Advancements in Gas Turbine Fuels from 1943 to ~~2005~~ 2025

ASME GT2005-68171
June 6, 2005

Tim Edwards
ex Fuels Branch
Propulsion Directorate
Air Force Research Laboratory

AFRL-WS 05-1238

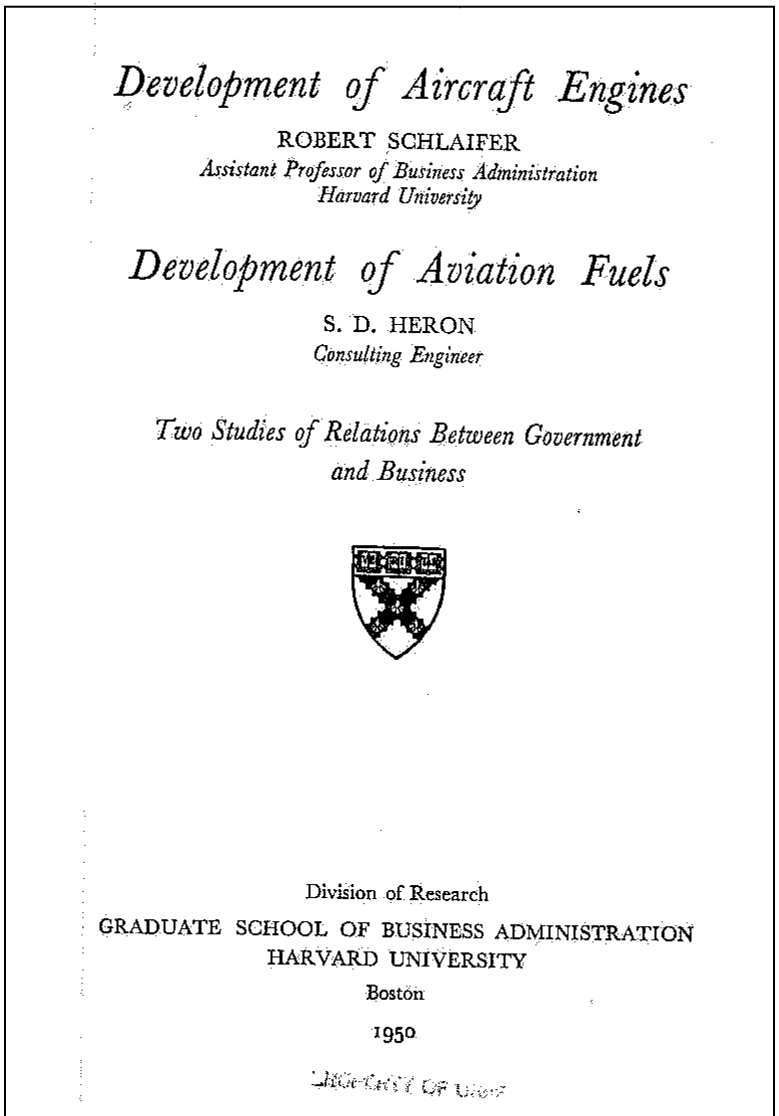
Resources

- Martel, C. R., “Military Jet Fuels, 1944-1987,” Air Force Wright Aeronautical Lab., Rept. AFWAL-TR-87-2062, Nov. 1987 (DTIC ADA186752).
- Dukek, W. G., et al., “Milestones in Aviation Fuels,” AIAA 69-779, 1969.
- Ogston, A., “A Short History of Aviation Gasoline Development, 1903-1980,” *Trends in Aviation Fuels and Lubricants*, SP-492, Society of Automotive Engineers, Warrendale, PA, 1981, pp. 1–14.
- Heron, S. D., “Development of Aircraft Engines and Fuels,” edited by R. Schlaifer and S. D. Heron, Harvard Univ., Boston, 1950, pp. 545–662.
- Edwards, T., "Advancements in Gas Turbine Fuels From 1943 to 2005," Journal of Engineering for Gas Turbines and Power, Vol. 129, pp. 13-290, 2007.
- Edwards, T., “Liquid Fuels and Propellants for Aerospace Propulsion: 1903–2003,” Journal of Propulsion and Power, Vol. 19, No. 6, November–December 2003.
- Chevron Aviation Fuel Handbook online

Higher Octane Avgas

- Army Air Corps at McCook/Wright Fields (Dayton) pushed engine benefits of higher octane fuels with TEL (Wright bros fuel est 38-50 octane)
- First specification for 100 octane in 1934 (100 octane in 1930 ~ $1/gal ($18.35 today))
- High octane fuels credited with key role in winning Battle of Britain
  - RR Merlin engine produced >5X more horsepower than WWI engine of same displacement
- Avgas production increased from 54 million gallons/yr in 1932 to 25 million gallons/DAY at end of WWII (169X)
- Culmination of avgas development was specification for 115/145 octane fuel (lean/rich)

Heron's Book



Development of Aircraft Engines

ROBERT SCHLAIFER

Assistant Professor of Business Administration

Harvard University

Development of Aviation Fuels

S. D. HERON

Consulting Engineer

Two Studies of Relations Between Government and Business

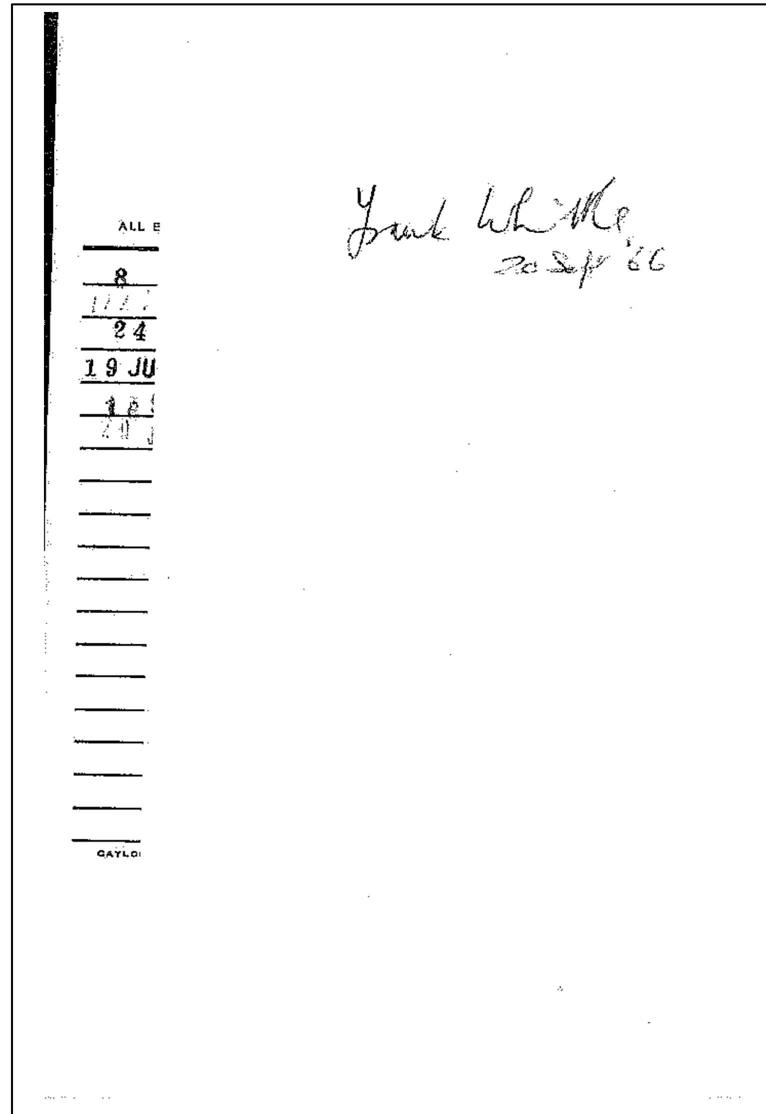
Division of Research

GRADUATE SCHOOL OF BUSINESS ADMINISTRATION

HARVARD UNIVERSITY

Boston

1950



ALL E

8

24

19 JU

GAYLO

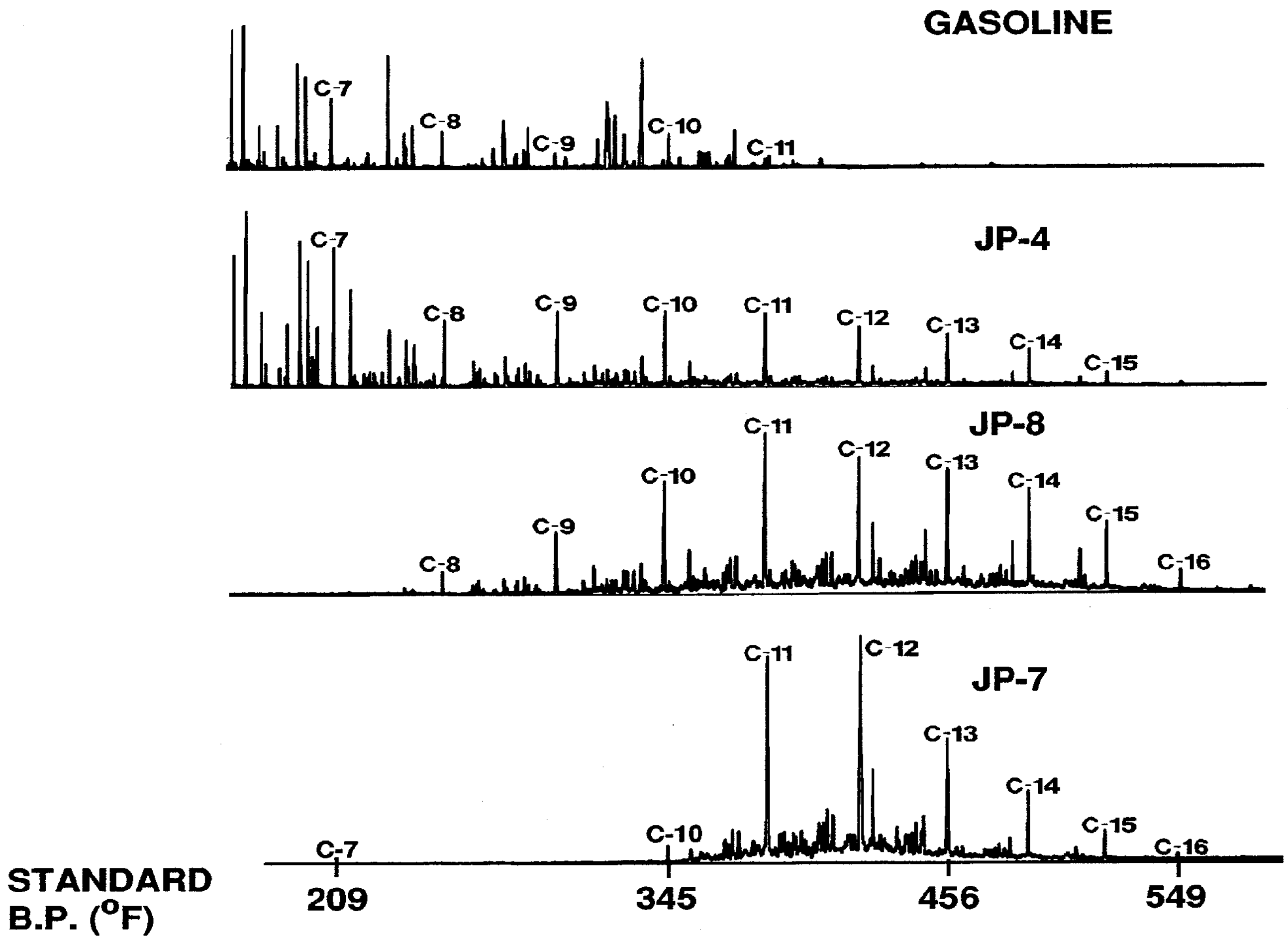
Frank Whittle

20 Sept '66

The Advent of the Gas Turbine

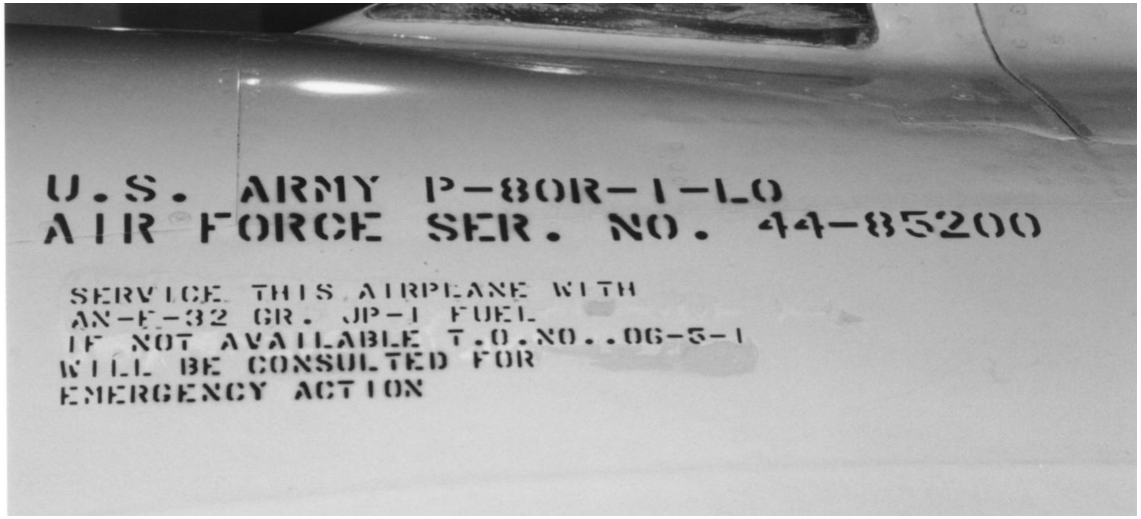
- Gas turbines can operate with a wide variety of fuels
- In late 40s/early 50s, specifications for "jet propellant" traded off availability (cost), freeze point, and volatility: JP-1, JP-2, JP-3 not satisfactory
- JP-4 was a mix of gasoline-range and kerosene – became primary military (AF) fuel from mid 1950s to 1980s
- Commercial and Navy jet fuels were kerosenes for fire safety reasons (Jet A/Jet A-1/JP-5)
- USAF switched to kerosene jet fuel in 1980s (JP-8)

Fuel Boiling Range

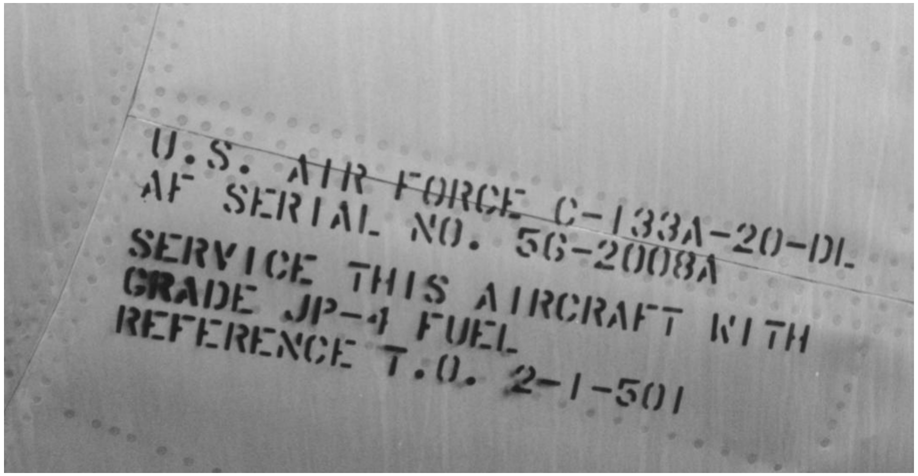


AF Museum Fine Print

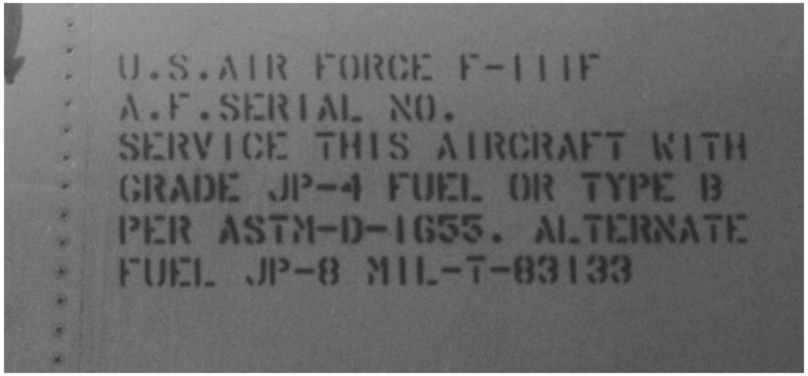
P-80: JP-1



C-133, B-52, B-58 etc.: JP-4



1980s planes: JP-4 or JP-8



Military Gas Turbine Fuels

Figure 3.1
U.S. Military Jet Fuels

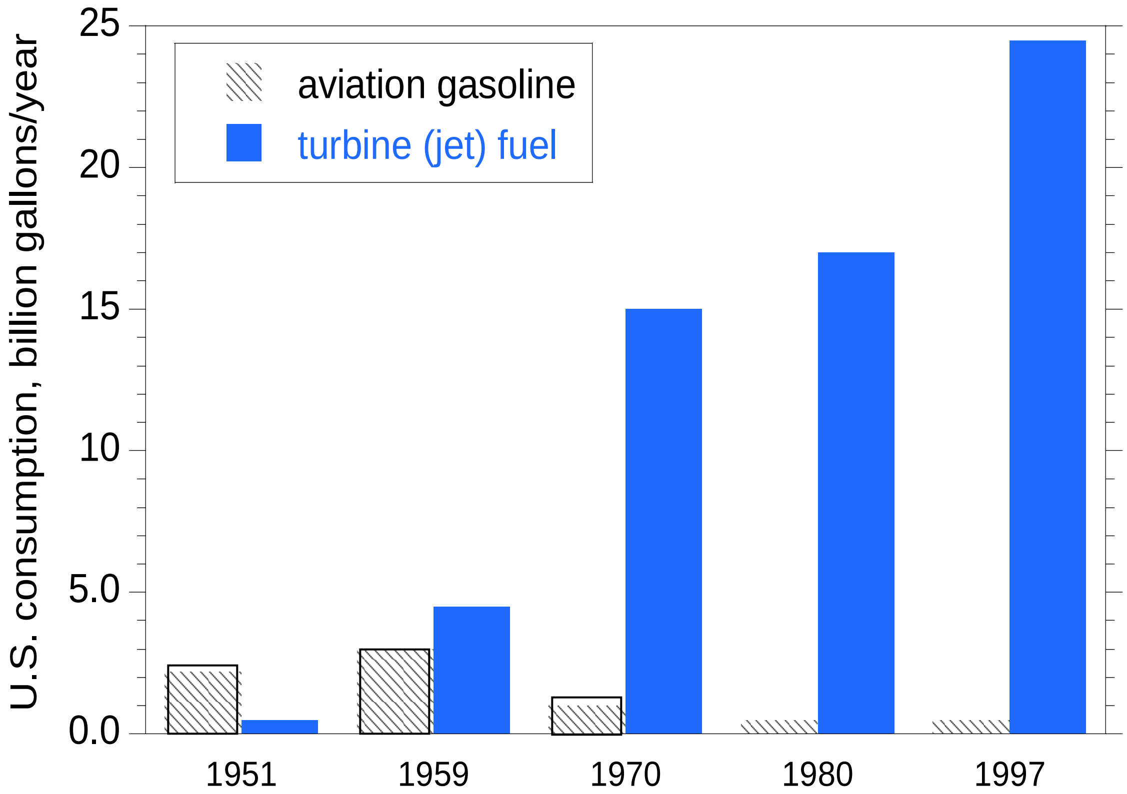
Fuel	Year Introduced	Type	RVP, psi	Freeze Point ºC max	Flash Point ºC min	Comments
JP-1	1944	kerosene		– 60	43	obsolete
JP-2	1945	wide-cut	= 2	– 60		obsolete
JP-3	1947	wide-cut	5 - 7	– 60		obsolete
JP-4	1951	wide-cut	2 - 3	– 72		U.S. Air Force fuel
JP-5	1952	kerosene		– 46	60	U.S. Navy fuel
JP-6	1956	kerosene		– 54		XB-70 program, obsolete
JPTS	1956	kerosene		– 53	43	Higher thermal stability
JP-7	1960	kerosene		– 43	60	Lower volatility, higher thermal stability
JP-8	1979	kerosene		– 47	38	U.S. Air Force fuel
JP-8+100	1998	kerosene		– 47	38	U.S. Air Force fuel containing an additive that provides improved thermal stability

JP stands for Jet Propulsion.

Chevron

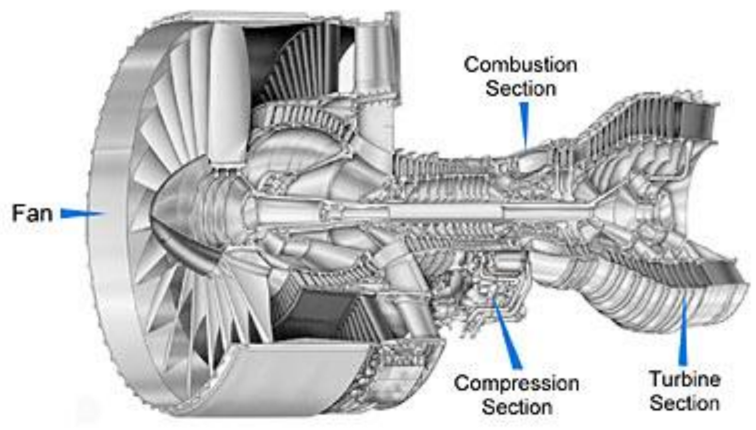
Aviation Fuel Changes

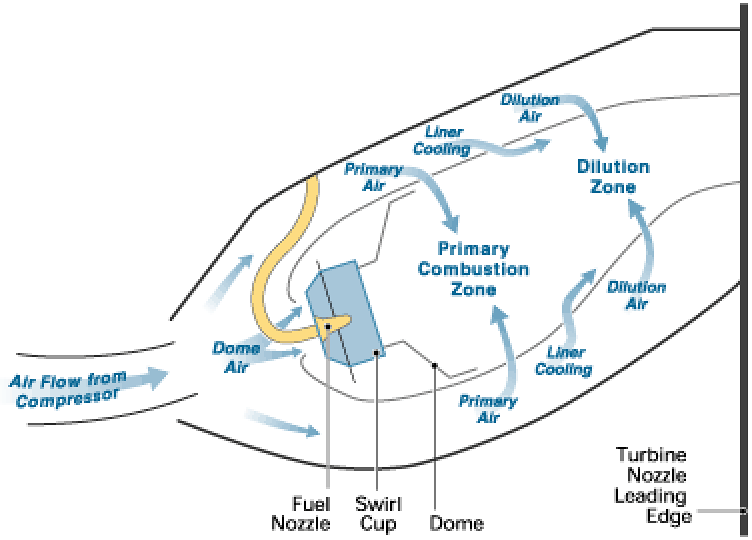
- First successful commercial jet airliner in 1959
- Current usage is roughly 10% military, 90% commercial in the U.S.



Gas Turbine Combustion

- **Key aspects of jet fuel for combustion:**
  - **Aromatics limit to minimize soot and liner heating**
  - **Freeze point and low T viscosity limits to ensure effective atomization (fluidity) at low fuel temperatures**
  - **Volatility limits to ensure effective vaporization**





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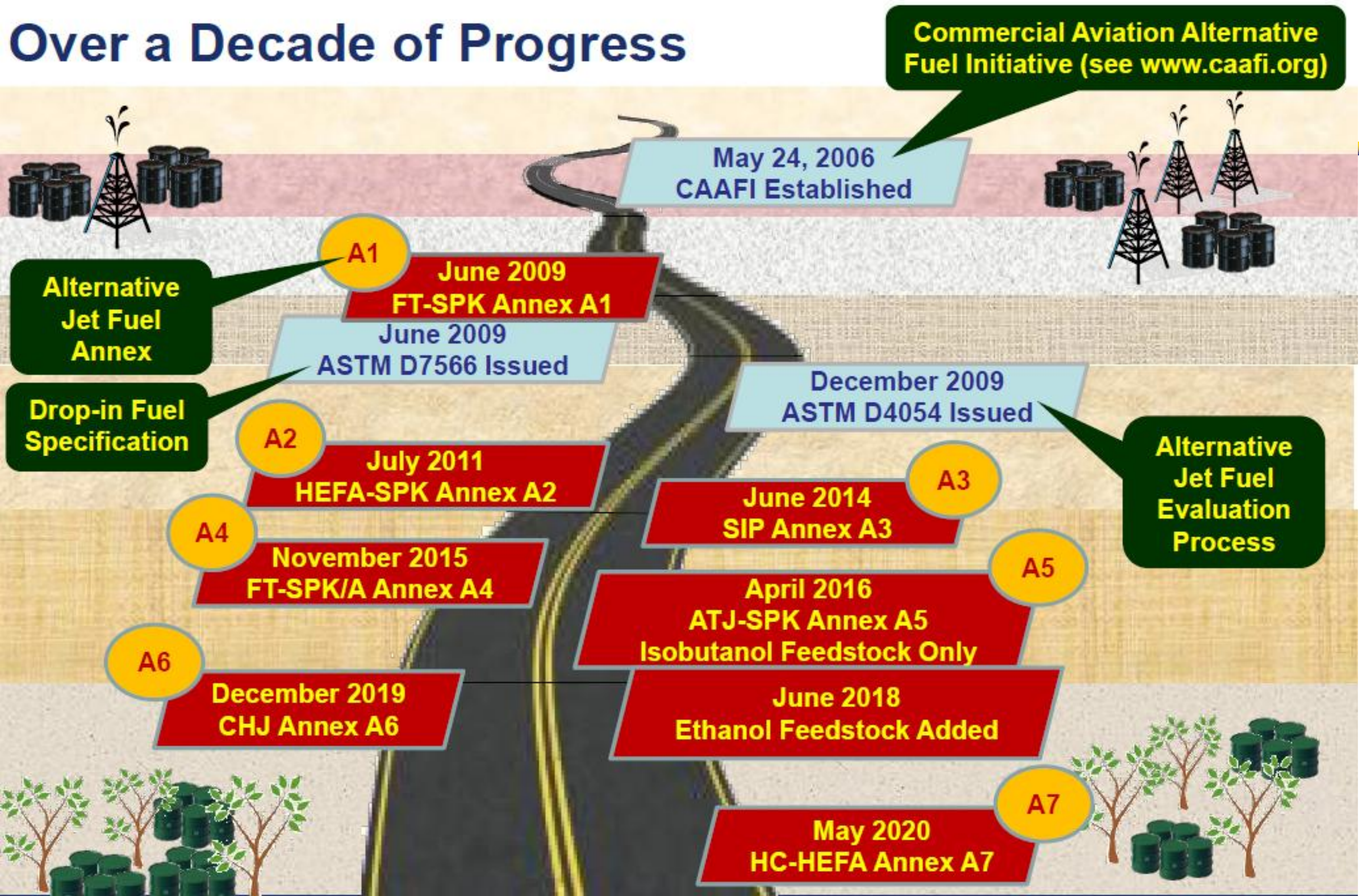
Where Are We Going From Here?

2005

- 2003: 177 million gallons/day of Jet A/Jet A-1/JP-8 (essentially identical) jet fuel used world-wide
- Fuel consistency a tremendous operational and financial benefit to all
- Changes on the horizon for "bulk" jet fuels:
  - Reduction in sulfur content (3000 ppm max to ?) X
  - Gradual introduction of non-petroleum-derived fuel components
    - Fischer-Tropsch process can make jet fuels/components from coal/natural gas X
  - Future fuel changes may come about from requirements for higher Mach flight X

Over a Decade of Progress



AF HEFA Certification

Table 1. Aircraft Certification and Test Completion Dates

MDS	Cert Date	Test Complete
C-17	4 Feb 2011	27 Aug 2011
F-16/F100/F110	29 Mar 2011	demo 21 May 2011
F-15	9 May 2011	22 Oct 2010
C-130 – all models	27 Feb 2012	5 Aug 2011
B-1	5 March 2012	
B-2	13 March 2012	
RQ-4A	27 March 2012	26 Oct 2011
U-28/PC-12	3 April 2012	
C-5	16 April 2012	
MQ-9	16 April 2012	27 Oct 2011
T-38	25 April 2012	
H-60	27 April 2012	
T-6	30 April 2012	
A-10	30 May 2012	25 Mar 2010
E-3	6 Sept 2012	
C-135	18 Sept 2012	
B-52	19 Sept 2012	
E-8	20 Sept 2012	
C-27J	30 Oct 2012	
H-1	14 Dec 2012	
F-22	2 May 2013	28 Mar 2011, 17 Jan 2012

- **ASTM D7566 certification efforts benefitted from significant military efforts 2006-2016 (and NJFCP later)**

First 50/50 HEFA Flight

- **A-10 2010**
- **Military focus – diesel engine performance, augmented engines, storage stability, material compatibility**

Switch to Commercial Fuel

NATO/EAPC UNCLASSIFIED

AFLP- 3747

ECTION 2 NATO GUIDE SPECIFICATION FOR AVIATION TURBINE FUEL: NATO CODE No F-24

0201. Product complying with this Guide Specification shall consist of kerosene type turbine fuel conforming to ASTM D1655 (Standard Specification for Aviation Turbine Fuels), Type Jet A, containing the following additives: treated with 0.07-0.10% by volume S-1745 Fuel System Icing Inhibitor (FSII), S-1747 Lubricity Improving Additive (LIA) per STANAG 3390, and Static Dissipater Additive (SDA), Stadis 450, blended into the fuel in sufficient concentration to increase the conductivity of the fuel to between 50 and 600 pS/m at ambient temperature or 29°C whichever is lower, when tested in accordance with ASTM D2624. Stadis 450 is manufactured by Innospec Fuel Specialties LLC.

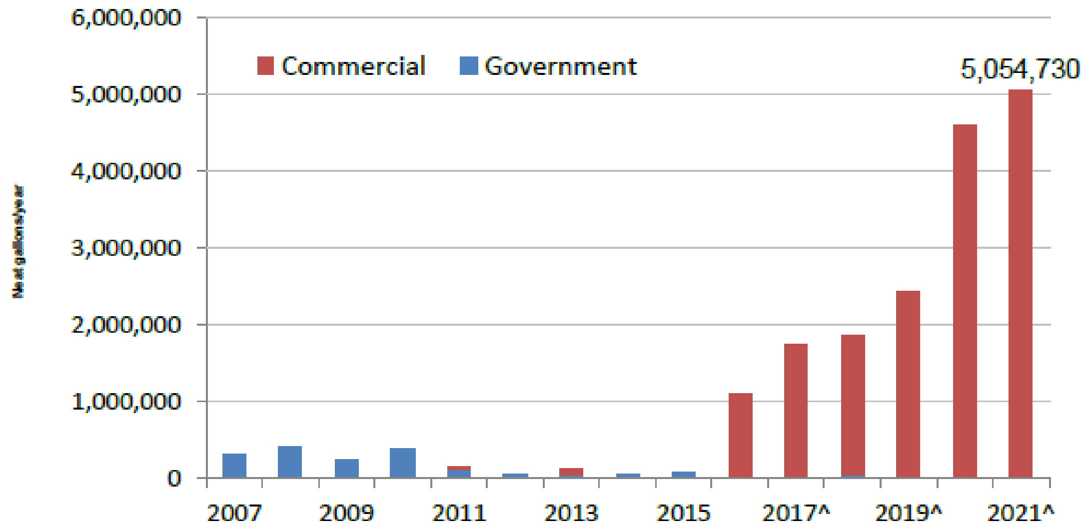
0106. Synthetic components meeting the requirements of ASTM D7566 (Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons) are allowed by several fuel specifications such as ASTM D1655, DEF STAN 91-91, MIL-DTL-5624, and MIL-DTL-83133, which characterize aviation turbine fuels defined by this STANAG. Before any fuel containing synthetic components may be delivered to a NATO aircraft it must first be ascertained that the appropriate clearance document(s) permitting its use have been obtained. Typically, clearances would be provided by the technical authority for the fuel in concert with the Original Equipment Manufacturers (OEM), weapon system manager, airworthiness authority and/or aircraft engineering officer.

Where we stand on U.S. SAF commercialization

Initiation under way, still early, but growing

- Six years of sustained & increasing commercial use
- 5.05 M gallons in 2021
- One commercial U.S. facility in operation
- Two facilities under construction (others in development)
- Cost delta with renewable diesel remains major challenge

U.S. Annual SAF Procurements*



*Reflects voluntarily reported data on use by U.S. airlines, U.S. government, manufacturers, other fuel users, and foreign carriers uplifting at U.S. airports.
^ 2017-2021 calculation incorporates data reported by EPA for RFS2 RINs for renewable jet fuel.

Alternative Fuel Awards

	Contract Number	Company	Product	Award / Option Date	Quantity	Cost per Gallon	Total	Feedstock	Service	Delivery Location	FY of Execution	Funding
1	07-D-0486	Shell	FT - Kerosene	6-Jun-07	315,000	$3.41	$1,074,150	Nat Gas	AF		2007	AF RDTE - FY 2007
2	08-D-0496	SASOL	FT - Kerosene	26-Jun-08	60,000	$3.75	$225,000	Coal	AF		2008	AF RDTE - FY 2008
3	08-D-0497	SASOL	FT - Kerosene	3-Jul-08	335,000	$3.90	$1,306,500	Coal	AF		2008	AF RDTE - FY 2008
4	09-D-0519	Sustainable Oils	HRJ5	31-Aug-09	40,000	$66.60	$2,664,000	Camelina	Navy	Pax River/Evandale, OH (GE)	2009	Navy & DLA ARRA RDT&E - FY 2009
5	09-D-0518	Solazyme	HRJ5	1-Sep-09	1,500	$149.00	$223,500	Algal Oil	Navy	Pax River	2009	DLA ARRA RDT&E - FY 2009
6	09-D-0520	Sustainable Oils	HRJ8	15-Sep-09	100,000	$66.80	$6,680,000	Camelina	AF	WPAFB, Arnold, Edwards	2009	AF RDTE - FY 2009
7	09-D-0517	UOP	HRJ8	15-Sep-09	100,000	$64.00	$6,400,000	Tallow	AF	WPAFB, Arnold, Edwards	2009	AF RDTE - FY 2009
8	09-D-0523	PM Group Int'l	FT F76	30-Sep-09	20,000	$7.00	$140,000	Nat Gas	Navy	ONR - Michigan	2009	Navy RDT&E - FY 2009
	Option	Sustainable Oils	HRJ5	29-Jun-10	150,000	$34.45	$5,167,500	Camelina	Navy	Pax River	2010	Navy RDT&E; DLA ARRA RDT&E - FY 2010
9	10-D-0489	Sustainable Oils	HRJ8	26-Jul-10	34,950	$38.60	$1,349,070	Camelina	Army	SWRI	2010	DLA ARRA RDT&E - FY 2010
	Option	Sustainable Oils	HRJ8	31-Aug-10	100,000	$34.90	$3,490,000	Camelina	AF	WPAFB, Arnold, Edwards	2010	AF RDTE - FY 2010
	Option	UOP	HRJ8	31-Aug-10	100,000	$32.40	$3,240,000	Tallow	AF	WPAFB, Arnold, Edwards	2010	AF RDTE - FY 2010
10	11-D-0526	Gevo	ATJ8	23-Sep-11	7,000	$59.00	$413,000	Alcohols	AF	WPAFB	2011	AF RDTE - FY 2011
	Option	Gevo	ATJ8	28-Sep-11	4,000	$59.00	$236,000	Alcohols	AF	WPAFB	2011	AF RDTE - FY 2011
11	11-D-0530	UOP	HRJ8	30-Sep-11	4,500	$33.00	$148,500	Camelina	Army	SWRI	2011	Army RDT&E - FY 2011
12	12-D-0549	Dynamic	HRJ5	30-Nov-11	100,000	$26.75	$2,675,000	UCO/Algal	Navy	Puget Sound	2012	Navy Ops - FY 2012
			HRD76	30-Nov-11	350,000	$26.75	$9,362,500	UCO/Algal	Navy	Puget Sound	2012	Navy Ops - FY 2012
13	12-D-0559	UOP	HRJ8	2-May-12	4,500	$29.90	$134,550	UCO/ICO	Army	SWRI	2012	Army RDT&E - FY 2012

Alternative Fuel Awards

	Contract Number	Company	Product	Award / Option Date	Quantity	Cost per Gallon	Total	Feedstock	Service	Delivery Location	FY of Execution	Funding
16	13-D-0452	Amyris	DSH76	22-Oct-12	3,000	$25.73	$77,190	Ferm. Sugar	Navy	Pax River	2013	Navy RDT&E – FY2013
17	13-D-0466	Gevo	ATJ8	22-Mar-13	3,650	$59.00	$215,350	Alcohols	Army	WPAFB/SWRI	2013	Army RDT&E - FY 2013
	Option	Amyris	DSH76	3-May-13	24,618	$25.73	$633,421	Ferm. Sugar	Navy	Pax River	2013	Navy RDT&E - FY 2013
	Option	Gevo	ATJ8	3-May-13	12,500	$59.00	$737,500	Alcohols	Army	WPAFB/SWRI	2013	Army RDT&E - FY 2013
18	13-D-0462	Gevo	ATJ5	23-May-13	850	$59.00	$50,150	Alcohols	Navy	Pax River	2013	Navy RDT&E – FY 2013
19	13-D-0488	Kior	HDCD76	26-Sep-13	6,500	$8.28	$53,790	Cellulose	Navy	Pax River	2013	Navy RDT&E - FY 2013
20	13-D-0489	Gevo	ATJ5	30-Sep-13	20,000	$59.00	$1,180,000	Alcohols	Navy	Pax River	2013	Navy RDT&E – FY2013
	Option	Kior	HDCD76	20-Dec-13	5,000	$9.50	$47,515	Cellulose	Navy	Pax River	2013	Navy RDT&E - FY 2013
21	14-D-0511	Amyris	DSH8	26-Sep-14	800	$22.06	$17,650	Ferm. Sugar	Army	SWRI	2014	Army RDT&E – FY2014
22	14-D-0509	ARA	CHCJ5	29-Sep-14	110,250	$50.00	$5,512,500	Renew. Oils	Navy	Pax River	2014	Navy RDT&E – FY 2014
	14-D-0509	ARA	CHCD76	29-Sep-14	101,250	$50.00	$5,062,500	Renew. Oils	Navy	Pax River	2014	Navy RDT&E – FY 2014
23	15-D-0516	AltAir	F76*	24-Sep-15	77,660,000	$2.15	$167,310,704	Renew. Oils	Navy	Various	2015	DLA Energy / Commodity Credit Corp (USDA)
TOTALS					79,763,947		$225,954,431					

HR/HEFA	1,085,450	$41,534,620	$38.26
FT	730,000	$2,745,650	$3.76
ATJ	93,000	$5,487,000	$59.00
DSH	43,336	$1,106,390	$25.66
HDCD	11,500	$57,525	$8.81
CHC	211,500	75,000	50.00

- **For Item 23, the finished product is comprised of 90% MILSPEC F-76 and 10% HEFA blendstock.**

Note: With the exception of Item 23, all contract items shown are 100% unblended products procured for military fuel certification purposes, and costs shown for each do not reflect actual operational fuel procurements. Item 23 represents the first DLA Energy bulk contract award for operational volumes of blended alternative fuel complying with an existing MILSPEC

777F ecoDemonstrator Program

2017

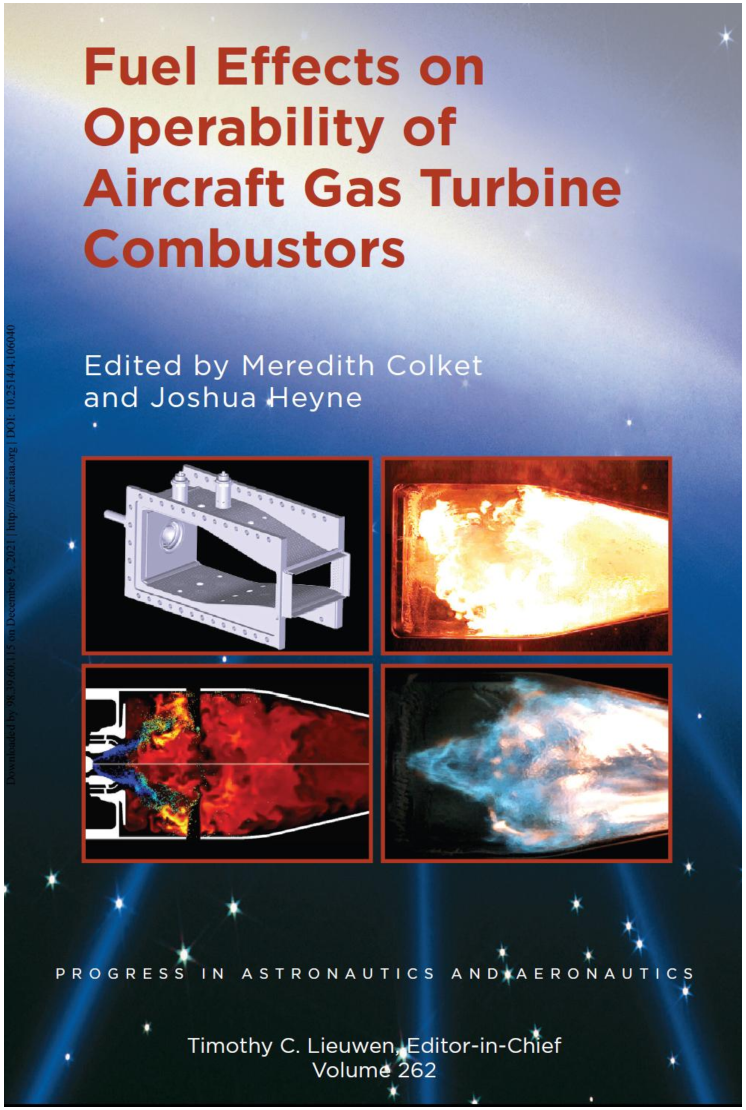
HEFA and Aircraft Information

- HEFA was sourced from:
  - AFRL (62,000 USG) => ½ Camelina and ½ Tallow
  - AltAir (59,000 USG) => Tallow
- HEFAs met ASTM D7566 requirements for the neat material (Annex 2) and BOCLE
  - HEFA was additized with SDA

- Aircraft: Boeing 777F
- Engines: GE90-110B1G02
- APU: Honeywell 331-500B

Nat’l Jet Fuel Combustion Program

- ~5 year program, with multiple funding agencies and many research groups involved
- Focus was fuel effects on operability
  - Lean blowout, altitude relight
  - Emissions
- Big, complicated “coalition of the willing”
- E.g., see next chart from regular meeting



2021

National Jet Fuels Combustion Program

Plans for AIAA Book

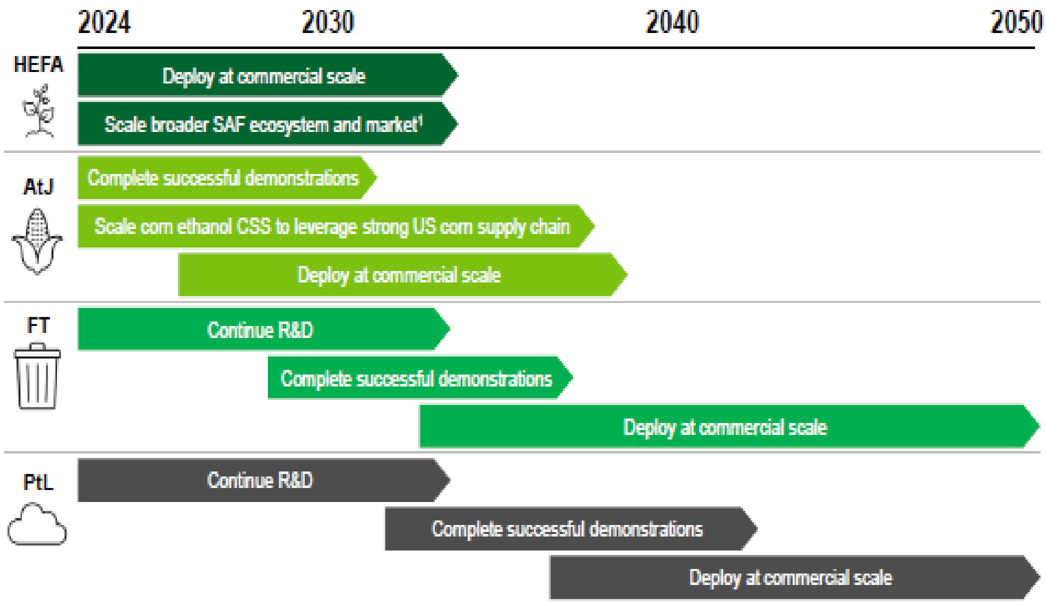
Josh Heyne

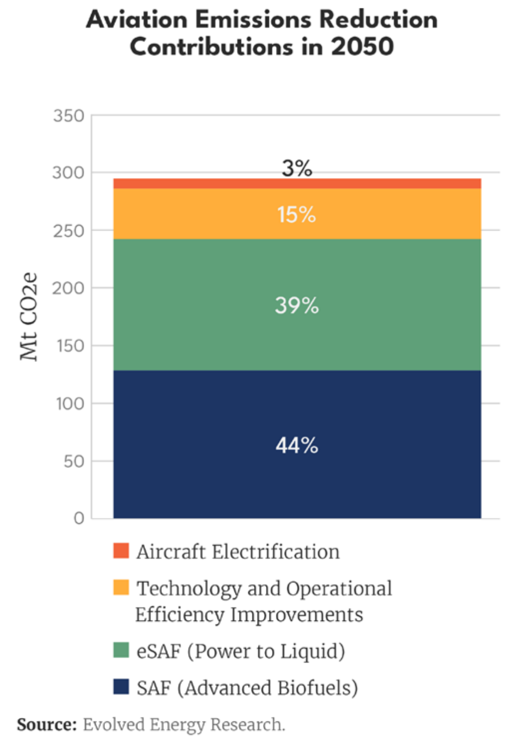
Med Colket

End-of-Year Meeting
Dec. 12-14, 2017
Dayton, OH

Future Issues

- **Net Zero by 2050 (~35 B gal/yr)**
- **Performance, certification of 100% SAF**





- **Military issues – diesel performance, long term storage, augmented (afterburning) fighter engines**

Particulates 2014

- **2025 – particulates seen as a significant contributor to climate change**

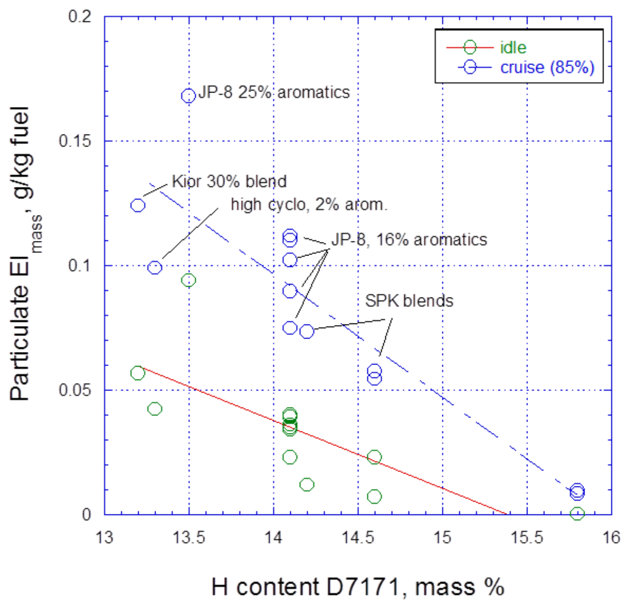


Figure 3.1.2 Particulate Mass Emissions in T63 Engine as a Function of Fuel Hydrogen Content

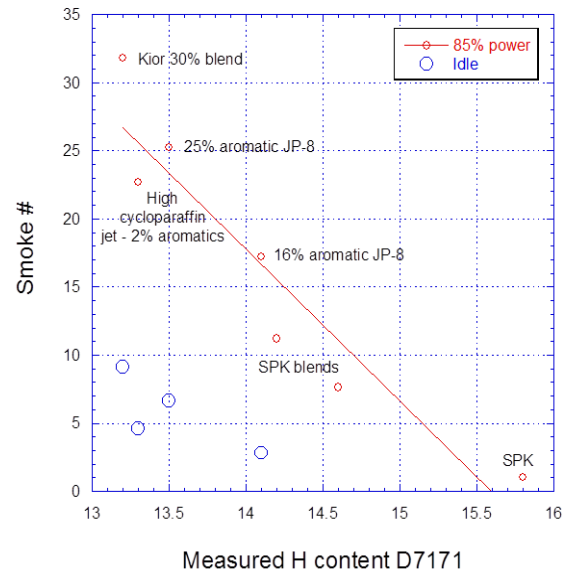


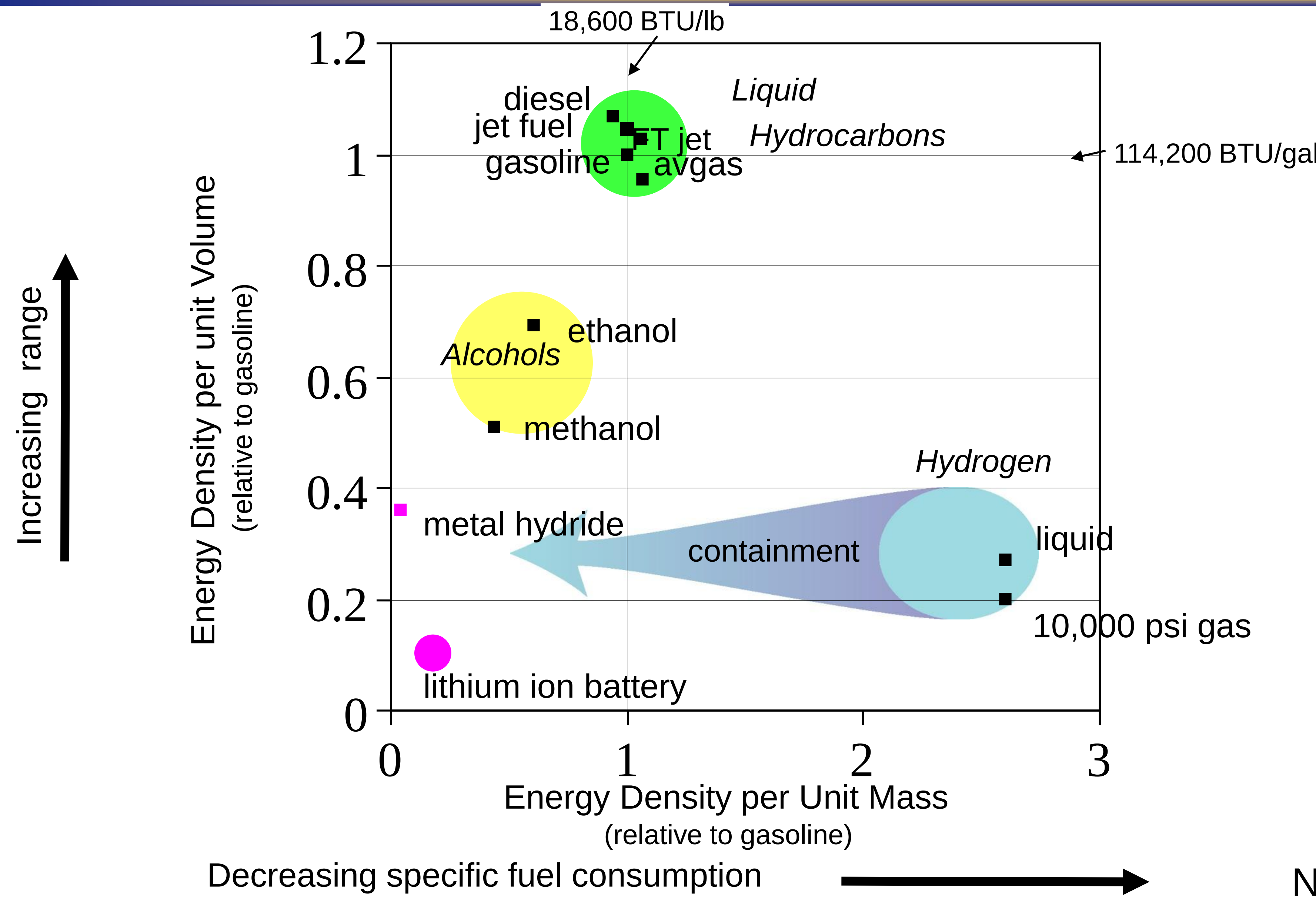
Figure 3.1.1 Smoke # in T63 as a Function of Fuel Hydrogen Content

- **2014 HDCJ (KiOR) research report – particulates controlled by fuel H/C ratio (H content), not primarily by aromatic content**

Summary 2025

- Avgas development efforts paced the improvement of reciprocating aircraft engines (huge scaleup 1932-1945)
- Turbine engine improvements have been much less dependent upon fuel development
  - Turbine fuels have been fairly constant since the late 1950s
- Bulk jet fuels are expected to remain constant for the near future (20 years)
- Future fuel changes may come about from requirements for higher Mach flight
- Future – SAF! (not H_2)

Energy Density Critical



Navy

Single Fuel Policy (SFP)

- Single Fuel Concept

1988 - *To achieve equipment interoperability through a single fuel for use on the battlefield and for land based air operations, ensuring that the specification of the fuel is standardised with its commercial equivalent in common use in NATO Europe, and that the physical and chemical characteristics of the fuel are such that it can be introduced, stored, transported and distributed by the NATO Pipeline System.*

- 2005 - Single Fuel Policy applicable NATO wide

Single Fuel Policy

Jet-A1

F-35

+ S-1745
+ S-1747

Military Aviation use

F-34

+ S-1750

F-63

SFP Implementation

- Stage 1 – Replacement of high volatile F-40 (Jet B with mil additives) with F-34 (Jet A-1 with mil additives) for use by land based aircraft- *Completed*
- Stage 2 – Replacement of diesel fuel F-54 with F-34 for use by land based vehicles/equipment with compression ignition or turbine engines- *Ongoing*
- Stage 3 – Elimination of gasoline from military use- *Ongoing*

SFP - Challenges

- Availability of F-34
- Power loss in certain (older) vehicles
- Minor modifications to (older) equipment might be needed
- Wide range of cetane number of synthetic fuels
- Possible reduction in lubricity
- Use of lubricity and cetane improver additives may be necessary (S-1750)
- Compatibility with engines using advanced emission reduction technologies
- Sulphur concentration below 15 mg/kg due to advance emission systems and strict environmental emission legislations