standard specification D1655 [42] defines specific types of jet fuels for civil use: Jet
24
25 A and Jet A-1. It specifies that jet fuels shall be appropriately sampled and tested to examine
26
27 their conformance to detailed requirements as to composition, volatility, fluidity, combustion,
28
29 corrosions, thermal stability, contaminants, and additives [42]. In 2009, ASTM established new
30
31 standard, ASTM D7566-09 [43], for aviation turbine fuels containing synthesized hydrocarbons
32
33 produced from Fischer-Tropsch synthesis. In 2011, an annex with requirements for synthetic fuel
34
35 components manufactured from HEFA was included in the new edition of ASTM D7566-11[44].
36
37 In the latest version of ASTM D7566-14c [45], the specification covers the manufacture of
38
39 aviation turbine fuels that consist of conventional and synthetic blending components, and is
40
41 intended to be used as a standard in describing the quality of aviation turbine fuels and synthetic
42
43 blending components. In addition, the fuel certified by ASTM D7566 meets all the requirements
44
45 of ASTM specification D1655 and can be regarded as D1655 fuel. This allows the new D7566
46
47 fuels to be seamlessly integrated into the current aircraft and infrastructures that are certificated
48
49 for the D1655 fuels.
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4 To streamline the approval process for new jet fuels, in 2009 ASTM issued D4054-09,
5
6 detailing the practice for qualification and approval of new aviation turbine fuels and fuel
7
8 additives [23]. This standard practice provides a framework for the certification of new jet fuels
9
10 and new fuel additives for use in commercial and military aviation gas turbine engines. Figure 2
11
12 shows the fuel and additive approval process specified by ASTM D4054-09 [46]. In can be seen
13
14 the certification process is composed of test program, OEM internal review, and specification
15
16 change. The test program that includes specification properties, fit-for-purpose properties,
17
18 component test, and engine test is intended to ensure the candidate fuel has no negative impact
19
20 on engine safety, durability, or performance. However, it is unlikely that all the tests need to be
21
22 performed, the OEMS should be consulted and will provide guidance on which tests are
23
24 applicable. The test results are then reviewed by the respective OEM and FAA, additional data
25
26 may be required based on the review. After the approval of a new fuel, if the OEM proposes
27
28 changes to specification ASTM 1655, the proposed changes must be reviewed and balloted. The
29
30 process is very rigorous and can go through several iterations before a change can be made to
31
32 specification ASTM D1655. The practice ASTM 4054 was developed as a guide by the aviation
33
34 gas-turbine engine OEMs with the support of ASTM international members, and the OEMs are
35
36 solely responsible for approval of a fuel or an additive in their respective engines and airframes.
37
38 It is also stated in the ASTM D7566 that synthetic fuels and blending components certified by
39
40 this standard specification should have been evaluated and approved in accordance with the
41
42 principles established in the standard practice of ASTM D4054.
43
44
45
46
47
48
49
50
51

52
53 Defense Standard 91-91 (DEF STAN 91-91) [47] issued on the behalf of Ministry of
54
55 Defense by the UK Aviation Fuels Committee is another standard for aviation turbine fuel that
56
57 defines the requirements for Jet A-1. Jet A-1 according to the DEF STAN 91-91 is very similar
58
59
60
61

1
2
3
4 to Jet A-1 defined by the ASTM D1655 except for a small number of areas where DEF STAN
5
6 91-91 is more stringent. Similar to ASTM D7566, DEF STAN 91-91 in its Annex D also
7
8 specifies the additional requirements for jet fuels that contain synthetic components. In addition,
9
10 we note that Sasol SSJF[®] and Sasol FSJF[®] fuels have been approved in DEF STAN 91-91 [47].
11
12

13
14 There are also many other national jet fuel specifications. Most of them are based on either
15
16 US (ASTM), UK (DEF STAN 91-91), or Russian (GOST 10227) specifications. There has been
17
18 increasing moves to harmonize the small differences between the ASTM and DEF STAN as well
19
20 as other national specifications.
21
22

23
24 As jet fuel supply becomes more complex with the development of alternative fuels, an
25
26 international specification known as Aviation Fuel Quality Requirements for Jointly Operated
27
28 Systems (AFQRJOS) Checklist has been proposed and recognized by a group of oil companies
29
30 called Joint Inspection Group (JIG) [48]. This checklist is the combination of the most stringent
31
32 requirements from ASTM and DEF STAN jet fuel specifications.
33
34

35 36 37 2.3. Fuel property evaluation 38

39
40 The starting point for assessing the feasibility of ‘drop-in’ alternative jet fuels is to evaluate their
41
42 fuel properties and compare them with the known and well-characterized specifications of the
43
44 conventional jet fuels. The proposed alternative jet fuel needs to be characterized with respect to
45
46 its composition and physico-chemical properties to ensure its safety, reliability, and
47
48 compatibility with today’s airframe components and aero-engines. Further, the fuel property
49
50 evaluation can provide insights into the fuel performance and its potential behavior during its
51
52 implementation.
53
54

55
56 A conventional jet fuel, such as Jet A, is a mixture of hundreds of hydrocarbons from
57
58 different molecular classes, including n-paraffins, iso-paraffins, cyclo-paraffins, and aromatics.
59
60

1
2
3
4 The different molecular classes can have different effects on the fuel properties such as density,
5
6 fluidity, volatility, energy content, and combustion characteristics. These properties mainly
7
8 depend on the bulk composition of the jet fuel and are weighted averages of all the individual
9
10 components [22]. Specifically, the higher concentration of long n-paraffins can increase fuel
11
12 energy content (per mass) and improve the combustion performance, but they can result in
13
14 poorer low-temperature properties. While more iso-paraffins can improve fuel low-temperature
15
16 properties, their reactivity is generally lower as compared to n-paraffins. On the other hand,
17
18 cyclo-paraffins and aromatics can lead to higher fuel density, but they have lower resistance to
19
20 flame extinction [49] and higher sooting propensity compared to normal and iso-paraffins [50].
21
22
23

24
25
26 Compared to conventional jet fuels, alternative jet fuels usually contain less molecular
27
28 classes. Table 1 shows and compares the ASTM standards and fuel properties of Jet A, JP-8, and
29
30 six representative alternative jet fuels, including Syntroleum S-8[®], Shell GTL[®], Sasol IPK[®] (Iso-
31
32 Paraffinic Kerosene), R-8, CHRJ (Camelina-based HRJ), and THRJ (Tallow-based HRJ). It can
33
34 be seen that these alternative jet fuels are primarily composed of iso- and normal paraffins with a
35
36 small fraction of cyclo-paraffins and negligible aromatics. Due to the different feedstocks and
37
38 manufacturing processes, there can be significant differences among the alternative jet fuels in
39
40 the spread of hydrocarbons as well as the ratio of normal to iso-paraffins and the presence of
41
42 cyclo-paraffins.
43
44
45
46
47

48
49 Again, the differences in fuel composition can result in different fuel properties. For
50
51 example, the freezing point is strongly dependent on the carbon number and the fraction of n-
52
53 paraffins. For the same carbon number, n-paraffins freeze at higher temperature than other
54
55 compounds. As shown in Table 1, Sasol IPK[®] has the lowest freezing point among all the fuels
56
57 due to its much smaller amount of n-paraffins. The viscosity of fuel is more related to the
58
59
60
61
62
63
64
65

1
2
3
4 molecular weight than the hydrocarbon class; Shell GTL[®] is the lightest fuel among all the
5
6 alternative jet fuels and thus has the lowest viscosity.
7
8

9 To control the fuel quality, fuel specifications are used to confine the fuel properties within
10 the acceptable range. In particular, alternative jet fuels should have a heat of combustion no less
11 than 42.8 MJ/kg, a flash point no less than 38°C, and a freezing point not greater than -47°C [54].
12
13 Most of requirements can be met by the alternative jet fuels that are listed in Table 1, except for
14 density. Alternative jet fuels usually have lower densities than the minimum requirement of 775
15 kg/m³ at 15°C specified in both ASTM D1655 and DEF STAN 91-91. The low density of
16 alternative jet fuels is attributed to their small quantity of cyclo-paraffins and aromatics and can
17 be a limiting factor in the blending ratio when blending with conventional jet fuels; it is therefore
18 expected that the addition of synthetic aromatics would enable the use of fully-synthetic jet fuels
19 [55].
20
21
22
23
24
25
26
27
28
29
30
31
32

33 Fuel volatility is also an important fuel property that indicates the tendency of the fuel to
34 vaporize and thus can further affect the ignition and combustion efficiency. Fuel volatility is
35 expressed through the distillation curves as shown in Fig. 3 (data are from Refs. [13,51,56]). It is
36 seen that S-8 has the highest boiling point distribution (BPD), while Shell GTL[®] and Sasol IPK[®]
37 have the lowest BPDs. Other alternative jet fuels compared have similar BPDs as conventional
38 Jet A and JP-8. In addition, the maximum and minimum of the distillation profiles based on the
39 maximum and minimum values at each respective recovery point from the CRC world fuel
40 survey [56] are also plotted in Fig. 3 as a reference. Although the alternative jet fuels can have
41 different BPDs compared to the petroleum samples, they all meet the ASTM specification
42 maximum limit [45].
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4 Furthermore, the relatively flat BPDs of Shell GTL[®] and Sasol IPK[®] are primarily due to the
5
6 lack of heavier fractions that would have come from the light distillate if available. Such BPDs
7
8 can have effects on the results of the ignition and altitude relight tests. In general, although fuel
9
10 volatility has no direct impact on the power or economy, less volatile fuels normally have higher
11
12 heating values and thus the combustion performance is indirectly affected. Fuels with a higher
13
14 front-end volatility (i.e. lower 10% distillation temperature) have a better starting and warm-up
15
16 performance, while the deposit formation, wear, and exhaust smoke can be increased for the
17
18 fuels with a higher back-end volatility (i.e. lower 90% distillation and end-point temperatures).
19
20 As such, fuels that fail to meet distillation requirements usually cause increased pollutant
21
22 emissions.
23
24
25
26
27

28 Thermal stability is usually improved for alternative jet fuels due to the absence of
29
30 impurities, i.e. hetero-atoms, sulfur compounds, etc. However, the lack of organic acids or other
31
32 polar compounds can decrease the lubricity of fuel. The JP-8 specification requires a maximum
33
34 lubricity rating of 0.655 wear scar diameter. In addition, lubricity additive is generally required
35
36 for FSJF to ensure adequate lubricity. The lack of aromatic compounds also can cause O-ring
37
38 seals to shrink, harden, and fail. ASTM D7566 requires a minimum aromatic content of 8.0% by
39
40 volume [45]. This limit is based on the operational experience to ensure that the required ‘fit-for-
41
42 purpose’ properties (e.g., seal swell, lubricity, and material compatibility) are maintained for
43
44 both semi-synthetic fuel blends and fully-synthetic jet fuels.
45
46
47
48
49

50 In summary, compared to conventional jet fuels, alternative jet fuels are less complex in
51
52 compositions. They have excellent thermal stability and low emissions. The lack of aromatics in
53
54 alternative jet fuels could cause issues in engine applications, such as material compatibility
55
56 (elastomer swelling/shrinkage), tank gauging (density), and additive compatibility (solubility)
57
58
59
60
61

1
2
3
4 [57]. However, these issues could be resolved and would not be a hindrance to the use of
5
6 alternative jet fuels. Although most of the alternative jet fuels developed to date would likely
7
8 meet the jet fuel specification standard, each of the alternative jet fuel can exhibit its own unique
9
10 behavior. The differences in fuel properties are related to their unique characteristics imparted on
11
12 the fuel by various feedstocks. Additional studies are necessary to better understand these
13
14 characteristics to ensure that they are not significantly outside our current experience with the
15
16 existing conventional jet fuels, especially considering the objective of drop-in replacement.
17
18
19
20
21

22 2.4. Combustor component tests

23
24 Though alternative jet fuels can meet the jet fuel specifications, engine OEMs still require to
25
26 conduct a series of tests to assess various fuel performances for different combustor components.
27
28 The component tests cover a wide range of fuel performances, such as fuel atomization, ignition,
29
30 extinction, lean blowout (LBO), and emissions. Due to the variation of components from
31
32 different engine OEMs, it is difficult to define a standard or criteria for the testing components
33
34 and the associated conditions. As a result, combustor component tests are often conducted at
35
36 OEMs' facilities using different components as appropriate. Table 2 lists recent combustor
37
38 component tests reported in the literature for alternative jet fuels including both FT and HRJ
39
40 fuels.
41
42
43
44
45
46

47 In the atomization tests, Williams [58] tested the Sasol FSFJ[®] using an auxiliary power units
48
49 (APUs) atomizer. The test results showed that Sasol FSJF[®] had similar spray opening pressures,
50
51 spray angles, and spray quality as Jet A at -40°C, but produced a smaller drop-size distribution
52
53 that can provide a better cold starting [58]. Lin et al. [59] compared the atomization between a
54
55 FT CTL and a conventional RP-3 jet fuel. A slightly smaller and more uniform droplet size
56
57 distribution was also found in the spray of FT CTL at relatively lower fuel pressures [59].
58
59
60
61
62
63
64
65

1
2
3
4 Kannaiyan and Sadr [60] compared the spray characteristics of two GTL fuels with Jet A-1 in a
5
6 pilot-scale pressure swirl nozzle, and found that GTL fuels have faster disintegration and
7
8 dispersion of the droplets in the core region compared to Jet A-1. The smaller droplet size of
9
10 Sasol FSFJ[®] and FT CTL tested in [58,59] and faster disintegration and dispersion of GTL fuel
11
12 droplets in [60] are believed to be caused by their lower viscosities compared to their counterpart
13
14 conventional jet fuels. It should be noted that the viscosities of alternative jet fuels are not
15
16 necessarily always lower than those of conventional jet fuels, as shown in Table 1. Sivakumar et
17
18 al. [61] studied the atomization characteristics of a mixture of 90% HRJ and 10% aromatics from
19
20 a simplex swirl atomizer. The results showed that the experimental measured SMD Of the tested
21
22 biofuel spray agrees well with a previously reported correlation intended for conventional
23
24 hydrocarbon fuel sprays from simplex swirl atomizers.
25
26
27
28
29
30

31 In the tests of ignition and altitude relight for alternative jet fuels, the results on Sasol FSJF[®]
32
33 [62], FT GTL [63], and FT SPKs [64] showed that the tested alternative jet fuels had similar
34
35 ignition performances as the conventional Jet A and Jet A-1; and it was also found in [64] that
36
37 fuels with lower iso-to-normal ratio tended to have better ignition performance. Hermann et al.
38
39 [65] studied and compared the ignition characteristics of a FT SPK and Jet A-1, and found that
40
41 the tested FT SPK ignited under slightly richer conditions than Jet A-1. Note that the tested FT
42
43 SPK in [65] has a higher flash point and a higher viscosity than Jet A-1. It was shown in [65] that
44
45 the higher viscosity of the tested FT SPK resulted in larger droplet size which can lead to poorer
46
47 fuel vaporization and thus inferior ignition performance. Lin et al. [59] demonstrated a leaner
48
49 ignition limit for the tested FT CTL as compared to RP-3 at low liner pressure drop conditions,
50
51 which was attributed to the lower viscosity of the tested FT CTL. In addition, Mosbach et al. [66]
52
53 studied the chemiluminescence of OH and CH radicals in the transient process of flame ignition
54
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4 for FT SPK fuels, showing no discernible differences between the tested SPK fuels and Jet A-1.
5
6 Burger et al. [67] studied the ignition and extinction behaviors of eight fuels, including
7
8 conventional Jet A-1, SPKs, aromatic solvents, and pure compounds, in a representative aero-
9
10 combustor. Their results showed that all the tested fuels have comparable ignition and extinction
11
12 performance to conventional Jet A-1.
13
14

15
16 While the lean blowout tests of [58,68] showed no significant differences between the tested
17
18 alternative jet fuels and conventional ones, the results of [59] demonstrated a better LBO
19
20 performance for the tested FT CTL than RP-3 at low liner pressure drop conditions, which could
21
22 be caused by the different fuel distillation curves as suggested by the authors. Burger et al. [69]
23
24 has systematically studied the lean blowout behavior of Sasol FSJF[®], SPK, Jet A-1, and other
25
26 fuel blends in a heterogeneous laboratory combustor. The LBO results were correlated with fuel
27
28 properties that included distillation profile, density, viscosity, flash point, and ignition delay. A
29
30 strong correlation was found between the LBO limits and the fuel volatility, i.e. stability limits
31
32 were reduced with decreasing volatility [69]. Density and viscosity were also found to have
33
34 positive correlations in that a decrease of density and viscosity resulted in lower LBO limits and
35
36 thus wider stability limits. Other fuel properties were found to have weak or no correlations with
37
38 the observed LBO behavior [69].
39
40
41
42
43
44

45
46 Combustor emission tests are typically conducted to measure the pollutant emissions such as
47
48 CO, NO_x, unburned hydrocarbon (UHC), and soot (smoke). In the tests for alternative jet fuels,
49
50 Biddle [70] found that Sasol FSJF[®] produced 4% less NO_x and 19% less CO than Jet A in the
51
52 landing and takeoff (LTO) cycle, while UHC emissions were only reported in the idle conditions
53
54 and were comparable for both fuels. The notable reduction in CO emissions was believed to be
55
56 caused by the finer droplet size of Sasol FSJF[®] in the fuel spray, as shown in [58]. Hermann et
57
58
59
60
61

1
2
3
4 al. [65] also studied the emissions of a FT SPK fuel at different inlet air temperatures and fuel/air
5 ratios (F/A). The results of [65] showed that CO emission index for SPK was higher than that for
6
7 Jet A-1 in the leaner conditions and was lower in the richer conditions; and NO_x emission index
8
9 for SPK was lower than that for Jet A-1 in all the tested conditions, except for rich conditions at
10
11 high inlet air temperatures. Shouse et al. [68] compared the emissions of a FT GTL with those of
12
13 JP-8 and found that CO emission of GTL was lower than that of JP-8 for all the tested F/A, while
14
15 NO_x emission of GTL was lower than that of JP-8 at leaner conditions, but higher at richer
16
17 conditions. Other tests of [59,71] showed no significant differences in CO and NO_x emissions
18
19 between the tested alternative and conventional jet fuels. Although differences are observed, the
20
21 emissions of CO and NO_x are generally in the same levels for both alternative and conventional
22
23 jet fuels; the major difference in emissions with alternative jet fuels is in soot emission. In
24
25 particular, the combustor emission tests of [65,68,70-72] all showed significant reductions in
26
27 soot (smoke) emission when using alternative jet fuels. For example, Pucher et al. [71] showed
28
29 that a 100% GTL and a 50/50 GTL/Jet A-1 blend had 83% and 65% reductions in smoke
30
31 emission, respectively, compared to the base Jet A-1 fuel; and a 100% HRJ had 96% reduction in
32
33 smoke emission. Furthermore, the combustor deposits study in [72] showed a significant
34
35 reduction in carbon and coke formation for using alternative jet fuels, as demonstrated in Fig. 4;
36
37 it was found that the synthetic 100% GTL and 50/50 GTL/Jet A-1 blend had 95% and 64%
38
39 reductions in combustor deposits compared to Jet A-1, respectively. The substantial reduction in
40
41 soot formation is, as expected, due to the lack of aromatic compounds in alternative jet fuels.
42
43
44
45
46
47
48
49
50
51
52

53 Based on the above-mentioned tests, it is seen that combustor performances can be
54
55 dependent on the fuel properties. However, due to the variation of the testing components and
56
57 operating conditions, the testing results can only be interpreted under their respective testing
58
59
60
61
62
63
64
65

1
2
3
4 environments. To continuously improve the fuel certification process, standard testing methods
5
6 are desirable in order to facilitate and streamline the testing practice. Though the current
7
8 combustor components tests can be very different from each other, it can still be concluded from
9
10 the testing results reported in the literature that the tested alternative jet fuels have no adverse
11
12 effects on the combustor efficiency and emissions as compared to conventional jet fuels. Further,
13
14 the soot emission can be drastically reduced when switching to or blending with alternative jet
15
16 fuels due to their lack of aromatic components.
17
18
19
20
21

22 2.5. Engine tests

23
24 Ground engine tests are required upon completion of the combustor component tests in order to
25
26 evaluate the fuel performance on the entire engine system. The purpose of the engine tests is to
27
28 ensure the reliability and safety of alternative jet fuels and also to evaluate their pollutant
29
30 emissions for all types of aero-engines such as turbofan, turboshaft, and APUs.
31
32
33

34 Recently, many engine tests have been conducted on various engines using conventional jet
35
36 fuels and alternative FT and HRJ fuels, as well as their fuel blends. For example, Bester and
37
38 Yates [73] conducted tests in a T63 gas turbine engine using FT SPK and Jet A-1; Bulzan et al.
39
40 [74] measured gaseous and particulate emissions in a CFM56-2C1 engine on NASA's DC-8
41
42 aircraft using two FT fuels, JP-8, and their 50/50 blends; Timko et al. [75] measured the
43
44 emissions in the PW 308 engine using FT and JP-8 fuels; Corporan and co-workers [76-78]
45
46 studied the emission characteristics of FT, HRJ, and JP-8 fuels in various aircraft engines;
47
48 Klingshirn et al. [79] evaluated the engine performance and emissions in a T63 turbine engine
49
50 using HRJ and JP-8 fuels. [Badami et al. \[80\] measured the emissions of Jet A, GTL, and a blend](#)
51
52 [of 70% Jet A and 30% jatropha methyl ester in a small-scale SR-30 engine.](#) [Khandelwal et al.](#)
53
54 [\[81\] compared emissions performance and vibration for Jet A-1 and two SPK fuels in a small gas](#)
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4 turbine engine. Altaher et al. [82] measured UHC and carbonyl compounds of Jet A-1, GTL,
5
6 HRJ, and HEFA from the exhaust gas of an APU gas turbine engine. Overall, the engine test
7
8 results for alternative jet fuels in the above-mentioned studies showed no operational anomalies
9
10 or detrimental effects on the engine performance compared to conventional jet fuels, while some
11
12 improvements were observed. Specifically, about 1.2% improvement in thermal efficiency was
13
14 observed in [73] for FT SPK compared to Jet A-1; the improvement was mostly attributed to the
15
16 higher H/C ratio and lack of aromatics of the tested FT SPK. Also, engine emission profiles
17
18 [73,74,78-81] showed that the differences in CO and NO_x emissions between conventional and
19
20 alternative jet fuels were small, while some notable improvements in CO emissions were
21
22 reported in [77]. All engine tests discussed herein showed dramatic reductions in soot and sulfur
23
24 oxide emissions, which is consistent with combustor emission tests mentioned in the previous
25
26 section. It was further found in [75,76] that the tested FT fuels produced smaller soot particles
27
28 than conventional JP-8. Moreover, despite the complex and varying engine combustor
29
30 characteristics, a strong correlation between relative PM emissions and engine power was
31
32 observed in [78]. It was suggested in [78] that this correlation can be potentially used to predict
33
34 alternative fuel PM emissions. However, additional tests and inclusion of fuel chemistry are
35
36 warranted to improve the robustness and validation of these correlations.
37
38
39
40
41
42
43
44
45

46 2.6. Flight tests

47
48 The flight test is the final testing step to demonstrate the use of a candidate jet fuel on a flying
49
50 aircraft. As more alternative jet fuels have been developed, flight tests have been conducted more
51
52 frequently for alternative jet fuels by many governments and commercial airlines.
53
54

55
56 Figure 5 summarizes the flight tests for alternative jet fuels since 2006. It is seen that the
57
58 USAF has been playing a leading role in flight demonstrations of alternative jet fuels.
59
60

1
2
3
4 Specifically, in 2006 USAF conducted a flight test on B-52 Stratofortress using a 50/50 blend of
5
6 FT synthetic S-8 and JP-8, and the B-52 was the first aircraft approved by USAF of the use of
7
8 alternative jet fuels [83]. Since then, a series of flight tests using FT synthetic fuel blends have
9
10 been conducted by USAF on different military aircraft including C-17, F15, F22, etc. In 2010,
11
12 USAF for the first time tested a blend of HRJ (CHRJ) and JP-8 on A-10 Thunderbolt. This test
13
14 was a part of the effort that aims to evaluating candidate bio-jet fuels from various biomass
15
16 materials with the least environmental impact. The CHRJ fuel blend has also been demonstrated
17
18 later on other military aircraft by both USAF and US Navy. In 2012, USAF first flew an A-10
19
20 aircraft with a new fuel blend derived from alcohol (alcohol-to-jet, ATJ). In 2014, US Navy also
21
22 conducted a test flight of F/A-18 Hornet fighter jet using an alcohol-based fuel blend. Both of the
23
24 tests have proven that ATJ is a viable alternative jet fuel.
25
26
27
28
29
30

31 Commercial airlines, aircraft OEMs, fuel manufacturers, and other government agencies
32
33 have also been active players in the flight tests of alternative jet fuels. In 2008, the Airbus A380
34
35 has become the first commercial aircraft to complete a flight using a FT GTL fuel blend. In the
36
37 same year, Virgin Atlantic Airways conducted the first biofuel test with a GE CF6-powered
38
39 Boeing 747-400 using a 20% mix of biofuel composed of babassu oil and coconut oil, while Air
40
41 New Zealand conducted a test flight using a Boeing 747-400 with a Rolls-Royce engine powered
42
43 by a biofuel blend of standard jet fuel and kerosene derived from jatropha oil. In 2010, the South
44
45 Africa fuel manufacturer Sasol has flown the world's first passenger aircraft using internationally
46
47 approved 100% synthetic jet fuel. In 2010, the Dutch military conducted the first flight test on
48
49 the Ah-64 Apache helicopter using a bio-jet fuel blend that was derived from waste cooking oil.
50
51 The first flight test using 100% bio-jet fuel was conducted by National Researcher of Canada in
52
53 2012; the bio-jet fuel was derived from carinata oil and met jet fuel specifications without
54
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4 blending. In 2014, a research campaign supported by NASA, German Aerospace Center, and
5
6 National Research Council of Canada has been underway in California to investigate the effects
7
8 of alternative fuels on aircraft emissions and contrail formation [84]. This research was focused
9
10 on the transition of industry to low-carbon and alternative propulsion systems. In 2014, Boeing
11
12 has completed the world’s first flight using ‘green diesel’, a sustainable bio-fuel made from
13
14 vegetable oils, waste cooking oil, and waste animal fats. In 2011, China conducted its first flight
15
16 demonstration on a Boeing 747 using a bio-jet fuel blend derived from jatropha. Subsequently in
17
18 2013, China’s first bio-jet fuel, CBF-1, developed by Sinopec was demonstrated on an Airbus
19
20 A320, while in the following year CBF-1 was approved by the Civil Aviation of Administration
21
22 of China for commercial use. In 2015, Hainan Airlines flight conducted China’s first commercial
23
24 flight using a 50–50 mix of conventional jet fuel and biofuel made from waste cooking oil on a
25
26 Boeing 737-800 passenger flight. To move toward a green aviation, many other airlines around
27
28 the world as shown in Fig. 5 have also conducted many flight tests using alternative jet fuels that
29
30 are derived from different sources, mostly from biomass.
31
32
33
34
35
36
37
38
39

40 **3. Fundamental Combustion Properties**

41
42 As the development of alternative jet fuels has been gaining more momentum, a great effort has
43
44 been devoted to the fundamental studies on alternative jet fuel characterization, mostly on the
45
46 combustion characteristics in order to gain better understanding of alternative fuel chemistry.
47
48 Since alternative jet fuels can vary significantly in composition as compared to conventional jet
49
50 fuels, such fundamental combustion studies can provide insights into the impact of fuel
51
52 properties on combustion and engine performance. The fundamental combustion properties of
53
54 interest include ignition characteristics, flame properties, extinction limits, emissions, and
55
56 combustion speciation. These combustion responses can be very sensitive to the fuel
57
58
59
60
61
62
63
64
65

1
2
3
4 compositions and molecular structures, and are directly linked to the engine performances such
5
6 as blowout, altitude relight, combustor efficiency, and emissions. Moreover, there are significant
7
8 cost benefits that can be obtained by developing a more streamline combustion testing programs
9
10 that includes these fundamental combustion studies [54]. The fundamental combustion data
11
12 obtained can enable fuel manufacturers to improve their fuel developing process and screen out
13
14 unacceptable fuels prior to expensive component and engine test. In addition, these fundamental
15
16 combustion data can facilitate the development of alternative jet fuel surrogates and their
17
18 chemical kinetic models that can be further used to enable quantitative emissions and
19
20 performance predictions using combustion modeling.
21
22
23
24
25
26

27 3.1 Autoignition delay time

28
29 Autoignition delay time is an important parameter in the combustor design of aircraft engines. In
30
31 engine combustion, rapid spontaneous ignition and the subsequent complete reaction of the fuel
32
33 are required to achieve efficient combustion. Most autoignition studies have been conducted for
34
35 homogeneous fuel/oxidizer mixtures in a closed device, such as shock tube and rapid
36
37 compression machine (RCM). Autoignition delay time measured in such devices is ideally solely
38
39 controlled by the chemical kinetics that depends on pressure and temperature histories of the
40
41 given fuel/oxidizer mixture, and can vary widely for different fuels. The autoignition delay time
42
43 is typically defined as the time interval between the starting reference point, e.g., the end of
44
45 compression in an RCM or the arrival of incident (or reflected) shock wave in a shock tube, and
46
47 the onset of ignition. The major difference between shock tube and RCM is their
48
49 testing/operating range; shock tube is more suitable in the high temperature range for short
50
51 ignition delay measurements, while RCM is generally used in the low-to-intermediate
52
53 temperature range for relatively longer ignition delay measurements. With the current
54
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4 development of RCM and shock tube facilities, their testing ranges can overlap with each other.
5
6 However, discrepancies were observed between shock tube and RCM data in some overlapping
7
8 ranges, and cautions need to be exercised by taking the facility effects into account when
9
10 interpreting and comparing the results from shock tube and RCM [85,86].
11
12

13
14 A number of studies have measured the autoignition delay times for conventional and
15
16 alternative jet fuels. For example, Vasu et al. [87] measured the autoignition delay times of Jet A
17
18 and JP-8 in a heated shock tube and in the temperature range of 715–1229 K and pressures of
19
20 17–51 atm; Kumar and Sung [88,89] measured the autoignition delay times in RCM for Jet A,
21
22 JP-8, and S-8 in the low-to-intermediate temperature range of 615–1100 K at pressures of 7, 15,
23
24 and 30 bar; Wang et al. [90] used a heated shock tube and measured the autoignition times of Jet
25
26 A, S-8, Shell GTL[®], and Sasol IPK[®] in a wide temperature range of 651–1381 K at pressures
27
28 varying from 8 to 39 atm; Allen et al. [91] measured the autoignition delay times of JP-8, CHRJ,
29
30 and THRJ in a RCM in a low temperature range of 625–730 K at pressures of 5, 10, and 20 atm.
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Zhu et al. [92] measured the ignition delay times of JP-8, HRJ, and FT fuels in the temperature range of 1047–1520 K, equivalence ratios of 0.25–2.2, and two pressure ranges of 2.07–8.27 atm for fuel/air mixtures and 15.9–44.0 atm for fuel/4%O₂/Ar mixtures. Valco et al. [93] measured the ignition delay times of JP-5, JP-8, two HRJ, and two FT fuels in RCM and shock tube in the temperature range of 625–1000 K and pressure of 20 atm. Figure 6 plots and compares the ignition delay times reported in the literature for various jet fuel/air mixtures at an equivalence ratio of 1.0 and a pressure of 20 atm. It is seen that in high temperature regime (>900 K) both conventional jet fuel (Jet A) and FT SPK fuels (S-8, Shell GTL[®], and Sasol IPK[®]) have similar ignition delay times. Below 900 K, Jet A and FT SPK fuels start to differ from each other, but all the jet fuels in Fig. 6 show a slightly decreasing ignition delay time with decreasing

1
2
3
4 temperature in a temperature range of approximately 750–900 K, thereby exhibiting a negative
5
6 temperature coefficient (NTC) response. It is further noted that the NTC regime is known to have
7
8 strong pressure dependence and to shift to higher temperatures with increasing pressures. While
9
10 the NTC regime may be relatively unimportant for the present aero-engines, this regime is
11
12 expected to be of increased interest in advanced, next-generation engines of high efficiency and
13
14 compression ratio.
15
16
17

18
19 In the low temperature regime (<750 K), there are notable differences in autoignition delay
20
21 times between conventional jet fuels and alternative FT and HRJ fuels. It appears that in the low-
22
23 to-intermediate temperature regime conventional jet fuels have longer autoignition delay times
24
25 than alternative jet fuels, except for Sasol IPK[®]. The relatively longer autoignition delay time of
26
27 Sasol IPK[®] is mainly attributed to its lack of reactive normal paraffins [90]. The different
28
29 ignition propensities observed in the low-to-intermediate temperature regime indicate that there
30
31 can be significant differences in the low-temperature chemistry, which is more specific and
32
33 sensitive to fuel composition and structure as compared to the high-temperature chemistry.
34
35 Recognizing that the NTC regime is expected to play an important role in future high-efficiency
36
37 aero-engines, the low-to-intermediate temperature chemistry of alternative jet fuels merits further
38
39 investigation. Other autoignition study of 50/50 (by volume) HRJ/JP-8 blends in the low
40
41 temperature regime showed that the autoignition delay times of binary fuel blends are always
42
43 bounded by the two baseline jet fuels [94].
44
45
46
47
48
49
50

51 3.2 Derived cetane number

52
53 Derived cetane number (DCN) is another parameter describing ignition characteristics in
54
55 compression ignition engines. The higher DCN value means shorter ignition delay time and more
56
57 likely the complete combustion of fuel charge in the combustor, which translates into a smoother
58
59
60
61

1
2
3
4 running and better performing engine with more power and less emissions. Unlike the
5
6 autoignition delay time measured for premixed, pre-vaporized mixtures in a homogenous
7
8 environment, the ignition delay time measured for determining DCN is defined as the time
9
10 interval from injection of the fuel to the start of combustion (hot ignition). The whole process
11
12 includes fuel spraying, vaporization, fuel/air mixing, and ignition. Thus the DCN derived from
13
14 this ignition delay time provides a direct measurement of ignition propensity in the compression
15
16 engine conditions. There are two ASTM standard devices for DCN measurement: fuel ignition
17
18 tester (FIT) [95] and ignition quality tester (IQT) [96]. Both devices utilize a constant volume
19
20 combustion chamber (0.60 ± 0.03 L for FIT and 0.213 ± 0.002 L for IQT) into which the fuel is
21
22 injected; the chamber is initially kept at 2.40 ± 0.02 MPa and 510 ± 50 °C for FIT and at
23
24 2.137 ± 0.007 MPa and 545 ± 30 °C for IQT. An empirical correlation is used to calculate the DCN
25
26 value based on the measured ignition delay time. Both FIT and IQT methods can produce fast,
27
28 repeatable, and reliable DCN results in a range of about 30 to 65, which is the typical range for
29
30 kerosene fuels.
31
32
33
34
35
36
37

38 The DCN values of conventional and alternative jet fuels reported in various studies
39
40 [53,57,97-99] are listed in Table 3. Jet A has a FIT DCN value of 49.35 determined by ASTM
41
42 7170 and an IQT DCN value of 47.1 determined by ASTM D6890, respectively. Though
43
44 differences are observed between FIT and IQT results, both dataset are consistent in trend for all
45
46 the jet fuels. From Table 3, it can also be seen that compared to Jet A and JP-8 all the alternative
47
48 jet fuels have notably higher DCN values, except for Sasol IPK[®] which has significantly lower
49
50 DCN values of ~33 and ~31 from FIT and IQT, respectively. The lower ignition propensity of
51
52 Sasol IPK[®] is consistent with the fact that Sasol IPK[®] is primarily composed of less reactive
53
54 branched alkanes. Although IPKs tend to have lower DCN values, they do not seem to impact on
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4 the engine performance. Therefore, there have been discussions within the community regarding
5
6 the relevance of cetane number to gas turbine engine operation, whether there is a need to
7
8 include ignition criteria for certification of alternative jet fuels, and if so, what the standard
9
10 should be.
11
12

13
14 The DCNs of conventional and alternative jet fuel blends were also measured in [53]. Figure
15
16 7 plots the DCN values of S-8/Jet A and Sasol IPK[®]/Jet A blends as a function of Jet A volume
17
18 fraction in the binary fuel blend. By definition, cetane number is a linear volumetric blend of the
19
20 blending contribution of all the components in the fuels. Most models predict the blending cetane
21
22 number based on linear combination of the cetane numbers of the components, even though there
23
24 is evidence that the linear assumption is not always correct [100]. It can be seen from Fig. 7 that
25
26 a fairly linear relationship is observed between DCN values and Jet A volume fraction in the
27
28 binary fuel blend. The linear relationship is likely due to the relatively simple composition of
29
30 alternative jet fuels. Similar linear trend has also been reported in IQT-DCN results for S-8/JP-8
31
32 and Shell GTL[®]/JP-8 blends [57].
33
34
35
36
37
38

39 3.3 Laminar flame speed 40

41 In the fundamental flame studies, laminar flame speed is one of the most important parameters of
42
43 the combustible fuel/oxidizer mixture. It is defined as the velocity of a steady, one-dimensional,
44
45 laminar propagation of a planar, adiabatic combustion wave into a uniform fuel/oxidizer mixture.
46
47 The laminar flame speed embodies the fundamental information on the diffusivity, reactivity,
48
49 and exothermicity of a given fuel/oxidizer mixture. On a practical level, laminar flame speed is
50
51 related to the fuel burning rate in the combustor, thus affects the combustion efficiency and
52
53 exhaust emissions. Over the years, several combustion facilities and techniques have been
54
55 explored and made available for measuring laminar flame speed [101]. These measurements
56
57
58
59
60
61
62
63
64
65

1
2
3
4 have employed either stationary burner flames held fixed by an upstream flow or propagating
5
6 flames in open and closed chambers. Due to the inherent imperfection in these measuring
7
8 techniques, most determinations of laminar flame speed require an extrapolation by eliminating
9
10 the effects of heat loss, flow non-uniformity, or/and flame curvature.
11
12

13
14 Recently, Kumar et al. [102] measured the laminar flame speeds of conventional Jet A and
15
16 alternative S-8 in a counterflow setup at preheat temperatures of 400, 450, and 470 K and a
17
18 pressure of 1 atm. Mz -Ahmed et al. [103] measured the laminar flame speeds of a CTL FSJF
19
20 and Jet A-1 at a preheat temperature of 473 K and pressures of 1 and 3 atm in a conical flame
21
22 burner. Also, Kick et al. [104] measured the laminar flame speeds of GTL and CTL FSJF at a
23
24 preheat temperature of 473 K and atmospheric pressure in a conical flame burner. Using an
25
26 explosion bomb, Vukadinovic et al. [105] measured the laminar flame speeds of Jet A-1, GTL,
27
28 and GTL blend with 20% aromatics at preheat temperatures of 373, 423, and 473 K and
29
30 pressures of 1, 2, and 4 atm. Furthermore, Hui et al. [53] measured the laminar flame speeds of
31
32 Jet A, S-8, Sasol IPK[®], and CHRJ in a counterflow burner at preheat temperatures of 400 and
33
34 470 K and a pressure of 1 atm. In a follow-up study using a high-pressure counterflow setup, Hui
35
36 and Sung [106] reported the laminar flame speeds of Jet A and S-8 with a preheat temperature of
37
38 400 K in the pressure range of 1–3 atm. Munzar et al. [107] measured the laminar flame speeds
39
40 of several blends of Jet A-1 and HRJ fuels at a preheat temperature of 400 K and atmospheric
41
42 pressure.
43
44
45
46
47
48
49

50
51 Figure 8 plots the literature data of atmospheric laminar flame speeds of conventional and
52
53 alternative jet fuels at a preheat temperature of about 473 K. [The laminar flame speed data were](#)
54
55 [taken from four research groups \[53,103-105\] using different flame configurations and](#)
56
57 [measurement techniques. Within each group, the measured laminar flames speeds of](#)
58
59
60
61
62
63
64
65

1
2
3
4 conventional and alternative jet fuels are quite similar, with the only exception for Jet A-1 at near
5
6 stoichiometric conditions in [104]. Differences in the laminar flame speeds among the groups are
7
8 mostly attributed to their different experimental techniques and the associated uncertainties in
9
10 measurements and extrapolation methods. Though the laminar flame speed data are scattered,
11
12 especially on the fuel rich side, all the data fall into a certain band of typical kerosene fuels. It is
13
14 well known that the laminar flame speed is strongly dictated by the flame temperature through
15
16 the Arrhenius kinetics, and the flame temperature is dependent on the heat of combustion. As
17
18 shown in Table 1, alternative jet fuels have similar heat of combustion as conventional jet fuels,
19
20 and hence both kinds of jet fuels are expected to have similar laminar flame speeds. Hui et al.
21
22 [53] have also suggested that the laminar flame speed, controlled by the high temperature
23
24 chemistry, is less sensitive to the fuel composition than ignition delay.
25
26
27
28
29
30

31 32 3.4 Extinction strain rate 33

34 Another important flame property is the flame extinction limit. The flame extinction can be
35
36 induced by either incomplete reaction or the non-equidiffusion of heat and mass in conjunction
37
38 with the flame stretch effect manifested by flow non-uniformity, flame curvature, and flow/flame
39
40 unsteadiness. In the counterflow configuration, the extinction limit is usually captured by the
41
42 strain rate of experienced by the flame at extinction. The extinction strain rate represents a
43
44 kinetics-affected phenomenon and characterizes the interaction between a characteristic
45
46 flame/flow time to a chemical reaction time. It is an important parameter to describe the flame
47
48 stability and is directly linked to the engine blowout. The extinction strain rate can be measured
49
50 both for premixed and non-premixed flames in a counterflow burner, and extinction is usually
51
52 achieved by gradually increasing the flow velocity (hence the strain rate) until a flame blowout is
53
54
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4 observed. The maximum axial velocity gradient ahead of the flame just prior to the extinction is
5
6 defined as the extinction strain rate.
7

8
9 Only a few studies have measured the extinction strain rates of conventional and alternative
10 jet fuels. In the same study of laminar flame speeds, Hui et al. [53] measured the extinction strain
11 rates of Jet A, S-8, Sasol IPK[®], and CHRJ in premixed flames at preheat temperatures of 400 and
12 470 K and a pressure of 1 atm, as shown in Fig. 9. It needs to be pointed out that the oxidizer
13 used in Ref. [53] was made of 86% N₂ and 14% O₂ by mole in order to achieve extinction at
14 moderate strain rates. The results in Fig. 9 show similar but slightly higher extinction strain rates
15 for alternative jet fuels compared to conventional Jet A. Ji et al. [108] also measured the
16 extinction strain rates of JP-8, S-8, Shell GTL[®], and R-8 using normal air in both premixed and
17 non-premixed flames at 403 K preheat temperature and atmospheric pressure. Similar
18 observation was made in [108] for both premixed and non-premixed flames that all the tested
19 alternative jet fuels had similar extinction strain rates, which were higher than that of
20 conventional JP-8. Dooley and co-workers [52,98] measured extinction strain rates of Jet A and
21 S-8 in non-premixed flames with fuel side temperature at 500 K and air side temperature at room
22 temperature. The results of [52,98] are plotted in Fig. 10, showing that alternative S-8 has
23 notably higher extinction strain rates than conventional Jet A in the non-premixed flames.
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44

45 Based on the above studies, it can be concluded that alternative jet fuels are more resistant to
46 flame extinction than conventional jet fuels, especially in the non-premixed flame environments.
47
48 The greater resistance is mostly due the absence of the less reactive aromatic components in the
49 alternative jet fuels. The results also suggest that flame extinction limit is relatively more
50 sensitive to the fuel composition than laminar flame speed.
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

3.5 Threshold sooting index

The threshold sooting index (TSI) is defined in Eq. (1) by Calocte and Manos [109] as:

$$\text{TSI} = a \left(\frac{\text{Molecular Weight}}{\text{Smoke point}} \right) + b, \quad (1)$$

where the smoke point is the maximum smoke-free laminar non-premixed flame height (mm), molecular weight is in g/mol, and the coefficients of a (mol·mm/g) and b (dimensionless) are experimental constants. The TSI is a macro measure of the tendency of a fuel to form soot under diffusive/mixing limited conditions, and a useful parameter in predicting soot formation in practical combustors based on basic fuel compositions. If a correlation can be demonstrated between the TSI value measured in laboratory and the amount of soot formed in practical systems, then TSI can also be used in the fuel production process to define the desired fuel components from a given feedstocks. A few studies (e.g., [110,111]) have proposed correlations for jet fuels in order to use TSI to predict soot formation in aircraft engines.

Table 4 lists the TSI values of several conventional and alternative jet fuels available in the literature. As expected, since conventional Jet A and JP-8 include aromatic components in their compositions, they have the highest TSIs. Among the alternative jet fuels, Sasol IPK[®] has the highest TSI due to its heavily branched alkane compositions. It is further noted that the soot propensities for different hydrocarbon classes are generally, but not strictly, ranked as aromatics > cyclic alkanes > branched alkanes > linear alkanes [109]. As Shell SPK[®] has the lowest TSI, it is most likely composed mainly of linear alkanes.

3.6 Combustion speciation

To further expand our combustion knowledge of alternative jet fuels with respect to their oxidation kinetics, speciation measurement is an important means to identify and quantify the important intermediate species and oxidation products. Speciation measurement is usually

1
2
3
4 conducted in a well/jet stirred reactor or flow reactor for premixed flames. Such speciation data
5
6 can be used to assess the fuel reactivity and to reveal possible pathways in the fuel oxidation
7
8 process. Highlighted below are a number of studies that have been devoted to the combustion
9
10 species measurements of alternative jet fuels.
11
12

13
14 Stouffer et al. [112] measured the oxidation products (CO_2 , H_2O), O_2 , and gaseous
15
16 emissions (CO , UHC) of FT S-8 and JP-8 in a jet stirred reactor. It was found that gaseous
17
18 emissions were similar for the two jet fuels and differences in the H_2O and CO_2 products
19
20 appeared to be directly related to the C/H ratio of the fuels. In addition, similar NO_x emissions
21
22 were found by Naik et al. [113] in counterflow premixed flames for S-8, Shell GTL[®], and R-8.
23
24 Won et al. [99] measured CO , CO_2 , CH_2O , O_2 , and H_2O for Shell IPK[®], CHRJ, Sasol IPK[®], and
25
26 JP-8 in a flow reactor. The results of [99] for O_2 and H_2O are shown in Fig. 11, based on which
27
28 the relative fuel reactivity can be ranked as Shell IPK[®] > CHRJ > JP-8 > Sasol IPK[®]. Other
29
30 species and heat release all showed similar trend in reactivity as Fig. 11. The lowest reactivity of
31
32 Sasol IPK[®] is consistent with the lowest DCN values measured both in FIT and IQT.
33
34
35
36
37

38
39 Mzé-Ahmed and coworkers [103,114] also measured intermediate species and oxidation
40
41 products of synthetic jet fuels and Jet A-1 in a jet stirred reactor. Their results showed strong
42
43 similarity between alternative and conventional jet fuels, whereas some differences were
44
45 observed mainly for some intermediate species, such as CH_2O , CH_4 , C_2H_4 , and C_3H_6 . Further,
46
47 Dagaut et al. [115] studied the oxidation of a GTL fuel at 10 atm over the temperature range of
48
49 550–1150 K in a jet stirred reactor. It was found that the GTL oxidized rapidly, yielding
50
51 saturated (mostly CH_4) and unsaturated (olefins) hydrocarbon intermediates, as well as
52
53 oxygenates (mainly CH_2O and CO) under the conditions studied. A comparison with Jet A-1
54
55 showed that both fuels oxidized similarly.
56
57
58
59
60
61
62
63
64
65

4. Surrogates for Alternative Jet Fuels

4.1 Surrogate fuel concept

Computational engine modeling is an essential complementary tool for the engine manufacturers to test new engine components on computer before fabricating expensive prototypes. It also can be used to predict the engine efficiency and exhaust emissions for newly developed alternative jet fuels. The predictability of the numerical simulations relies on the fuel models of high-fidelity that can accurately describe the fuel properties and behaviors in different engine components and operating conditions. However, practical jet fuels are composed of hundreds of hydrocarbons from different molecular classes. The complexity of fuel composition makes it impossible for direct engine simulations even with today's computational power. A pragmatic way to overcome this difficulty is to use a surrogate fuel model. The underlying concept of a surrogate fuel is to mimic the behaviors of the target real fuel with manageable size that can be computed in a reasonable time frame. A surrogate is defined as a mixture of a limited number of hydrocarbons whose composition can be formulated in order to best emulate real fuel properties, such as physical properties, chemical properties, or even both. Edwards and Maurice [116] have defined two types of surrogates: physical surrogate and chemical surrogate. Physical surrogates are constructed to reproduce the thermophysical properties such as viscosity, thermal conductivity, energy density, distillation curves, surface tension, phase diagram etc. On the other hand, chemical surrogates are generally designed to have the same chemical-class composition and molecular weight as the target real fuels to reproduce selected aspects of combustion characteristics. A single component surrogate may be able to reproduce one or a few combustion characteristics of the target real fuel, but is not likely to capture a broader range of characteristics and certainly cannot reflect the carbon number distribution and molecular classes of real fuels.

1
2
3
4 As a consequence, multi-component surrogates are usually favored for their broader applications.
5
6 In addition, capturing some physical properties in chemical surrogates is also useful in
7
8 combustion modeling where fuel atomization and evaporation are involved.
9

10 11 12 4.2 Surrogate formulation 13

14
15 Over the years, the surrogate strategy has received considerable attention for conventional jet
16
17 fuels (e.g., [52,97,116-120]). Recognizing that surrogate models can be a powerful tool to the
18
19 screening process by reducing the number of expensive full-scale rig and engine tests required to
20
21 certify a candidate jet fuel, recent progress has been contributing to surrogate formation for
22
23 alternative jet fuels. Table 5 summarizes recent developments of surrogates for alternative jet
24
25 fuels [98,113-115,121-124]. It is seen that based on different intended applications for various
26
27 alternative jet fuels, their surrogates can differ significantly in the compositions and validation
28
29 targets, as well as the methodologies with which they were formulated.
30
31
32

33
34 Huber et al. [121] proposed a seven-component surrogate mixture to represent
35
36 thermophysical properties of the synthetic S-8 fuel. An advanced distillation curve measurement
37
38 [125] was employed to improve the volatility characteristics of the surrogate to better emulate
39
40 the thermodynamic and transport properties of real S-8 fuel. In Huber et al. [121], the surrogate
41
42 was formulated through two steps: (1) candidate component selection based on real fuel
43
44 composition analysis and (2) composition determination through a multi-property regression that
45
46 minimizes the differences between experimental and predicted thermophysical property data of
47
48 S-8. The results of Huber et al. [121] showed that the proposed surrogate matched very well with
49
50 S-8 in terms of distillation curve, and the density, speed of sound, thermal conductivity, and
51
52 viscosity of the surrogate were also found to agree fairly well with those of S-8. Later, Huber et
53
54 al. [122] further demonstrated the use of on-demand equations of state (EOS) to develop a
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4 surrogate model that describes the volatility behavior of a biomass-based fuel. Following the
5
6 same step (1) described in [121], Huber et al. [122] first generated the EOS from the NIST
7
8 ThermoData Engine [126], and subsequently used the EOS to determine the surrogate
9
10 composition. A five-component surrogate was developed based on the on-demand EOS approach
11
12 and was shown to be able to represent the distillation curve of S-8 within 0.1% accuracy [122].
13
14

15
16 Naik et al. [113] developed a detailed, high-temperature (above 1000 K) chemical kinetic
17
18 model for the proposed surrogates of two FT fuels (i.e. Shell GTL[®] and S-8) and one HRJ fuel
19
20 (i.e. R-8). A software tool known as the surrogate blend optimizer (SBO) was employed to
21
22 determine an optimum surrogate blend composition for the target real fuel by matching the user-
23
24 defined performance targets which can include any combination of chemical composition, cetane
25
26 number, H/C molar ratio, lower heating value, density, and true boiling point curve. A genetic
27
28 algorithm and a direction set algorithm were also implemented in SBO for global and local
29
30 optimizations, respectively [113]. The two FT fuel surrogates were validated against laminar
31
32 flame speeds, extinction strain rates, and NO_x data measured in counterflow premixed flames. It
33
34 was found in [113] that the two FT fuel surrogates with the detailed kinetic model were able to
35
36 accurately predict these combustion properties of the real FT jet fuels.
37
38
39
40
41

42
43 Dooley et al. [98] proposed a two-component surrogate for S-8 to emulate its gas-phase
44
45 chemical kinetic combustion phenomena. This S-8 surrogate was formulated on a specific basis
46
47 through the sharing of H/C molar ratio, DCN, TSI, and average molecular weight. The distinct
48
49 chemical functionalities [97] that describe the production/consumption of intermediate species
50
51 were also used in selecting candidate surrogate components that can produce the same distinct
52
53 chemical functionalities as the real fuel components. The final composition of the surrogate in
54
55 [98] was determined by matching certain combustion property targets, such as ignition delay
56
57
58
59
60
61
62
63
64
65

1
2
3
4 time, laminar flame speed, extinction strain rate, etc. The two-component S-8 surrogate was
5
6 further validated against species concentration data measured in a flow reactor, shock tube
7
8 ignition delay data, and non-premixed flame extinction strain rates [98]. The good agreement
9
10 between the surrogate and S-8 indicated that the underlying theory of distinct chemical
11
12 functionalities, in addition to the combustion oriented metrics, is appropriate in surrogate fuel
13
14 formulation [98].
15
16
17

18
19 Other studies on surrogate formulation for alternative jet fuels are also noted. Slavinskaya et
20
21 al. [124] used an optimization method with a similar set of criteria as Naik et al. [113] to propose
22
23 surrogates for synthetic GTL, while Mzé-Ahmed et al. [103] and Dagaut et al. [115] proposed
24
25 their surrogates based on matching the oxidation species with those of the target alternative jet
26
27 fuels. It is of interest to point out that both [103] and [115] suggested the inclusion of cyclo-
28
29 paraffins and aromatics in their surrogate composition.
30
31
32
33

34 35 **5. Concluding Remarks and Future Directions**

36
37
38 To achieve a sustainable and green aviation, alternative jet fuels hold enormous potential in
39
40 reducing the energy reliance on petroleum as well as aviation emissions. Initiatives have been
41
42 developed around the globe to explore all sorts of alternative fuel sources and the associated
43
44 technologies for the comprehensive use of alternative fuels in aviation. Alternative jet fuels can
45
46 be derived from a wide variety of feedstocks such as coal, natural gas, and biomass. Due to the
47
48 different feedstocks, each alternative jet fuel has its own unique behavior and must be certified
49
50 through a series of rigorous evaluation and tests before commercialization. Many alternative jet
51
52 fuels developed up to date have already been demonstrated successfully in both military and
53
54 commercial aircraft. The results are encouraging in that they have shown no adverse effects on
55
56 the combustor efficiency and gaseous emissions, while a significant reduction in soot emissions
57
58
59
60
61

1
2
3
4 can be achieved compared to conventional jet fuels. In addition, beyond improvements in fuel
5
6 efficiency, renewable jet fuels offer another means to reduce net carbon emissions.
7
8

9 As environmental and geopolitical concerns are driving demand for petroleum alternatives
10
11 in aviation, it is also of importance to develop sustainability metrics for alternative jet fuels. The
12
13 metrics include, but are not limited to, renewability, economic viability, environmental impact,
14
15 energy security, etc. For commercial purpose in particular, alternative jet fuels need to be
16
17 sustainable, able to be produced domestically and with diversity, cost-competitive, and capable
18
19 of being produced in large quantities, as well as to have well-characterized life-cycle GHG
20
21 footprint. Since life-cycle CO₂ emissions can vary significantly, depending on the nature of the
22
23 feedstocks, it is essential to carry out analysis of the life-cycle costs and the environmental side
24
25 effects of potential alternatives. The preferred new jet fuels should be carbon-neutral and their
26
27 production can avoid the potential conflicts in land use and energy-food-water systems such that
28
29 the aggressive goal of industry CO₂ emissions reduction roadmap can be met. It is also worth
30
31 noting that the aviation sector will continue to undergo extensive development in alternative
32
33 aviation fuels and to explore novel options beyond the current FT SPK and HRJ/HEFA.
34
35
36
37
38
39

40 Recent progress in the certification process for alternative jet fuels is reviewed in this paper.
41
42 The certification process consists of extensive tests including initial physical property and
43
44 composition tests, rig and component tests, engine tests, and flight tests. While this process has
45
46 been codified in different countries, the approval process is under continuous refinement to
47
48 reduce cost and improve the quality of the data obtained. Due to regulatory issues, the near-term
49
50 goal for alternative jet fuel producers is to create a true ‘drop-in replacement’ fuel. Therefore, the
51
52 premise for approving alternative jet fuels is that they must be fully interchangeable with current
53
54 fuels in performance and handling without compromising flight safety. Although the similarity
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4 of SPK and HRJ fuels, which does not depend on feedstock, is expected to increase the fuel
5
6 choice and flexibility, the fact that different processes can produce alternative jet fuels with
7
8 dramatically different compositions leads to the current interest in continuous improvement of
9
10 the fuel certification program. Recognizing that ‘drop-in’ petroleum replacements and
11
12 blendstocks are the focus in near term and the applications of fully synthetic jet fuels are the
13
14 mid-term goal, combustion ‘rules and tools’ for alternative jet fuels are needed to better
15
16 understand the impact of fuel properties on combustor performance in order to ensure reliable
17
18 operation of the engine.
19
20
21
22

23
24 Since alternative jet fuels can vary significantly in composition as compared to conventional
25
26 jet fuels, substitution of conventional jet fuels with alternative jet fuels requires understanding of
27
28 similarities and differences in fuel properties (both physical and chemical) and comprehensive
29
30 knowledge of the combustion characteristics of alternative jet fuels. In addition, there are
31
32 significant cost benefits in developing a more streamlined combustion testing program that
33
34 includes fundamental characterization. Fundamental combustion datasets of interest include
35
36 autoignition delay times, laminar flame speeds, extinction limits, and combustion species profiles,
37
38 which are of direct relevance to ignition and altitude relight, flame propagation, lean blowout,
39
40 and engine emissions, respectively. In this review, the fundamental combustion studies to date
41
42 are highlighted and discussed. Some differences in combustion characteristics among alternative
43
44 jet fuels and as compared to their conventional counterparts can be attributed to the differences
45
46 in fuel composition. In general, the high temperature chemistry is relatively less sensitive to the
47
48 fuel composition variations, while the low-to-intermediate temperature chemistry as well as the
49
50 NTC response (if exists) can be more fuel specific. In view of the increasing importance of low-
51
52 to-intermediate chemistry and potential NTC behavior in the next-generation aero-engines of
53
54
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4 high compression ratio, further chemical kinetic studies under the less-understood high-pressure,
5
6 low-temperature, engine relevant conditions are strongly recommended. For combustion
7
8 modeling of alternative jet fuels, several surrogate fuel models including both physical and
9
10 chemical surrogates have been proposed and validated against real fuel properties (physical and
11
12 combustion); all of them were found to be able to adequately predict the real fuel behaviors in
13
14 their intended aspects. Further studies on alternative jet fuel combustion are warranted for a
15
16 better understanding of fuel oxidation chemistry and comprehensive surrogate models with a
17
18 wider range of predictability.
19
20
21
22

23
24 Finally, the importance of fundamental combustion research on alternative jet fuels cannot
25
26 be over-emphasized and its goals for a sustainable and green aviation should include the
27
28 development of viable technologies to assess the feasibility of alternative fuels in aviation
29
30 applications as well as the advancement of validated physics-based models to enable quantitative
31
32 emissions and performance predictions using combustion modeling. It is also of practical
33
34 importance that fundamental combustion research can provide guidance for developing ‘rules
35
36 and tools’ expediting certification and integration of new alternative jet fuels with petroleum-
37
38 derived products and current propulsion systems/infrastructure. Ultimately, fundamental
39
40 combustion research and tests should facilitate and lead to the development of cost-effective
41
42 screening of alternative jet fuels, the design for advancing existing and new aero-combustor
43
44 concepts, and the integration of new non-petroleum-derived alternative fuel resources into the
45
46 aviation sector.
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Acknowledgements

The work at Beijing University of Aeronautics and Astronautics was supported by the Project 51306010 of National Natural Science Foundation of China and China's Programme of Introducing Talents of Discipline to Universities – 111 Project under Grant No. B08009. The work at the University of Connecticut was supported as part of the Combustion Energy Frontier Research Center, an Energy Frontier Research Center funded by the US Department of Energy, Office of Science, Office of Basic Energy Sciences, under Award Number DE-SC0001198. The authors also would like thank Dr. Greg Pucher of the Royal Military College of Canada for providing Fig. 4.

1
2
3
4 **References**
5

6 [1] The Outlook for Energy: A View to 2040. ExxonMobil; 2015. Retrieved April 15, 2015, from
7
8 [http://cdn.exxonmobil.com/~//media/Reports/Outlook For Energy/2015/2015-Outlook-for-](http://cdn.exxonmobil.com/~//media/Reports/Outlook For Energy/2015/2015-Outlook-for-Energy_print-resolution.pdf)
9
10 [Energy_print-resolution.pdf](http://cdn.exxonmobil.com/~//media/Reports/Outlook For Energy/2015/2015-Outlook-for-Energy_print-resolution.pdf)
11
12

13 [2] Chèze B, Gastineau P, Chevallier J. Forecasting world and regional aviation jet fuel demands
14
15 to the mid-term (2025). *Energy Policy* 2011;39:5147-58.
16
17

18 [3] IPCC special report on renewable energy sources and climate change mitigation. 2011.
19
20 Retrieved April 15, 2015, from
21

22
23 http://www.unclearn.org/sites/www.unclearn.org/files/inventory/ipcc_summary_for_pm.pdf
24
25

26 [4] Aviation & Emissions A Primer. Federal Aviation Administration Office of Environment and
27
28 Energy; 2005. Retrieved April 15, 2015 from
29

30
31 http://www.faa.gov/regulations_policies/policy_guidance/envir_policy/media/aeprimer.pdf
32
33

34 [5] Penner JE, Lister DH, Griggs DJ, Dokken DJ, McFarland M. Aviation and the Global
35
36 Atmosphere: Cambridge University Press; 1999.
37

38 [6] Resolution on the implementation of the aviation “CNG2020” strategy. IATA (The
39
40 International Air Transport Association); 2010. Retrieved April 15, 2015 from
41

42
43 <http://www.iata.org/pressroom/pr/documents/agm69-resolution-cng2020.pdf>
44
45

46 [7] Brown N. Alternative jet fuels - Feedstock development, processing and conversion research
47
48 & regional supply and refining infrastructure. Federal Aviation Administration; 2012. Retrieved
49

50
51 April 15, 2015 from
52

53 [http://www.faa.gov/about/office_org/headquarters_offices/ang/offices/management/coe/media/pd](http://www.faa.gov/about/office_org/headquarters_offices/ang/offices/management/coe/media/pdf/ajfepMeeting/Alternative%20Fuels%20-%20Part%201.pdf)
54
55 [f/ajfepMeeting/Alternative%20Fuels%20-%20Part%201.pdf](http://www.faa.gov/about/office_org/headquarters_offices/ang/offices/management/coe/media/pdf/ajfepMeeting/Alternative%20Fuels%20-%20Part%201.pdf)
56
57

- 1
2
3
4 [8] Edwards T. Advancements in gas turbine fuels from 1943 to 2005. *J Eng Gas Turb Power*
5
6 2007;129:13-20.
7
8
9 [9] Chiamonti D, Prussi M, Buffi M, Tacconi D. Sustainable bio kerosene: Process routes and
10
11 industrial demonstration activities in aviation biofuels. *Appl Energ* 2014;136:767-74
12
13
14 [10] Harrison WE. The drivers for alternative aviation fuels. Department of Defense Presentation;
15
16 2006. Retrieved April 15, 2015 from
17
18 [https://78f66f4de19f3837d6a9a7dfb2fe0ebed1dc53d3.googledrive.com/host/0B610OR9Z8sSrM](https://78f66f4de19f3837d6a9a7dfb2fe0ebed1dc53d3.googledrive.com/host/0B610OR9Z8sSrMGJ5WXJ4WmZBeWc/265_Harrison.pdf)
19
20 [GJ5WXJ4WmZBeWc/265_Harrison.pdf](https://78f66f4de19f3837d6a9a7dfb2fe0ebed1dc53d3.googledrive.com/host/0B610OR9Z8sSrMGJ5WXJ4WmZBeWc/265_Harrison.pdf)
21
22
23 [11] Stratton RW, Wong HM, Hileman JI. Life cycle greenhouse gas emissions from alternative
24
25 jet fuels. Partnership of Air Transportation Noise and Emissions Reduction. Massachusetts
26
27 Institute of Technology, Cambridge, MA; 2010. Retrieved April 15, 2015 from
28
29 <http://web.mit.edu/aeroastro/partner/reports/proj28/partner-proj28-2010-001.pdf>
30
31
32 [12] Carbon Dioxide Capture and Storage. Intergovernmental Panel on Climate Change (IPCC)
33
34 Special Report, Cambridge University Press; 2005.
35
36
37 [13] Corporan E, Edwards T, Shafer L, DeWitt MJ, Klingshirn C, Zabarnick S, et al. Chemical,
38
39 thermal stability, seal swell, and emissions studies of alternative jet fuels. *Energ Fuel*
40
41 2011;25:955-66.
42
43
44 [14] Lokesh K, Sethi V, Nikolaidis T, Goodger E, Nalianda D. Life cycle greenhouse gas analysis
45
46 of biojet fuels with a technical investigation into their impact on jet engine performance.
47
48 *Biomass Bioenerg* 2015;77:26-44.
49
50
51 [15] Hill J. Environmental costs and benefits of transportation biofuel production from food- and
52
53 lignocellulose-based energy crops. A review. *Agron Sustain Dev* 2007;27:1-12.
54
55
56
57
58
59
60
61
62
63
64
65

- 1
2
3
4 [16] Trivedi P, Olcay H, Staples MD, Withers MR, Malina R, Barrett SR. (2015). Energy return
5 on investment for alternative jet fuels. *Appl Energ* 2015;141:167-74.
6
7
8
9 [17] Hileman JI and Stratton RW. Alternative jet fuel feasibility. *Transport Policy* 2014;34:52-62.
10
11 [18] Staples MD, Malina R, Olcay H, Pearlson MN, Hileman JI, Boies A, Barrett SR. Lifecycle
12 greenhouse gas footprint and minimum selling price of renewable diesel and jet fuel from
13 fermentation and advanced fermentation production technologies. *Energy Environ*
14 *Sci* 2014;7(5):1545-54.
15
16
17
18
19 [19] Staples MD, Olcay H, Malina R, Trivedi P, Pearlson MN, Strzepek K, Barrett SR. Water
20 consumption footprint and land requirements of large-scale alternative diesel and jet fuel
21 production. *Environ Sci Technol* 2013;47(21):12557-65.
22
23
24
25
26 [20] Atsonios K, Kougioumtzis M-A, Panopoulos KD, Kakaras E. Alternative thermochemical
27 routes for aviation biofuels via alcohols synthesis: Process modeling, techno-economic
28 assessment and comparison. *Appl Energ* 2015;138:346-66.
29
30
31
32 [21] Wolters F, Bank R, Schaefer M. Potential impact of renewable fuels and technological
33 innovations on global air traffic emissions development by 2050. ASME Turbo Expo, Düsseldorf
34 2014. GT2014-25087.
35
36
37 [22] Lamprecht D. Fischer-Tropsch fuel for use by the U.S. military as battlefield-use fuel of the
38 future. *Energy Fuel* 2007;21:1448-53.
39
40
41 [23] U.S. Air Force Energy Strategic Plan. U.S. Air Force; 2013. Retrieved April 15, 2015 from
42 <http://www.safie.hq.af.mil/shared/media/document/AFD-130325-124.pdf>
43
44
45 [24] Commercial Aviation Alternative Fuels Initiative. International Civil Aviation Organization.
46 Retrieved April 15, 2015 from
47 <http://www.icao.int/environmental-protection/GFAAF/Pages/Project.aspx?ProjectID=10>
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

- 1
2
3
4 [25] ALFA-BIRD:Alternative fuels and biofuels for aircraft development overview of main
5 results. Frankfurt Airport, Germany: 2nd AirTN Forum; 2012. Retrieved April 15, 2015 from
6
7
8
9 <http://www.airtn.eu/downloads/airtn-alfabird-web-sent-2012.pdf>
10
11 [26] Sustainable Way for Alternative Fuels and Energy in Aviation. SWAFEA Final Report;
12 2011. Retrieved April 15, 2015 from
13
14
15
16 <http://www.icao.int/environmental->
17
18 [protection/GFAAF/Documents/SW_WP9_D.9.1%20Final%20report_released%20July2011.pdf](http://www.icao.int/environmental-protection/GFAAF/Documents/SW_WP9_D.9.1%20Final%20report_released%20July2011.pdf)
19
20
21 [27] Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on
22 the promotion of the use of energy from renewable sources and amending and subsequently
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65
- [27] Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. 2009. Retrieved April 15, 2015 from <http://faolex.fao.org/docs/pdf/eur88009.pdf>
- [28] Commercial Aviation Alternative Fuels Initiative. Retrieved April 15, 2015 from <http://www.caafi.org/news/NewsArchive.aspx>
- [29] Gupta KK, Rehman A, Sarviya RM. Bio-fuels for the gas turbine: A review. *Renew Sust Energ Rev* 2010;14:2946-55.
- [30] Law CK. Fuel options for next-generation chemical propulsion. *AIAA Journal* 2012;50:19-36.
- [31] Liu G, Yan B, Chen G. Technical review on jet fuel production. *Renew Sust Energ Rev* 2013;25:59-70.
- [32] Chuck CJ and Donnelly J. The compatibility of potential bioderived fuels with Jet A-1 aviation kerosene. *Appl Energ* 2014;118:83-91.
- [33] Kallio P, Pásztor A, Akhtar MK, Jones PR. Renewable jet fuel. *Curr Opin Biotech* 2014;26:50-55.

- 1
2
3
4 [34] Hari TK, Yaakob Z, Binitha NN. Aviation biofuel from renewable resources: Routes,
5 opportunities and challenges. *Renew Sust Energ Rev* 2015;42:1234-44.
6
7
8
9 [35] Murphy HT, O'Connell DA, Raison RJ, Warden AC, Booth TH, Herr A, et al. Biomass
10 production for sustainable aviation fuels: a regional case study in Queensland. *Renew Sust Energ*
11 *Rev* 2015;44:738-50.
12
13
14
15 [36] Cremonoz PA, Feroldi M, de Araújo AV, Borges MN, Meier TW, Feiden A, (2015). Biofuels
16 in Brazilian aviation: Current scenario and prospects. *Renew Sust Energ Rev* 2015;43:1063-72.
17
18
19 [37] Blakey S, Rye L, Wilson CW. Aviation gas turbine alternative fuels: A review. *Pro Combust*
20 *Inst* 2011;33:2863-85.
21
22
23
24 [38] Path to Alternative Jet Fuel Readiness. CAAFI; 2011. Retrieved April 15, 2015 from
25
26 http://www.caafi.org/information/pdf/Path_to_Aviation_Alternative_Fuel_Readiness_posted_20
27
28 [11_12.pdf](http://www.caafi.org/information/pdf/Path_to_Aviation_Alternative_Fuel_Readiness_posted_20)
29
30
31
32 [39] Withers MR, Malina R, Gilmore CK, Gibbs JM, Trigg C, Wolfe PJ, et al. Economic and
33 environmental assessment of liquefied natural gas as a supplemental aircraft fuel. *Prog Aerosp*
34 *Sci* 2014;66:17-36.
35
36
37
38 [40] Christensen D, Peineke C, Tamboer B, Hagenzieker R, Druten Lv. Business Case &
39 Implementation Strategies. European Commission's Directorate General for Mobility and
40 Transport; 2011.
41
42
43 [41] Winchester N, McConnachie D, Wollersheim C, Waitz IA. Economic and emissions impacts
44 of renewable fuel goals for aviation in the US. *Transport Res A-Pol* 2013;58:116-28.
45
46
47
48 [42] Standard Specification for Aviation Turbine Fuels. ASTM D1655-15. Retrieved April 15,
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

- 1
2
3
4 [43] Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons.
5
6 ASTM D7566-09. Retrieved April 15, 2015 from
7
8 <http://www.astm.org/DATABASE.CART/HISTORICAL/D7566-09.htm>
9
10
11 [44] Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons.
12
13 ASTM D7566-11. Retrieved April 15, 2015 from
14
15 <http://www.astm.org/DATABASE.CART/HISTORICAL/D7566-11.htm>
16
17
18 [45] Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons.
19
20 ASTM D7566-14c. Retrieved April 15, 2015 from <http://www.astm.org/Standards/D7566.htm>
21
22
23 [46] Standard Practice for Qualification and Approval of New Aviation Turbine Fuels and Fuel
24
25 Additives. ASTM D4054-09. Retrieved April 15, 2015 from
26
27 <http://www.astm.org/DATABASE.CART/HISTORICAL/D4054-09.htm>
28
29
30 [47] Defence Standard 91-91, Issue 7–Turbine Fuel, Kerosine Type, Jet A-1. NATO Code: F-35.
31
32 Joint Service Designation: AVTUR. Technical Report, Ministry of Defence, 2011. Retrieved
33
34 April 15, 2015 from
35
36 http://www.seta-analytics.com/documents/Defstan_91-91_R7.pdf
37
38
39 [48] Aviation Fuel Quality Requirements for Jointly Operated Systems (AFQRJOS). Joint
40
41 Inspection Group; 2012. Retrieved April 15, 2015 from
42
43 [http://www.jigonline.com/wp-content/uploads/2012/05/Bulletin-51-AFQRJOS-Issue-26-May-](http://www.jigonline.com/wp-content/uploads/2012/05/Bulletin-51-AFQRJOS-Issue-26-May-2012.pdf)
44
45
46
47
48
49
50 [49] Holley AT, Dong Y, Andac MG, Egolfopoulos FN, Edwards T. Ignition and extinction of
51
52 non-premixed flames of single-component liquid hydrocarbons, jet fuels, and their surrogates.
53
54 Pro Combust Inst 2007;31:1205-13.
55
56
57
58
59
60
61
62
63
64
65

- 1
2
3
4 [50] Nakakita K, Akihama K, Weissman W, Farrell J. Effect of the hydrocarbon molecular
5
6 structure in diesel fuel on the in-cylinder soot formation and exhaust emissions. Int J Engine Res
7
8 2005;6:187-205.
9
- 10
11 [51] Rahmes TF, Kinder JD, Henry TM, Crenfeldt G, LeDuc GF, Zombanakis GP, et al.
12
13 Sustainable bio-derived synthetic paraffinic kerosene (Bio-SPK) jet fuel flights and engine tests
14
15 program results. 9th AIAA Aviation Technology, Integration, and Operations Conference, South
16
17 Carolina 2009. AIAA2009-7002.
18
19
- 20
21 [52] Dooley S, Won SH, Chaos M, Heyne J, Ju Y, Dryer FL, et al. A jet fuel surrogate formulated
22
23 by real fuel properties. Combust Flame 2010;157:2333-9.
24
25
- 26 [53] Hui X, Kumar K, Sung CJ, Edwards T, Gardner D. Experimental studies on the combustion
27
28 characteristics of alternative jet fuels. Fuel 2012;98:176-82.
29
30
- 31 [54] Edwards T, Moses C, Dryer F. Evaluation of combustion performance of alternative aviation
32
33 fuels. 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Nashville 2010.
34
35 AIAA2010-7155.
36
37
- 38 [55] Moses CA. Development of the protocol for acceptance of synthetic fuels under commercial
39
40 specification. Coordinating Research Council Report AV-2-04, Alpharetta, GA September 2007.
41
42 Retrieved April 15, 2015 from
43
44 [http://crcao.com/reports/recentstudies2007/AV-02-04/AV-2-04%20Final%20Report%20-](http://crcao.com/reports/recentstudies2007/AV-02-04/AV-2-04%20Final%20Report%20-%20FINAL2%20March%202-2008.pdf)
45
46 [%20FINAL2%20March%202-2008.pdf](http://crcao.com/reports/recentstudies2007/AV-02-04/AV-2-04%20Final%20Report%20-%20FINAL2%20March%202-2008.pdf)
47
48
- 49
50 [56] Hadaller O and Johnson J. World fuel sampling program. Coordinating Research Council,
51
52 Inc, CRC Report; 2006. Retrieved April 15, 2015 from
53
54 [http://mycommittees.api.org/rasa/jfm/Shared%20Documents/Resource%20Materials/Compositio](http://mycommittees.api.org/rasa/jfm/Shared%20Documents/Resource%20Materials/Composition%20data/World%20Fuel%20Sampling%20Program%202006%20Report.pdf)
55
56 [n%20data/World%20Fuel%20Sampling%20Program%202006%20Report.pdf](http://mycommittees.api.org/rasa/jfm/Shared%20Documents/Resource%20Materials/Composition%20data/World%20Fuel%20Sampling%20Program%202006%20Report.pdf)
57
58
59
60
61
62
63
64
65

- 1
2
3
4 [57] Bessee GB, Hutzler SA, Wilson GR. Propulsion and Power Rapid Response Research and
5 Development (R&D) Support. Delivery Order 0011: Analysis of Synthetic Aviation Fuels. DTIC
6 Document; 2011. Retrieved April 15, 2015 from
7
8
9
10
11 <http://www.dtic.mil/cgi-bin/GetTRDoc?Location=U2&doc=GetTRDoc.pdf&AD=ADA547232>
12
13
14 [58] Williams R. Final report evaluation of sasol fully synthetic jet fuel for approval for use as
15 Jet A-1 fuel. Honeywell Aerospace; 2007. Report No. 21-13781.
16
17
18 [59] Lin Y, Lin Y, Zhang C, Xu Q, Sung CJ, Liu G. Evaluation of combustion performance of a
19 coal-derived synthetic jet fuel. ASME Turbo Expo, Copenhagen 2012. GT2012-68604.
20
21
22
23 [60] Kannaiyan K and Sadr R. Experimental investigation of spray characteristics of alternative
24 aviation fuels. *Energy Convers Manage* 2014;88:1060-9.
25
26
27
28 [61] Sivakumar D, Vaneswaram SK, Sakthikumar R, Raghunandan BN. Analysis on the
29 atomization characteristics of aviation biofuel discharging from simplex swirl atomizer. *Int J*
30 *Multiphas Flow* 2015;72:88-96.
31
32
33
34 [62] Herman F. Cold day ignition and altitude relight testing of SASOL fully synthetic aviation
35 kerosene -- External report to Southwest Research Institute, Rolls-Royce PLC 2007. Report No
36 DNS.126274.
37
38
39
40
41
42
43 [63] Rye L and Wilson CW. The influence of alternative fuel composition on gas turbine ignition
44 performance. *Fuel* 2012;96:277-83.
45
46
47
48 [64] Fyffe D, Moran J, Kannaiyan K, Al-Sharshani A, Sadr R. Effect of GTL-like jet fuel
49 composition on gt engine altitude ignition performance: Part I--Combustor operability. ASME
50 Turbo Expo, Vancouver 2011. GT2011-45487.
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

- 1
2
3
4 [65] Hermann F, Hedemalm P, Orbay R, Gabrielsson R, Klingmann J. Comparison of
5 combustion properties between a synthetic jet fuel and conventional Jet A-1. ASME Turbo Expo,
6 Nevada 2005. GT2005-68540.
7
8
9
10
11 [66] Mosbach T, Gebel GC, Clercq PL, Sadr R, Kannaiyan K, Al-Sharshani A. Investigation of
12 GTL-like jet fuel composition on GT engine altitude ignition and combustion performance: Part
13 II--Detailed Diagnostics. ASME Turbo Expo, Vancouver 2011. GT2011-45510.
14
15
16
17
18 [67] Burger V, Mosbach T, Yates A, Gunasekaran B. Fuel influence on targeted gas turbine
19 combustion properties part II: Detailed results. ASME Turbo Expo, Düsseldorf 2014. GT2014-
20 25105.
21
22
23
24
25
26 [68] Shouse DT, Neuroth C, Hendricks RC, Lynch A, Frayne C, Stutrud JS, et al. Alternate-
27 fueled combustor-sector performance: Part A: Combustor performance Part B: Combustor
28 emissions. 2010. ISROMAC13-2010-49.
29
30
31
32
33 [69] Burger V, Yates A, Viljoen C. Influence of fuel physical properties and reaction rate on
34 threshold heterogeneous gas turbine combustion. ASME Turbo Expo, Copenhagen 2012.
35 GT2012-68153.
36
37
38
39
40 [70] Biddle T. Pratt & Whitney emissions test to determine the effect of sasol fully synthetic jet-a
41 fuel on the emissions of a commercial combustor. Southwest Research Institute; 2007.
42
43
44
45 [71] Pucher G, Poitras P, Allan W, LaViolette M. Emissions from a gas turbine sector rig
46 operated with synthetic aviation and biodiesel fuel. J Eng Gas Turb Power 2011;133:111502.
47
48
49
50 [72] Pucher G, Allan W, Poitras P. Characteristics of deposits in gas turbine combustion
51 chambers using synthetic and conventional jet fuels. J Eng Gas Turb Power 2013;135:071502.
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4 [73] Bester N, Yates A. Assessment of the operational performance of Fischer-Tropsch synthetic-
5
6 paraffinic kerosene in a T63 gas turbine compared to conventional Jet A-1 fuel. ASME Turbo
7
8 Expo, Orlando 2009. GT2009-60333.
9

10
11 [74] Bulzan D, Anderson B, Wey C, Howard R, Winstead E, Beyersdorf A, et al. Gaseous and
12
13 particulate emissions results of the NASA alternative aviation fuel experiment (AAFEX). ASME
14
15 Turbo Expo, Glasgow 2010. GT2010-23524.
16
17

18
19 [75] Timko MT, Yu Z, Onasch TB, Wong HW, Miake-Lye RC, Beyersdorf AJ, et al. Particulate
20
21 emissions of gas turbine engine combustion of a Fischer–Tropsch synthetic fuel. *Energ Fuel*
22
23 2010;24:5883-96.
24
25

26 [76] Corporan E, DeWitt MJ, Klingshirn CD, Striebich R, Cheng MD. Emissions characteristics
27
28 of military helicopter engines with JP-8 and Fischer-Tropsch fuels. *J Propul Power* 2010;26:317-
29
30 24.
31
32

33 [77] Corporan E, DeWitt MJ, Klingshirn CD, Anneken D. Alternative fuels tests on a C-17
34
35 aircraft: Emissions characteristics. Air Force Research Laboratory; 2010. Retrieved April 15,
36
37 2015 from <http://www.dtic.mil/dtic/tr/fulltext/u2/a536842.pdf>
38
39

40 [78] Corporan E, DeWitt MJ, Klingshirn CD, Anneken D, Streibich R, Shafer L. Comparisons of
41
42 emissions characteristics of several turbine engines burning Fischer-Tropsch and hydroprocessed
43
44 esters and fatty acids alternative jet fuels. ASME Turbo Expo, Copenhagen 2012. GT2012-
45
46 68656.
47
48

49 [79] Klingshirn CD, DeWitt M, Striebich R, Anneken D, Shafer L, Corporan E, et al.
50
51 Hydroprocessed renewable jet fuel evaluation, performance, and emissions in a T63 turbine
52
53 engine. *J Eng Gas Turb Power* 2012;134:051506.
54
55
56
57
58
59
60
61
62
63
64
65

- 1
2
3
4 [80] Badami M, Nuccio P, Pastrone D, Signoretto A. Performance of a small-scale turbojet
5 engine fed with traditional and alternative fuels. *Energ Convers Manage* 2014;82:219-28.
6
7
8
9 [81] Khandelwal B, Roy S, Lord C, Blakey S. Comparison of vibrations and emissions of
10 conventional jet fuel with stressed 100% SPK and fully formulated synthetic jet fuel. *Aerospace*
11 2014;1(2):52-66.
12
13
14
15 [82] Altaher MA, Li H, Blakey S, Chung W. NMHC and VOC speciation of the exhaust gas from
16 a gas turbine engine using alternative, renewable and conventional Jet A-1 aviation fuels. *ASME*
17 *Turbo Expo, Düsseldorf 2014. GT2014-25445.*
18
19
20
21 [83] Fritschen JM. U.S. air force Fisher-Tropsch alternative fuel development: six-step
22 demonstration. *US Air Force T&E Days. Destin, Florida 2007.*
23
24
25 [84] ACCESS II: A team effort by NASA, DLR, NRC. 2014. Retrieved April 15, 2015 from
26 <http://www.nasa.gov/centers/armstrong/Features/ACCESSIIateameffort.html>
27
28
29
30
31 [85] Petersen EL, Lamnaouer M, Vries J, Curran H, Simmie J, Fikri M, et al. Discrepancies
32 between shock tube and rapid compression machine ignition at low temperatures and high
33 pressures. *Shock Waves* 2009;739-44.
34
35
36 [86] Sung CJ and Curran HJ. Using rapid compression machines for chemical kinetics studies.
37 *Prog Energ Combust* 2014;44:1-18 .
38
39
40 [87] Vasu SS, Davidson DF, Hanson RK. Jet fuel ignition delay times: Shock tube experiments
41 over wide conditions and surrogate model predictions. *Combust Flame* 2008;152:125-43.
42
43
44 [88] Kumar K and Sung CJ. A comparative experimental study of the autoignition characteristics
45 of alternative and conventional jet fuel/oxidizer mixtures. *Fuel* 2010;89:2853-63.
46
47
48 [89] Kumar K and Sung CJ. An experimental study of the autoignition characteristics of
49 conventional jet fuel/oxidizer mixtures: Jet-A and JP-8. *Combust Flame* 2010;157:676-85.
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

- 1
2
3
4 [90] Wang H and Oehlschlaeger MA. Autoignition studies of conventional and Fischer–Tropsch
5
6 jet fuels. *Fuel* 2012;98:249-58.
7
8
9 [91] Allen C, Toulson E, Edwards T, Lee T. Application of a novel charge preparation approach
10
11 to testing the autoignition characteristics of JP-8 and camelina hydroprocessed renewable jet fuel
12
13 in a rapid compression machine. *Combust Flame* 2012;159:2780-8.
14
15
16 [92] Zhu Y, Li S, Davidson DF, Hanson RK. Ignition delay times of conventional and alternative
17
18 fuels behind reflected shock waves. *Proc Combust Inst* 2015;35(1):241-8.
19
20
21 [93] Valco D, Gentz G, Allen C, Colket M, Edwards T, Gowdagiri S, et al. Autoignition behavior
22
23 of synthetic alternative jet fuels: An examination of chemical composition effects on ignition
24
25 delays at low to intermediate temperatures. *Proc Combust Inst* 2015;35(3):2983-91.
26
27
28 [94] Daniel V, Casey A, Tonghun L. Autoignition behavior of petroleum-based and
29
30 hydroprocessed renewable jet fuel blends in a rapid compression machine. 51st AIAA Aerospace
31
32 Sciences Meeting including the New Horizons Forum and Aerospace Exposition, Grapevine
33
34 2013. AIAA2013-0896.
35
36
37 [95] Standard Test Method for Determination of Derived Cetane Number (DCN) of Diesel Fuel
38
39 Oils—Fixed Range Injection Period, Constant Volume Combustion Chamber Method. ASTM
40
41 D7170; 2012.
42
43
44 [96] Standard Test Method for Determination of Ignition Delay and Derived Cetane Number
45
46 (DCN) of Diesel Fuel Oils by Combustion in a Constant Volume Chamber. ASTM D6890; 2012.
47
48
49 [97] Dooley S, Won SH, Heyne J, Farouk TI, Ju Y, Dryer FL, et al. The experimental evaluation
50
51 of a methodology for surrogate fuel formulation to emulate gas phase combustion kinetic
52
53 phenomena. *Combust Flame* 2012;159:1444-66.
54
55
56
57
58
59
60
61
62
63
64
65

- 1
2
3
4 [98] Dooley S, Won SH, Jahangirian S, Ju Y, Dryer FL, Wang H, et al. The combustion kinetics
5
6 of a synthetic paraffinic jet aviation fuel and a fundamentally formulated, experimentally
7
8 validated surrogate fuel. *Combust Flame* 2012;159:3014-20.
9
10
11 [99] Won SH, Veloo PS, Santner J, Ju Y, Dryer FL. Comparative evaluation of global combustion
12
13 properties of alternative jet fuels. 51st AIAA Aerospace Sciences Meeting including the New
14
15 Horizons Forum and Aerospace Exposition, Grapevine 2013. AIAA 2013-0156.
16
17
18 [100] Ghosh P and Jaffe SB. Detailed composition-based model for predicting the cetane number
19
20 of diesel fuels. *Ind Eng Chem Res* 2006;45:346-51.
21
22
23 [101] Law CK. *Combustion physics*: Cambridge University Press; 2006.
24
25
26 [102] Kumar K, Sung CJ, Hui X. Laminar flame speeds and extinction limits of conventional and
27
28 alternative jet fuels. *Fuel* 2011;90:1004-11.
29
30
31 [103] Mz -Ahmed A, Dagaut P, Hadj-Ali K, Dayma G. Oxidation of a coal-to-liquid synthetic jet
32
33 fuel: experimental and chemical kinetic modeling study. *Energ Fuel* 2012;26:6070-9.
34
35
36 [104] Kick T, Herbst J, Kathrotia T, Marquetand J, Braun-Unkhoff M, Naumann C, et al. An
37
38 experimental and modeling study of burning velocities of possible future synthetic jet fuels.
39
40 *Energy* 2012;43:111-23.
41
42
43 [105] Vukadinovic V, Habisreuther P, Zarzalis N. Experimental study on combustion
44
45 characteristics of conventional and alternative liquid fuels. *J Eng Gas Turb Power*
46
47 2012;134:121504.
48
49
50 [106] Hui X and Sung CJ. Laminar flame speeds of transportation-relevant hydrocarbons and jet
51
52 fuels at elevated temperatures and pressures. *Fuel* 2013;109:191-200.
53
54
55
56
57
58
59
60
61
62
63
64
65

- 1
2
3
4 [107] Munzar JD, Zia A, Versailles P, Jimenez R, Akih-Kumgeh B, Bergthorson JM. Comparison
5
6 of laminar flame speeds, extinction stretch rates and vapor pressures of Jet A-1/HRJ biojet fuel
7
8 blends. ASME Turbo Expo, Düsseldorf 2014. GT2014-25951.
9
10
11 [108] Ji C, Wang YL, Egolfopoulos FN. Flame studies of conventional and alternative jet fuels. J
12
13 Propul Power 2011;27:856-63.
14
15
16 [109] Calcote H and Manos D. Effect of molecular structure on incipient soot formation.
17
18 Combust Flame 1983;49:289-304.
19
20
21 [110] Gill R and Olson D. Estimation of soot thresholds for fuel mixtures. Combust Sci Technol
22
23 1984;40:307-15.
24
25
26 [111] Yang Y, Boehman AL, Santoro RJ. A study of jet fuel sooting tendency using the threshold
27
28 sooting index (TSI) model. Combust Flame 2007;149:191-205.
29
30
31 [112] Stouffer SD, Pawlik R, Justinger G, Heyne J, Zelina J, Ballal D. Combustion performance
32
33 and emissions characteristics for a well stirred reactor for low volatility hydrocarbon fuels. 43rd
34
35 AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Cincinnati 2007. AIAA2007-
36
37 5663.
38
39
40 [113] Naik CV, Puduppakkam KV, Modak A, Meeks E, Wang YL, Feng Q, et al. Detailed
41
42 chemical kinetic mechanism for surrogates of alternative jet fuels. Combust Flame
43
44 2011;158:434-45.
45
46
47 [114] Mzé-Ahmed A, Hadj-Ali K, Dievart P, Dagaut P. Kinetics of oxidation of a synthetic jet
48
49 fuel in a jet-stirred reactor: experimental and modeling study. Energ Fuel 2010;24:4904-11.
50
51
52 [115] Dagaut P, Karsenty F, Dayma G, Diévert P, Hadj-Ali K, Mzé-Ahmed A, et al. Experimental
53
54 and detailed kinetic model for the oxidation of a Gas to Liquid (GtL) jet fuel. Combust Flame
55
56 2014;161:835-47.
57
58
59
60
61
62
63
64
65

- 1
2
3
4 [116] Edwards T and Maurice LQ. Surrogate mixtures to represent complex aviation and rocket
5
6 fuels. *J Propul Power* 2001;17:461-6.
7
8
9 [117] Colket M, Edwards T, Williams S, Cernansky NP, Miller DL, Egolfopoulos F, et al.
10
11 Development of an experimental database and kinetic models for surrogate jet fuels. 45th AIAA
12
13 Aerospace Sciences Meeting and Exhibit, Cincinnati 2007. AIAA2007-770
14
15
16 [118] Violi A, Yan S, Eddings E, Sarofim A, Granata S, Faravelli T, et al. Experimental
17
18 formulation and kinetic model for JP-8 surrogate mixtures. *Combust Sci Technol* 2002;174:399-
19
20 417.
21
22
23 [119] Dryer FL, Jahangirian S, Dooley S, Won SH, Heyne JS, Iyer VR, et al. Emulating the
24
25 combustion behavior of real jet aviation fuels by surrogate mixtures of hydrocarbon fluid blends:
26
27 implications for science and engineering. *Energ Fuel* 2014;28(5):3474-85.
28
29
30 [120] Kim D, Martz J, Violi A. A surrogate for emulating the physical and chemical properties of
31
32 conventional jet fuel. *Combust Flame* 2014;161(6):1489-98.
33
34
35 [121] Huber ML, Smith BL, Ott LS, Bruno TJ. Surrogate mixture model for the thermophysical
36
37 properties of synthetic aviation fuel S-8: Explicit application of the advanced distillation curve.
38
39 *Energ Fuel* 2008;22:1104-14.
40
41
42 [122] Huber M, Bruno T, Chirico R, Diky V, Kazakov A, Lemmon E, et al. Equations of state on
43
44 demand: application for surrogate fuel development. *Int J Thermophys* 2011;32:596-613.
45
46
47 [123] Mawid MA. Development of a detailed chemical kinetic mechanism for mixtures of JP-8
48
49 fuel and Fischer-Tropsch-Based synthetic jet fuel. 43rd AIAA/ASME/SAE/ASEE Joint
50
51 Propulsion Conference and Exhibit, Cincinnati 2007. AIAA2007-5668.
52
53
54 [124] Slavinskaya NA, Zizin A, Aigner M. On model design of a surrogate fuel formulation. *J*
55
56 *Eng Gas Turb Power* 2010;132:111501.
57
58
59
60
61
62
63
64
65

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

[125] Bruno TJ and Smith BL. Improvements in the measurement of distillation curves. 2. Application to aerospace/aviation fuels RP-1 and S-8. Ind Eng Chem Res 2006;45:4381-8.

[126] Frenkel M, Chirico R, Diky V, Muzny C, Lemmon E, Yan X, et al. NIST ThermoData Engine. NIST Standard Reference Database 103b, Version. 2008;5.

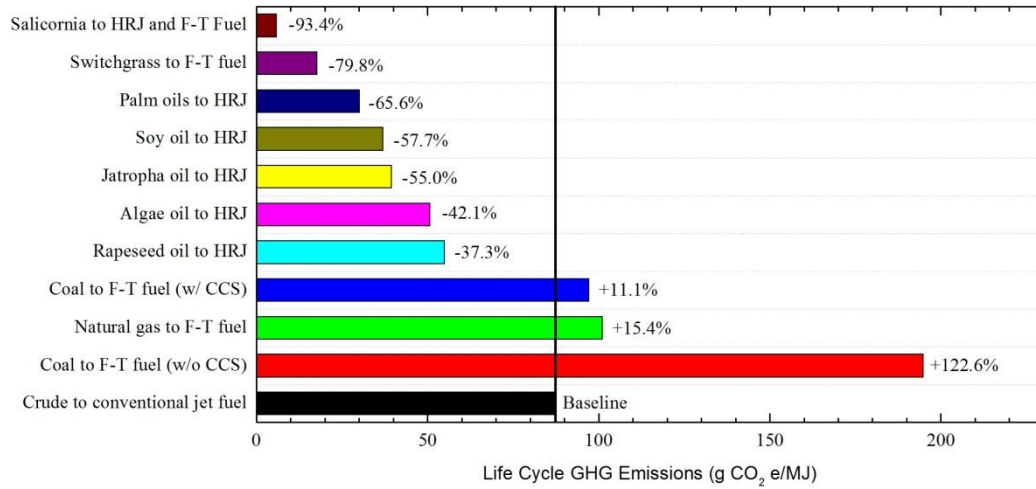


Figure 1 – Life-cycle greenhouse gas emissions for conventional and alternative jet fuels. The units of ‘g CO₂ e/MJ’ represent the CO₂ equivalent emissions per unit of energy [11].

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

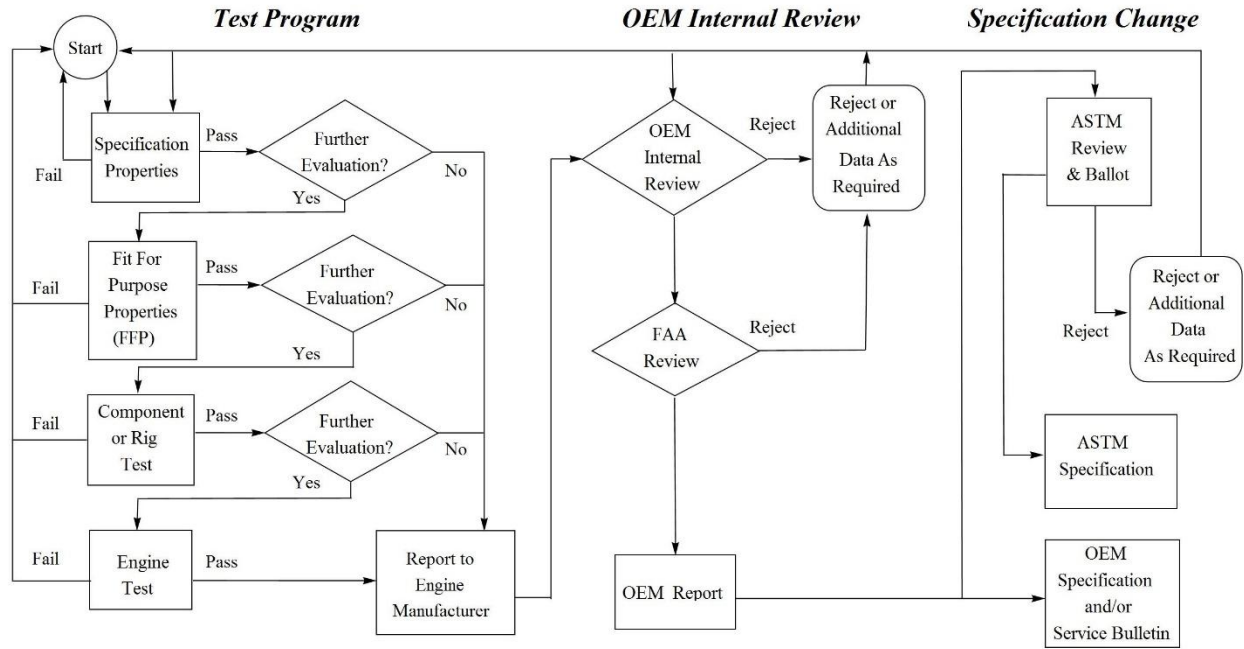


Figure 2 – Overview of fuel and additive approval process [46].

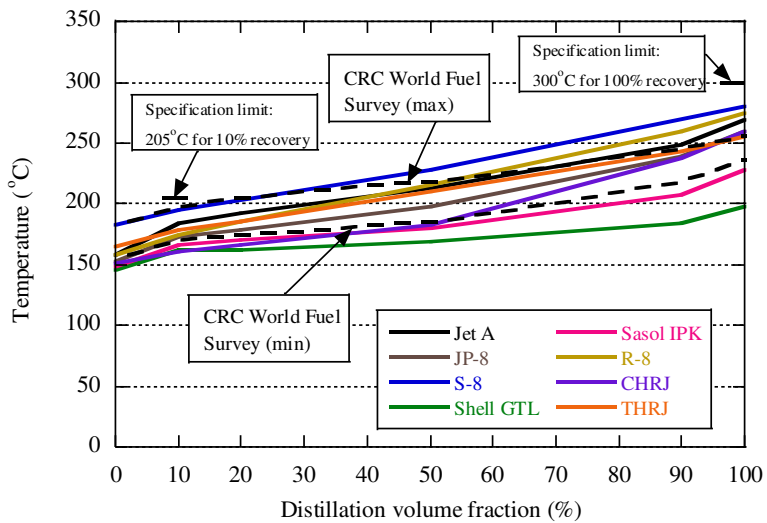


Figure 1 – Distillation curves of conventional and alternative jet fuels. Data were taken from Refs. [13,51,56].

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

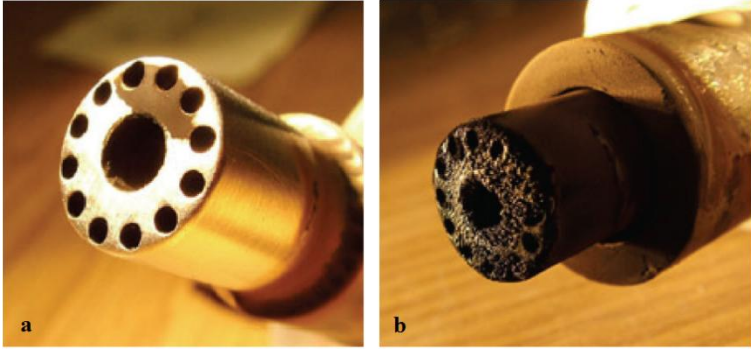


Figure 2 – Igniter deposits: (a) 100% synthetic fuel and (b) Jet A-1 [50] (Courtesy: G. Pucher).

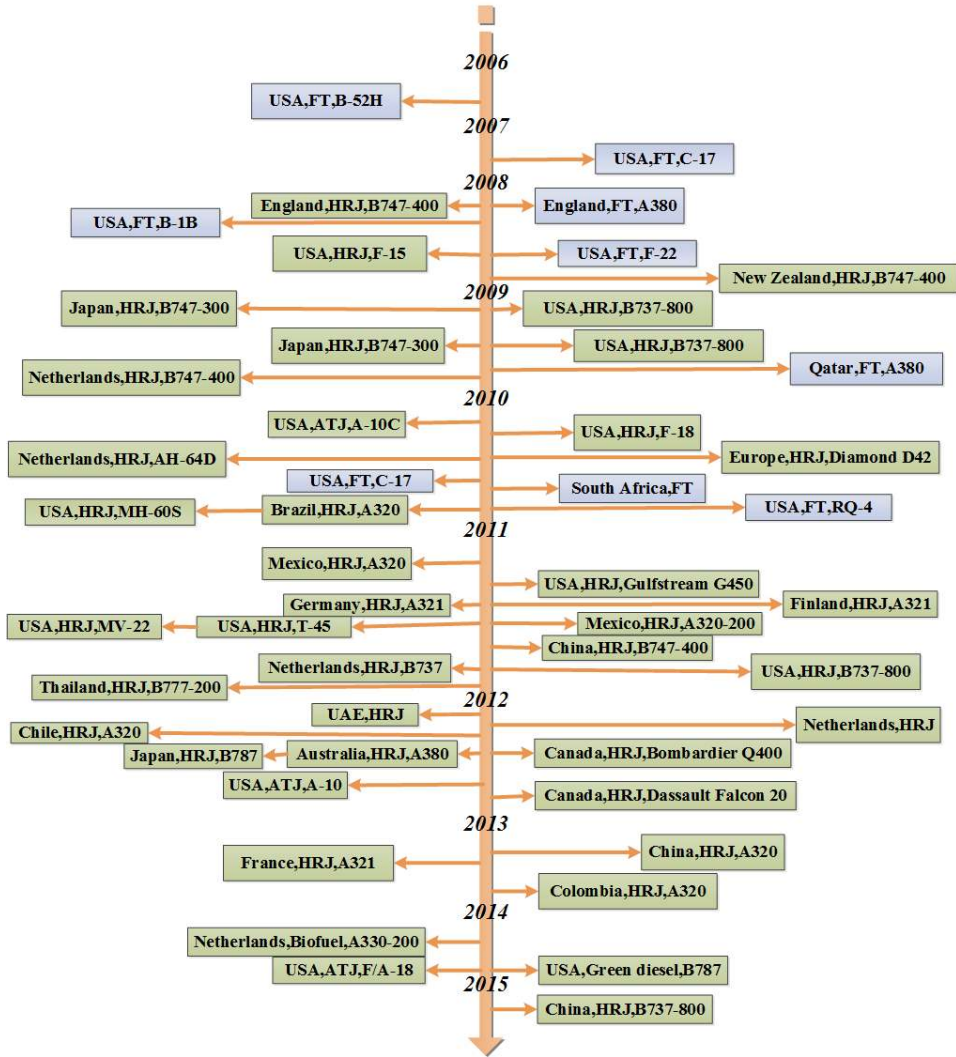


Figure 3 – Flight tests using alternative jet fuels as of 2006.

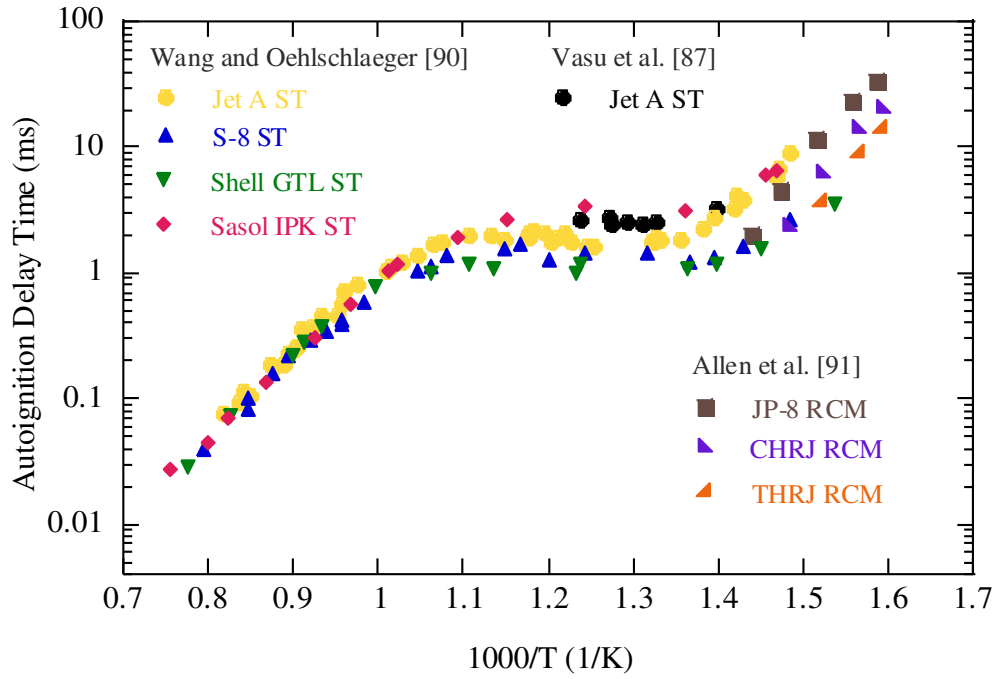


Figure 4 – Autoignition delay times of various stoichiometric jet fuel/air mixtures at a pressure of 20 atm measured in two shock tubes (STs) and a rapid compression machine (RCM). Data are from Refs. [87,90,91].

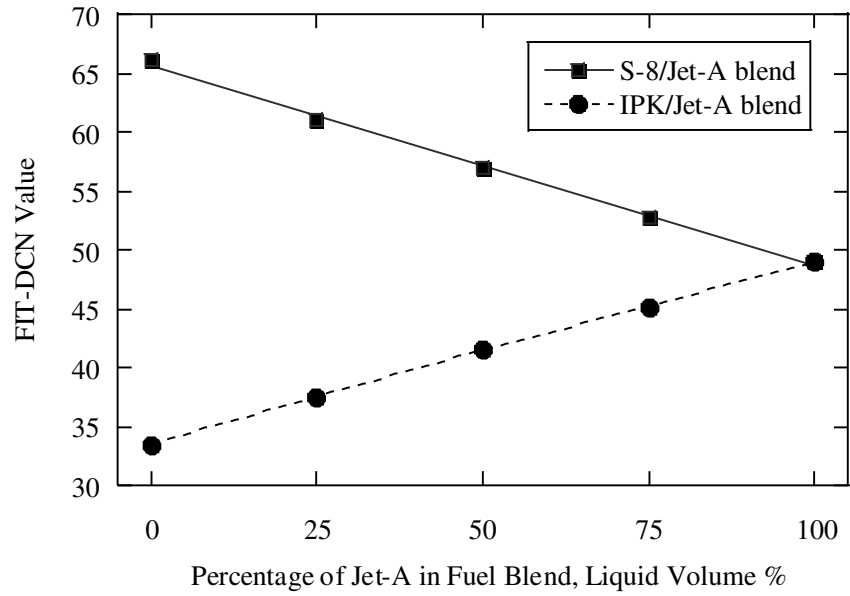


Figure 5 – FIT-DCN values of binary blends of conventional and alternative jet fuels [53].

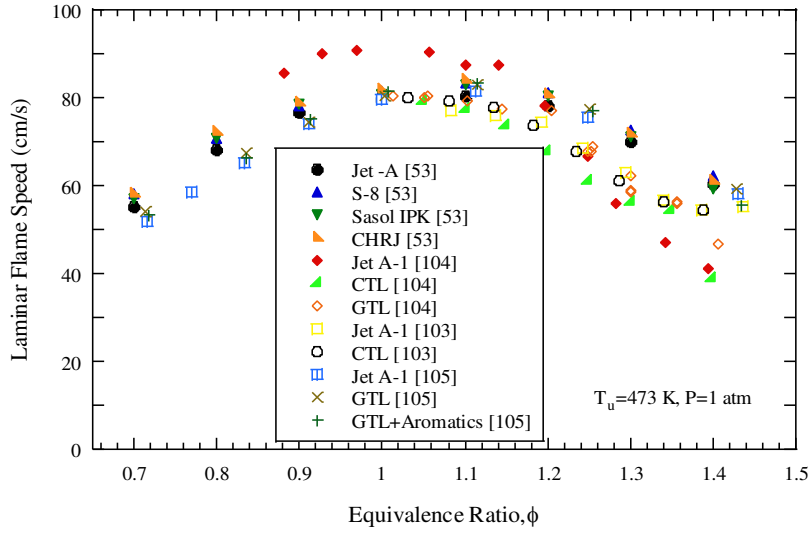


Figure 6 – Laminar flame speeds of various jet fuel/air mixtures at preheat temperature of about $T_u=473$ K and pressure of $P=1$ atm. Data were taken from Refs. [53,103-105].

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

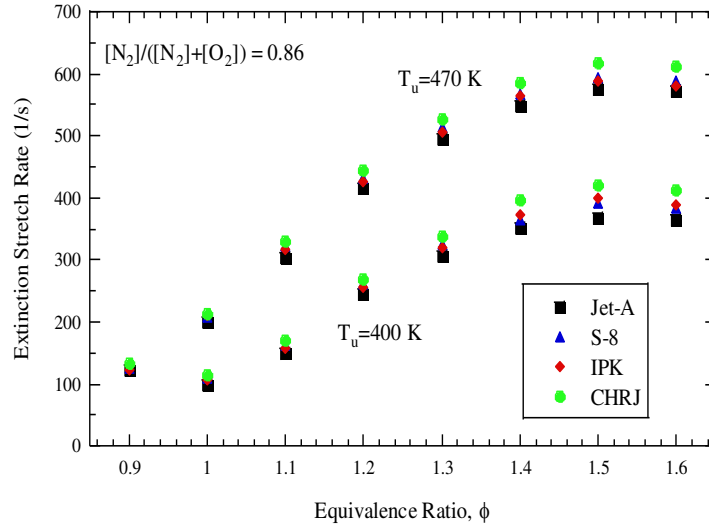


Figure 7 – Extinction strain rates of Jet A/oxidizer, S-8/oxidizer, IPK/oxidizer, and CHRJ/oxidizer at 400 K and 470 K preheat temperatures as a function of equivalence ratio [53].

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

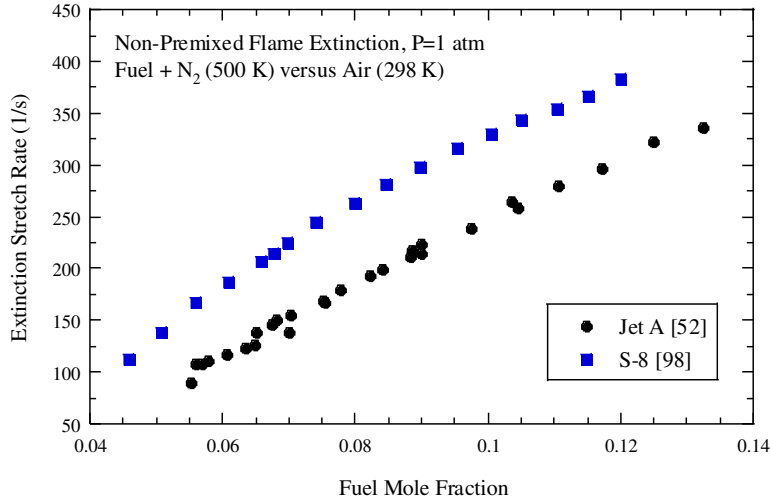


Figure 8 – Extinction strain rates of Jet A [52] and S-8 [98] in atmospheric non-premixed flames with fuel/N₂ temperature of 500 K and air temperature of 298 K.

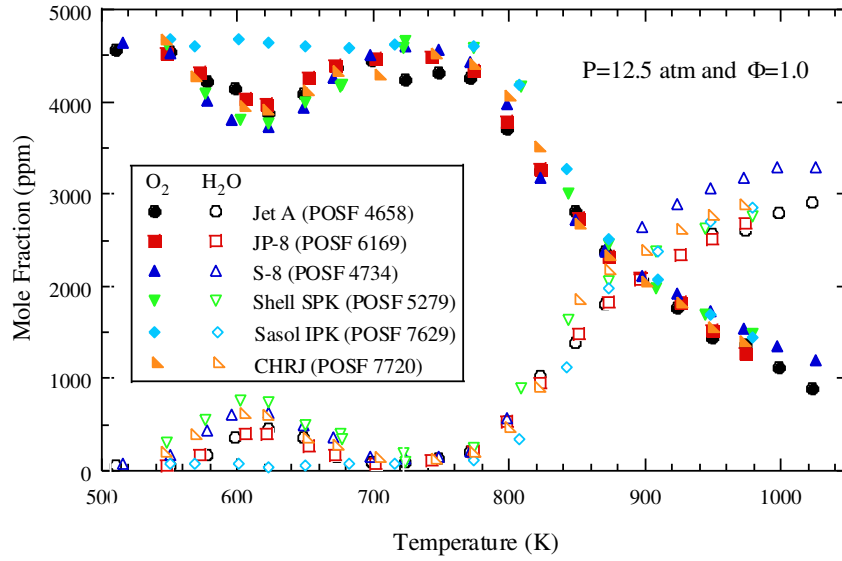


Figure 9 – Comparison of species data from flow reactor oxidation of conventional and alternative jet fuels [99].

Table 1 – ASTM standard and properties of conventional and alternative jet fuels.

Property	ASTM standard	Jet A	JP-8	S-8	Shell GTL®	Sasol IPK®	R-8	CHRJ	THRJ
POSF number	--	4658	3773	4734	5172	5642	5469	6152	6308
Composition									
n-paraffins, % wt	--	28	19	17.7	53.3	2.1	13.1	10.2	8.8
iso-paraffins, % wt	--	29	38.2	82	45.7	88	--	78.9	89.4
cyclo-paraffins, % wt	--	20	24.1	<0.4	<1.0	9	--	11.1	2.1
aromatics, % wt	Report	20	13.5	<0.1	<0.2	<0.5	--	<0.2	<0.4
total sulfur, % wt	max 0.3	--	0.0064	<0.001	<0.001	<0.001	<0.001	<0.0018	<0.003
Distillation									
initial boiling point, °C	Report	158	152	182	146	149	158	151	165
10% recovered, °C	max 205	184	173	195	162	166	175	161	179
20% recovered, °C	Report	192	179	--	162	170	185	166	185
50% recovered, °C	Report	213	198	228	169	180	215	182	210
90% recovered, °C	Report	248	239	--	184	208	260	237	243
final boiling point, °C	max 300	269	260	280	198	228	274	259	255
Flash point, °C	min 38	47	48	49	44	44	48	43	55
Freezing point, °C	max -47	-49	-49	-59	-54	<-78	-49	<-77	-62
Density @ 15°C, kg/m ³	775–840	806	790	757	737	762	762	751	758
Viscosity @ -20°C, cSt	max 8.0	5.2	4.1	4.6	2.6	3.6	5.5	3.3	5.3
Neat heat of combustion, MJ/kg	min 42.8	42.8	43	44.1	44.2	44	44.1	44.3	44.1
Smoke point, mm	min 19.0	21	25	>43	40	>40	>40	50	>40
H/C molar ratio	--	1.957	1.937	2.152	2.202	2.119	2.152	2.169	2.152
Molecular weight, g/mol	--	142	153	168	146	156	177	160	174

Data were taken from Refs. [13,42,51-53]

“Report” – The product of the test program that formally documents all data and information compiled during the evaluation process.

Table 2 – Combustor component tests for alternative jet fuels.

Performance targets	Testing components	Testing fuel
Atomization	Auxiliary power units (APUs) atomizer (2007) [58]	Sasol FSJF®
	Pressure-swirl atomizer (2012,2014,2015) [59,60,61]	FT CTL, GTL, HRJ
Ignition and altitude relight	Full-annular Trent combustor (2007) [62]	Sasol FSJF®
	Annular-can combustor sector (2012) [63]	Shell GTL®
	Twin-sector combustor (2011) [64,66]	FT SPKs
	Single can-type combustor (2005) [65]	FT SPK
	Single cup rectangular combustor (2012) [59]	FT CTL
	RQL combustor (2014) [67]	SPK
Lean blowout	Full-scale annular combustor (2007) [58]	Sasol FSJF®
	Three-cup combustor sector (2010) [68]	Shell GTL®
	Single cup rectangular combustor (2012) [59]	FT CTL
	Heterogeneous combustor (2012) [69]	Sasol FSJF®, GTL, SPK
	RQL combustor (2014) [67]	SPK
Emissions, smoke, and carbon deposit	Four-nozzle arc combustor sector (2007) [70]	Sasol FSJF®
	Single can-type combustor (2005) [65]	FT SPK
	Three-cup combustor sector (2010) [68]	Shell GTL®
	Twin-sector combustor (2011) [66]	FT SPKs
	Single cup rectangular combustor (2012) [59]	FT CTL
	Can-annular combustor (2011,2013) [71,72]	CTL, GTL, HRJ, FAME

Sources: Refs. [58-72]

Table 3 – Derived cetane numbers of conventional and alternative jet fuels.

Fuel		DCN	
Name	POSF#	FIT, ASTM D7170	IQT, ASTM D6890
Jet A	4658	49.35 [53]	47.1 [97]
JP-8	6169	-	47.3 [99]
Syntroleum S-8 [®]	4734	66.50 [53]	58.7 [98]
Shell GTL [®]	5172	64.69 [53]	59.1[57]
Shell SPK [®]	5729	-	58.4 [99]
Sasol IPK [®]	5642	33.46 [53]	31.28 [57]
Sasol IPK [®]	7629	-	31.1 [99]
R-8	5469	66.27 [53]	-
Camelina HRJ	6152	60.70 [53]	53.94 [57]
Camelina HRJ	7720	-	58.9 [99]
Tallow HRJ	6308	65.85 [53]	58.1 [99]

Data were taken from Refs. [53,57,97-99]

Table 4 – Threshold sooting indices of conventional and alternative jet fuels.

Fuel		TSI
Name	POSF#	
Jet A	4658	21.4 [97]
JP-8	6169	19.28 [99]
Shell SPK [®]	5729	9.11 [99]
Sasol IPK [®]	7629	17.28 [99]
Camelina HRJ	7720	11.99 [99]
Tallow HRJ	6308	11.58 [99]

Data were taken from Refs. [97,99]

Table 5 – Surrogates for various alternative jet fuels.

Reference	Target real fuel	Surrogate fuel	Validation targets
Huber et al. [121]	S-8	n-nonane/2,6-dimethyloctane/ 3-methyldecane/n-tridecane/n-tetradecane/ n-pentadecane/n-hexadecane 0.03/0.28/0.34/0.13/0.20/0.015/0.005 (by mole)	Density, thermal conductivity, sound speed, viscosity, distillation curve
Huber et al. [122]	Bio-SPK	4-methyloctane/2,5-dimethylnonane/ 2,3,5-trimethyldecane/n-tridecane/ n-pentadecane 0.105/0.281/0.164/0.227/0.223 (by mole)	Distillation curve
Mawid et al. [123]	S-8	n-decane/iso-octane 0.60/0.40 (by volume)	Autoignition delay time and species profile
Naik et al. [113]	S-8	iso-octane/n-decane/n-dodecane 0.32/0.25/0.43 (by mole)	Laminar flame speed, extinction strain rate, NO _x
	Shell GTL [®]	iso-octane/n-decane/n-dodecane 0.28/0.61/0.11 (by mole)	
Dooley et al. [98]	S-8	n-dodecane/iso-octane 0.519/0.481 (by mole)	Species profile, autoignition delay time, extinction strain rate
Slavinskaya et al. [124]	GTL	propyl-cyclohexane/2,7-dimethyloctane/ 2-methyldecane/n-decane 0.15/0.17/0.32/0.36 (by volume)	Physical properties
		propyl-cyclohexane/n-decane/iso-octane 0.15/0.36/0.49 (by volume)	Autoignition delay time
		propyl-cyclohexane/n-decane/ 2-methyldecane/iso-octane 0.15/0.36/0.32/0.17 (by volume)	
Mzé-Ahmed et al. [114]	CTL	n-decane/iso-octane/ n-propylcyclohexane/ n-propylbenzene 0.395/0.130/0.373/0.102 (by mole)	Species profile, autoignition delay time, laminar flame speed
Dagaut et al [115]	GTL	n-decane/iso-octane/n-propylcyclohexane 0.577/0.332/0.091 (by mole)	Species profile, autoignition delay time, laminar flame speed
		n-decane/iso-octane/n-propylcyclohexane 0.699/0.214/0.087 (by mole)	

Sources: Refs. [98,113-115,121-124]