Airborne Science Mission Capabilities of the NASA DC-8 and Possible Alternative Aircraft

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Age-related concerns associated with operating the 50-year-old NASA Airborne Science Program DC-8 Flying Laboratory aircraft are raising concerns about the prospects of someday retiring the NASA DC-8. Given that eventuality, this study examines how current and anticipated science requirements can be incorporated with aeronautical performance and cost metrics for assessing, comparing, and down-selecting candidate replacement aircraft. A literature review of NASA DC-8 missions and interviews with current DC-8 science users provides context for the initial phase of this study and offers a pathway for collecting aircraft specifications. Performance models are developed and calibrated against published range-payload data for various mission fuel and payload weight combinations. The models are extended to three airborne science missions, with payload weights ranging from 30,000-52,000 lb and mission ranges up to 5,050 nmi. Results point towards the 767-200ER aircraft as a top contender offering a bit more experimenter floor-space, payload capacity, and range than the NASA DC-8, and to the U.S. Navy P-8 aircraft as a viable option offering perhaps not too much less of those items, with the relative benefit of using less fuel per mission.

I. Nomenclature

ALT	=	flight altitude above sea level
ASP	=	Airborne Science Program
DC-8	=	The NASA Airborne Science Program DC-8-72 aircraft, N817NA
E	=	engine (1E, all E)
EIS	=	entry into service
EW	=	aircraft empty weight (manufactured weight)
MTOW	=	maximum takeoff weight
n	=	number of aircraft
nmi	=	nautical miles
OEW	=	aircraft operating empty weight
Wt, wt	=	weight
ZFW	=	aircraft operating empty weight plus payload weight

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II. Introduction

The NASA Airborne Sciences Program (ASP) maintains and operates a diversified fleet of aircraft that facilitate state-of-the-art geophysical and atmospheric scientific investigations. With a maximum payload greater than 50,000 pounds and a maximum range greater than 5,700 nautical miles [1], the NASA DC-8 (Fig. 1) features prominently in the ASP fleet as the preferred platform for carrying out global tropospheric science campaigns. The NASA ASP DC-8-72 variant (N817NA) was manufactured in 1969, but the remaining service life of the airframe remains rather high, as instrumentation setup and turnaround times associated with a full slate of science campaigns limit the DC-8 to about 500 flight-hours per year [2-4]. After NASA acquired the DC-8 in 1985, it was modernized with four new sets of wing pylons and CFM56-2-C1 turbofan engines and extensively customized for scientific needs before re-introduction as the Airborne Science Program's Flying Laboratory in August 1987 [5]. However, as these and other age-mitigating factors become more frequently offset by the negative consequences of aging, concerns are growing within the ASP about controlling long-term operational costs and maintaining mission readiness. Putting aside the fitness of the DC-8 aircraft itself, operating a 1960's-era aircraft in the 21st century presents difficulties including a shortage of trained flight crew, few remaining flight simulators, decreasing supplies of reliable spare parts, high fuel costs, and lack of suitable ground handling equipment at destination airports. These and other issues indicate that NASA's DC-8 may be forced into retirement in the coming decades.

Fig. 1 NASA's DC-8 Flying Laboratory.

NASA's DC-8 has been customized to include dozens of viewports, provisions to mount air-sampling probes, secondary electrical power to run dozens of instruments for concurrent experiments, and communications equipment to allow for corroboration of measurements from other platforms for various science campaigns. A full accounting of DC-8 customizations can be found in the NASA DC-8 Airborne Laboratory Experimenter Handbook [5]. The NASA ASP website, https://airbornescience.nasa.gov [6] includes additional information about the DC-8, and offers interactive tools for examining how the DC-8 has been configured for Airborne Science Campaigns in the past.

This study focuses on identifying aircraft options for sustaining the unique, state-of-the-art atmospheric science capabilities afforded by the NASA DC-8 Flying Laboratory, in terms of mission readiness and platform performance, with some consideration of the complementary scientific capabilities offered by other aircraft in the ASP fleet. It is recognized that the utility for atmospheric research of the DC-8 or a candidate replacement aircraft likely extends to other types of airborne geophysical research; however, determining how such factors might influence identifying candidate replacement platforms, or change the composition of the ASP fleet, is not pursued herein.

The study was completed in several phases that included first gathering information suitable for developing science requirements and metrics that could be matched to a database of airplane characteristics created for this effort. Six airplanes then were down-selected for further evaluation based on metrics scores, additional review, and discussions with pilots, scientists, and engineers. The aircraft were the modified NASA (Douglas) DC-8, Gulfstream G-V, Boeing P-8 (military variant of the 737-900ER), Boeing 767-200ER, Airbus A-330-200, and the Boeing 777-200LR. Performance analysis models of each aircraft were developed and calibrated against published range-payload data for nominal transport missions. This step was necessary for developing the capability to analyze off-nominal airborne science missions, with experimental requirements that may require flying a repeating series of climb-descend segments, cruising for long durations at low altitudes, or following some other unusual trajectory. The calibrated models were extended for evaluating aircraft performance for a small set of such previously flown airborne science missions featuring different flight paths and payloads. Results are communicated in a manner that compares the current DC-8 capabilities against the utility of candidate replacement aircraft and provides a basis for future decisions.

III. ASP DC-8 Requirements and Metrics Development

Discussions regarding the future of the DC-8 Flying Laboratory are in the earliest stages, so there were few prescriptive requirements guiding this study. The scope was intentionally broad; however, the objective was to characterize the current capabilities and limitations, and point out suitable options for maintaining the capabilities of the DC-8 within the ASP fleet. The initial research direction was guided by experience gained from similar cross-disciplinary studies that underscores the importance of listening and working openly with scientists when translating scientific procedures, objectives, and instrumentation requirements to a set of airplane parameter specifications, performance requirements, and metrics suitable for aeronautical design or analysis. Understanding how scientists envision using the platform to meet their objectives can also influence the aeronautics concepts of operations and thereby affect the eventual airplane analysis results at a fundamental level. After a literature review and some airborne science familiarization, this study began with meetings, interviews, and site visits with the personnel and facilities associated with the operation and use of NASA's DC-8.

A. Requirements Overview

An initial phase of research was reserved for gathering information and identifying the science requirements and metrics for evaluating various DC-8 replacement options, including the use of one or more existing aircraft, ordering a custom-manufactured aircraft, or overhauling the already customized DC-8. This involved reviewing background documentation of prior communications among the scientific, programmatic, and engineering groups associated with NASA's DC-8. Time spent organizing and reading available email communications provided insights to the origins of this study, and the roles and viewpoints of the various stakeholders. More in-depth understanding of the ASP aircraft fleet capabilities and scientific objectives was obtained by accessing information available on the Airborne Science website, and by reviewing internal programmatic documents such as NASA DC-8 Flying Laboratory: A Justified Investment [6], and the Airborne Science Program 2017 Annual Report [7]. The information was helpful for developing questions that could be asked during planned discussions with the atmospheric scientists. Other documentation about the performance, sizing, and design layouts of nearly 50 different aircraft were reviewed and organized for subsequent use during later phases of this study [8-20].

Interviews with NASA Langley Research Center (LaRC) atmospheric scientists and a tour of the local science facilities and instruments proved beneficial to understanding how scientists view the DC-8 platform, in relation to their scientific instruments and their data collection needs. The first-hand flight experience of the investigators yields the aeronautical perspective needed for offering well-informed and detailed insights to the DC-8 performance capabilities and limitations, especially as applied to their own instrumentation and measurement needs. The informed opinions provided useful common ground for discussing aircraft performance requirements, design features, and other capabilities, and it became clear that a good deal of thought already had been given to identifying and substantiating personally favored replacement platform options. It was necessary to keep in mind that informed observations inherently reflect individual perspectives. For example, one might report that the DC-8 payload capacity is not limiting, as evidenced by their needs or observations of multiple scientific teams and instruments on board a large-scale campaign. However, another scientist interested in collecting high altitude samples during that same campaign might report the contrary fact that the DC-8 rarely reaches altitudes of 40,000 feet until late in the flight. This study sought to distinguish and explain such competing facts utilizing aeronautics analysis methods.

The DC-8 fuselage is extensively customized and the experimenter floor space and instrumentation can be modified as necessary. However, scientists are adept at conjuring novel uses of the airplane capabilities, design geometry, and floor space layouts as needed to acquire scientific measurements. If a replacement platform were made available, it seems certain that newly conceived experiments eventually would be set up to capitalize on the presence of some angle, distance, alignment, or other nuanced feature arising from differences between the DC-8 and that new platform. This is an important consideration because it demonstrates a certain bond between the airborne scientists and the DC-8 laboratory, manifested as confidence that the DC-8 can always meet their experimental needs, and that current and envisioned science modifications are predictable, proven, and safe. Apparent benefits of candidate replacement aircraft must therefore be weighed against studying, funding, and customizing a new aircraft laboratory, including the need to safely expand the operational envelope of an untested scientific aircraft system.

B. Summary of Facts Gathered from Interviews with ASP Personnel

Notes were taken during every meeting with ASP personnel; content from those notes was extracted and organized for writing the following section. The scope of the summary is not comprehensive, but allowed for setting context and identifying recurring themes during the requirements development phase of this study.

1. *Aircraft Performance*

Central to many atmospheric investigations is measuring columns of atmosphere, so flying higher is a most desirable aircraft performance capability. The suggestion of an aircraft platform capable of providing DC-8-type measurements at flight altitudes of 50,000 feet was supported strongly by a room full of atmospheric scientists. Feedback also indicated the need for a scientific platform capable of off-design operations throughout the flight envelope, including, for example, the 8-hour endurance western wildfire smoke-sampling mission flown by the DC-8 distantly downwind above Arkansas and Missouri, only 1,000-1,500 feet above the ground. A point was raised that obtaining two scientific aircraft might enable data collection through horizontal slices of the atmosphere column at two different flight altitudes simultaneously.

For science campaigns with extensive instrumentation and many investigators, the maximum payload weight is less constraining than available floor space and emergency exit access. This provides flexibility because extra instrument design weight can be accommodated, but contrasts with the scientific utility of collecting data at altitudes above 40,000 feet. Aircraft weight is a primary factor that limits the DC-8 to altitudes below 40,000 feet. The interpretations emphasize the need for modeling, analyzing, and quantifying science mission profiles, and for explaining differences relative to the manufacturer's published range-payload data. Customized information is tabulated in the DC-8 Experimenter's Handbook, and researchers at NASA's Armstrong Flight Research Center maintain additional information on DC-8 and science payload size and weight specifications. ASP policy requires the DC-8 is loaded with the fullest possible complement of payloads and investigative teams for each science campaign.

When discussing engine-out scenarios (the loss of power from an engine during flight), scientists expressed concerns about operational reliability and safety of an aircraft configured with only two engines, versus the four engines of the DC-8. One recalled a flight experience in which the loss of an engine forced the shutdown of only one experiment, as the other experiments could be powered by the operating engines. On the contrary, another stated that arguments in favor of four engines, based on maintaining a subset of the planned experimentation were moot, as all experimentation should be expected to cease, with operations focusing only on a safe return. These concerns prompted one analysis case of this study in which engine failure is modeled to occur midway through the 5,050 nautical mile long-range transport mission without alternate landing sites.

2. *Power Sources*

The electrical power sources available on the DC-8 include 28V DC, 115V/60Hz, or 115V/400Hz/kVA. Most researchers aim for instrument designs tapping the 60Hz option, converting to DC as commonly practiced. Experimenters can make use of electrical power generated by the engines as both 115V single-phase and 115V/200V three-phase 400 Hz power [4]. Electrical power generated by the engines is distributed to scientific instrumentation with use of a functionally practical analog switchboard console that is operated by the Mission Director crewmember. Instruments are typically set up and powered-on several hours before each flight, with power supplied by an auxiliary power unit during that period, but scientists must provide a means of switching to the primary power source once the DC-8 is underway. Scientists operating power-hungry instrumentation must take special care planning their power usage to avoid causing electrical problems such as instrument damage or fires.

A final note on the electrical power supply is that the 28V DC option may require using thick and heavy copper wiring for powering outboard systems, and that wing hard points can be useful for carrying that weight. Investigators noted wing hard points are desirable, and that eight probes had been mounted to available hard points on the ASP P-3 Orion wings. Some instruments have been designed for packaging within pods attached to hard-point pylons under the DC-8 wing; currently, the DC-8 is capable of carrying a maximum of four such pods.

3. *Standardized Equipment Racks and Instrumentation Setup*

There are standard rack sizes for use throughout the ASP aircraft fleet. For the DC-8, NASA personnel track the loaded instrument weights and centers of gravity to prevent instruments from tipping during flight operations, and for aircraft loading and balance calculations. Three different skeleton racks are approved, some of which can be used on other ASP experimental platforms. The maximum rack height is limited to 54 in. by overhead bins on the DC-8, but the P-3 platform allows for the use of racks with a maximum height of 58 in.

The floors of the laboratory platform must be sturdy, as some of these scientific instruments are quite heavy; for example, the A-Toms telescope instrument is over 2,000 lb. Researchers noted that the DC-8 door sizes are small enough to prevent or complicate loading large instrumentation. Instruments too big to fit through the DC-8 doors must be disassembled before loading, reassembled before use, and disassembled again for unloading. As each task can require days to complete, an aircraft with large doors would save time and effort by eliminating the need for researchers to modify large equipment that otherwise is too large to fit through the DC-8 doors.

4. In-situ Atmosphere Sampling

Two scientists reported their research involves sampling the atmosphere in various locations, times, and altitudes, including during unusual or transient conditions such as the presence of smoke plumes caused by wildfires. The atmosphere sampling inlets for those purposes are modular and designed to fit in the oversized (as originally manufactured) DC-8 windows. For experiments when the sampling ports are not used, the windows can be put back in place. It was noted that aircraft with fuselage mounted engines positioned downstream (aft) and somewhat aligned with externally mounted scientific equipment would be susceptible to foreign object damage and engine failure if the scientific equipment were to come loose or break off.

Flight speeds are not adjusted to regulate sampling rates as a function of the atmospheric density or instrument sensitivity. Instead, pumps are used to suck outside air into the instruments as necessary. So-called "sticky atmospheric gas species" may chemically react with metallic inlet tubes and pumps, and correcting for this effect can be difficult. The width and arrangement of the DC-8 laboratory helps minimize these effects, as the customized racks for securing instruments and pumps are near the sides of the fuselage, shortening the tubing path lengths from the outside air samples to the instrument detectors. For mass spectrometers, the 2 in. diameter inlet sampling tubes designed for use in the DC-8 windows are deemed appropriate. The DC-8 is noteworthy for featuring the longest commercially manufactured narrow-body fuselage; scientists utilize that fuselage length for acquiring simultaneous spatially separated measurements for on-board real time data corroboration.

Scientists reported that the geographical extent, vertical profiles, and complexity of the atmospheric sampling experiments require an accommodating and capable platform like the DC-8. The DC-8 is a fast aircraft capable of flying away from its exhaust plume contaminants. The requirement for avoiding such contamination disqualifies low-speed aircraft as potential replacement platforms.

Atmospheric pollutant studies were described that require localized sampling above ground station sensors within cities. In these instances, turning radius and slower flight speeds can be important aircraft performance considerations. Based on experience, scientists estimated the ASP P-3 turning radius as 2.0-2.5 km, versus 7.0-8.0 km for the DC-8, and agreed that the DC-8 would not be suitable for such scientific applications.

5. Scientific Instrumentation Payloads and Technology Readiness

Scientific payloads on the DC-8 platform tend to be heavy, large, and with less refined but more advanced technology, some of which requires the trouble-shooting expertise of the scientists. In contrast, scientific payloads on aircraft like the ASP ER-2 generally are configured for more narrowly focused and standardized measurements, utilizing devices that have been refined, miniaturized, and automated. In addition, the DC-8 instruments can be cheaper to build since optimizing for minimum weight and autonomous operation is not required. Although both instrumentation types have merit, they are best suited for use on different platforms.

6. Descriptions of Various DC-8 Modifications

Two pairs of zenith-nadir aligned ports are installed on the DC-8, and each pair is offset longitudinally along the fuselage. They are offset from the centerline of the fuselage to eliminate blocking a center aisle walkway. The preference for simultaneously measuring in both directions was noted for gathering data for a complete column of the atmosphere. LIDAR investigations make use of a starboard pair of view ports that are positioned directly above and below each other. There is also a port station that has an additional upward port for instruments that require two upward looking ports, and ports which are directed +/- 67 degrees from horizontal, as viewed toward the outside.

Some instruments gather spectral data through optically transparent ports directly contacting outside air, whereas others view through existing windows. One experiment requires zenith- and nadir-looking telescopes that connect directly to specially designed, optically transparent panes that are 1.5 in. thick with an 18 in. diameter. The "optical cells" are designed to support the pressure differential between the inside and outside of the aircraft and are recessed slightly below the fuselage exterior mold line. When not in use, a fuselage-conforming fairing is drawn closed to protect the ports from the external environment. The setup and dimensional specifications that have been found useful over time, as installed on the DC-8, provide a natural basis for standardizing and implementing similar optical ports on other ASP aircraft.

Another experiment requires shining a laser through existing windows onto reflective patches mounted to the inboard side of the DC-8 outboard engines. The reflection is detected to allow remotely measuring atmospheric gas species without disturbing the external flow or atmosphere constituents. Longer, direct laser-to-reflector paths are considered best for this experiment, so a preference was expressed for the outboard engine surfaces of the DC-8 versus the inboard engine surface locations of a two-engine aircraft. Consensus opinion among scientists and engineers settled on winglets as possibly best suited for these needs.

7. Aircraft Structure, Layout, and Configuration

Many experiments require an unobstructed view of the upper hemisphere of the sky. Aircraft configurations with "T-tail" stabilizers obstruct sensor views, block sunlight, or cast shadows that interfere with solar flux measurements, and limit the available positions for mounting flux sensors. None of the researchers disputed that T-tails are problematic for atmospheric science needs; however, the ASP portfolio does include Gulfstream G-III and G-V aircraft that each feature T-tails. One particularly difficult G-V modification aimed at circumventing some of these concerns required embedding two redundant fiber optic cables along the top half of the fuselage, up the leading edge of the vertical tail, and on to the top of the T-tail. Though the modification was successfully implemented, there was agreement that the T-tail vantage point is usable for only a limited number of experiment types.

The need for a robust, predictable, and more-than-capable platform (i.e., not at the limits of the operational envelope during routine missions) were principal demands. This included the desire for a structurally over-designed fuselage like the DC-8 that would be amenable to cutouts and externally mounted equipment. Obtaining such a forgiving fuselage might become challenging, with modern aircraft designs featuring extensive applications of composites, or optimized and fully stressed aluminum skins with no margin for cutting holes.

During flight operations, scientists remain seated at their consoles, alongside instruments that are positioned near the fuselage walls for science purposes. The long and "wide enough" DC-8 fuselage is preferred over a “wide-body” fuselage because a wider central aisle likely would be wasted space. Similarly, it was suggested that military transport aircraft would provide too much width, unusable overhead volume, and excess payload capacity. However, in the case of larger science campaigns, a wider fuselage might provide payload configuration options that would also meet safety requirements for providing straight aisles with unimpeded access to emergency exits. Normally, the forward lavatory is declared "off-limits" to avoid contaminating air samples measured downstream at mid- and rear-fuselage locations, and there was unanimous agreement that at least one aft lavatory would be a non-negotiable requirement when the time comes for selecting a DC-8 replacement.

Gas bottles for instruments are positioned in the fuselage and strapped onto standard racks if space is available; for large campaigns when equipment fills the cabin, they are moved into the “pit” below deck. Additional items stored inside the aft pit include spare DC-8 tires and a tow bar for use at airports without the ramp equipment to accommodate or service 1960’s-era airplanes.

IV. Candidate Aircraft Performance

Knowledge gained from the DC-8 airborne scientists and support personnel highlighted the unique scientific utility of the DC-8. Identifying possible replacement candidates began with a qualitative review of many different aircraft, followed by detailed modeling and quantitative assessments of down-selected promising candidates.

A. Candidate Aircraft Selection

Like the DC-8, the only viable option for the ASP is to consider modification of existing aircraft, rather than development of a clean-sheet capability that meets all of the experimenter’s needs. To start, the team brainstormed a large list of aircraft that could be used to meet these needs, which included a one-for-one replacement of current capabilities of the DC-8 as well as an aggregate of multiple aircraft to meet these needs. Table 1 provides a representative sample of the various civil transport, freighter, military cargo, and remotely piloted aircraft that were considered as potentially suitable replacement platforms. Performance, cost, size, and other specifications were extracted and compiled for each aircraft, based on available reference documents. Experimenter’s handbooks and the manufacturer’s airport planning documents were especially useful for obtaining range-payload diagrams and geometry sizing information that would be needed for subsequently developing geometry and performance analysis models of down-selected replacement aircraft candidates.

Table 1 Representative List of Aircraft for Metrics Development, Rank, and Down-selection

NASA Aircraft	Medium Transports	Large Transports	Military Aircraft	Freighters
DC-8-72	A-320	A-330neo -800 / -900	P-8 Poseidon	B-737 -800 BCF
P3-Orion	A-321neo -LR	A-330 -200 / -300	P-3	B-747 -8F
G-III, G-V	B-737 MAX-8 / MAX-9	A-340 -300	KC-767	B-767F
ER-2	B-737 -800w / -900w	A-350 -900	C-130 / KC-130	B-777F
Ikhana	B-757 -200w	A-380	C-17	
WB-57F		B-767 -200ER	MTS-RJ	
B-747 (SOFIA)		B-767 -300ER / -400ER	Global Hawk	
		B-777 -200 / -200LR		
		B-777 -300 / -300ER		
		B-777 -X / -8X / 9X		
		B-787 -8 / -9		

Aircraft design data were collected, varying in total amount, degree of completeness, and quality for each aircraft shown in Table 1. The aircraft were scrutinized via five subjective categories: airplane configuration layout, science adaptability, airplane performance, cost, and miscellaneous. Individual data elements were assigned a category and scored on a merit scale of 1-10, which allowed for calculating average aggregate category scores and ranking the airplane by category and combined scores.

This process helped to clarify quickly that some aircraft may not be suitable for a number of different reasons. NASA rarely allocates resources to purchase new aircraft, particularly for missions such as those sponsored by ASP that do not involve research in new, innovative aircraft configurations ("X-planes"). Instead, NASA tends to receive surplus aircraft from other government organizations, or purchase used aircraft on the secondary market. As such, instead of focusing on a particular type of aircraft, the study moved to select aircraft representative of different payload, size, and technology eras to determine the relative performance of these aircraft on legacy NASA DC-8 missions. These refined candidates are shown in Table 2, with the final candidates shown by the red arrows in the table. These final aircraft are the Gulfstream G-V, the Boeing 737-700ER/900ER (used to create models for the Boeing P-8 Poseidon built from the same airframe as a military variant), the Boeing 767-200ER, the Airbus A330-200, and the Boeing 777-200LR. The baseline Douglas DC-8-72, which is NASA's current aircraft used for this role, is modeled as well for comparison purposes.

B. Aircraft Size Comparison

Geometry models were created in OpenVSP [21] to create a common comparison tool for size-related metrics, as well as to generate inputs to some of the other performance models using a common reference approach. These geometry models were calibrated to 3-view schematics provided in the ASP Experimenter's Handbooks or airport planning documents. Fig. 2 compares the DC-8 OpenVSP geometry model and the DC-8 Experimenter's Handbook 3-view schematic. Similar models were created for all down-selected analysis aircraft. A comparison of the plan views of all candidate aircraft is shown in Fig. 3, which illustrates one of the driving metrics associated with the study: how much hangar/storage space is necessary as compared to the current DC-8. Fig. 4 shows a comparison of the front and side views of the aircraft. Both Figs. 3 and 4 also include estimates of aircraft range, payload, and gross weight, along with salient linear dimensions. Note that the Boeing 737-900ER and P-8 are essentially the same overall size, with the major differences having to do with arrangement of internal systems.

C. Range-Payload Calibrations

Performance models were developed using NASA's Flight Optimization System (FLOPS) [22] software to ensure that all aircraft performance comparisons were generated from a common reference approach. These aircraft performance models were developed and calibrated to match the published range-payload capabilities of the candidate replacement aircraft. For each aircraft, the FLOPS model aircraft weights were input based on information obtained from either the Experimenter's Handbooks or the Airport Planning Documents. Standard transport missions were also defined based on range-payload details and charts available in the Airport Planning Documents. Within each analysis model, an optimization scheme was added to minimize the FLOPS range-payload residual errors as FLOPS performance parameters were adjusted. Once minimized, the parameters plus the known calibrated weights could be input to the analysis model to obtain range-payload results that matched the published range-payload information.

Table 2 Aircraft Service Periods and Size Trends

	Airplane	MTOW lb	R&D Period	EIS	Notes
	Gulfstream				
	G-III	70,000	mid '70s	1980	NASA AFRC, C-20B
→	G-V	95,000	mid '90s	1997	NASA JSC, NCAR
	Boeing 737	*representative*			
	/ 100 / 200	115,000	mid '60s	1968	Gen 1
	/ 300 / 400 / 500	145,000	early '80s	1984	Gen 2 (Classic)
	/ 600 / 700 / 800 / 900	170,000	early '90s	1997	Gen 3 (Next-Gen)
→	/ 700ER / 900ER / P-8	188,000	early '00s	2007	OEW: ERs > P8
	/ Max 8 / Max 9	195,000	early '10s	2017	Gen 4 (Max)
	Douglas DC-8				
	DC-8-62	335,000	early '50s	1959	first passenger jets
→	DC-8-72-N417A	>335000	early '60s	1967	~ -62 w/ new engines
	Boeing 757				
	757-200 *not*	256,000	mid, late '70s	1982	post-727, dev. w/ 767
	757-300 *selected*	272,000	mid '90s	1999	fuel efficient, short range
	Boeing 767				
	767-200	317,000	late '70s	1982	~1/3 767s
→	767-200ER	388,000	late '70s	1984	ERs: Lg Fwd cargo door
	767-300	352,000	early '80s	1986	+21 ft fuseL (300-200)
	767-300ER	413,000	early '80s	1988	ERs: mid-fuse tank
	KC-46-Pegasus	-	2010s	2018	tanker version
	Airbus A330				
	A330-300	467,000	early '80s	1994	
→	A330-200	514,000	2000s	2003	longest range variant
	A330- 200 -300	533,000	2010s	2015	range/payload variants
	Boeing 777				
	777-200	545,000	late '80s	1995	200, 300 wingtip rake=0
	777-200ER	658,000	late '80s	1997	ERs, LR: +Rake, +Span
	777-300	660,000	early 2000s	1998	+35 ft fuseL (300s-200s)
	777-300ER	777,000	late '80s	2004	Thrust: 300ER > all above
→	777-200LR	768,000	early 2000s	2006	Thrust: LR > 300ER

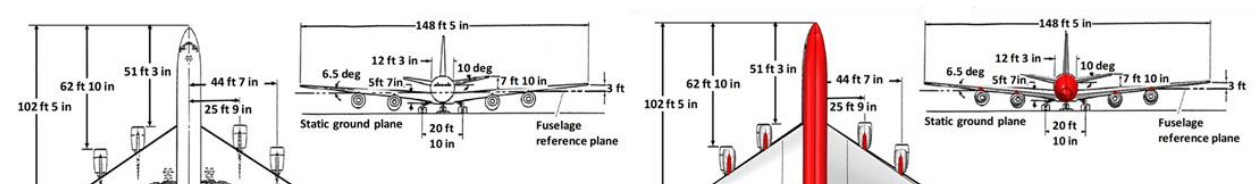

Fig. 2 NASA DC-8 (N817NA) *Experimenter's Handbook* 3-view geometry and model overlay comparison.

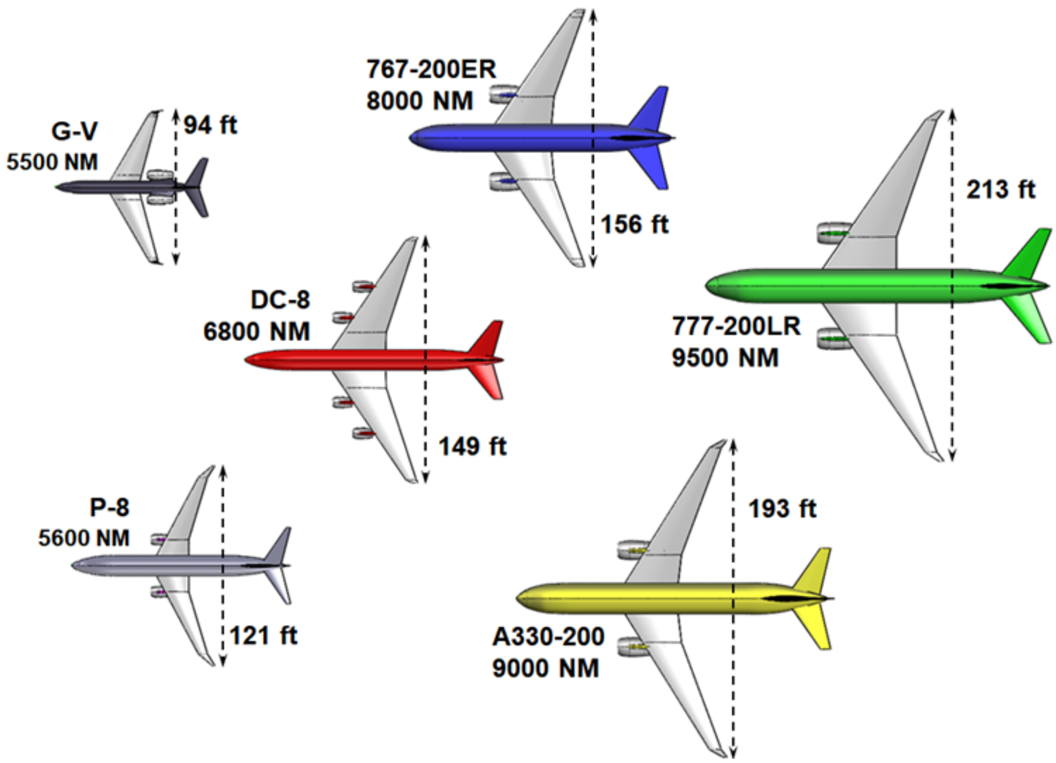

Fig. 3 Aircraft top-views showing wingspans and approximate maximum ranges.

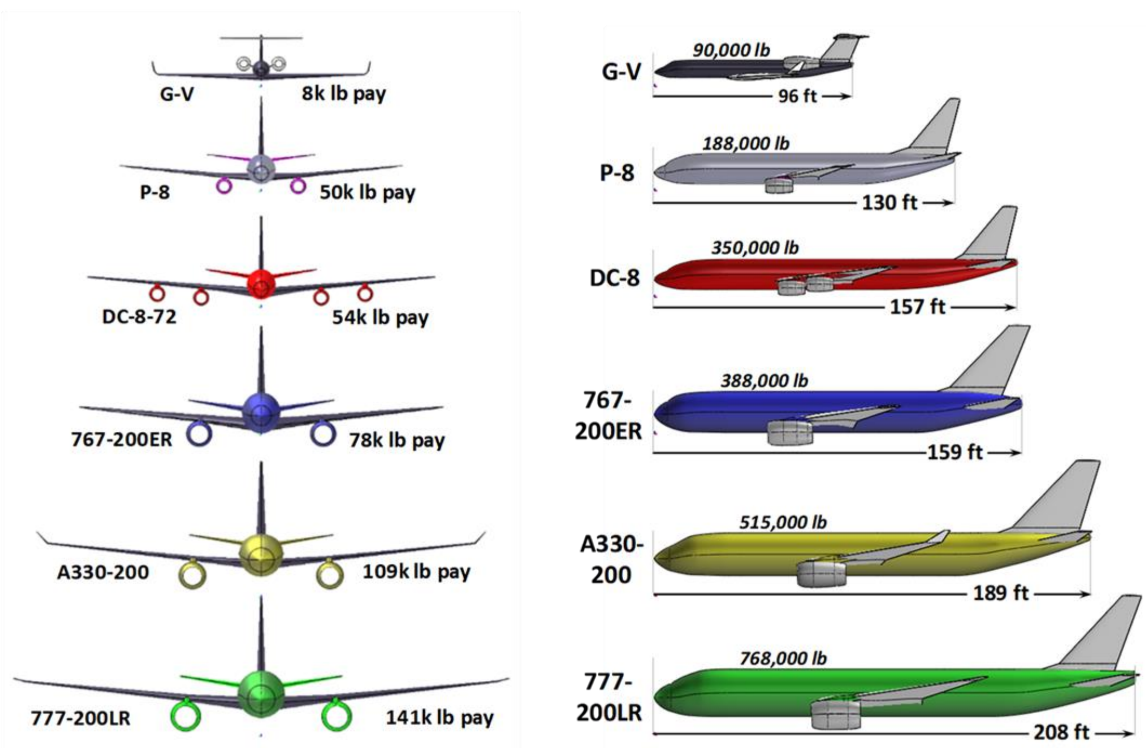

Fig. 4 Aircraft front and side-views showing fuselage lengths, maximum payloads and gross weights.

Three calibration missions were used for the aircraft performance models. These were (1) flight with maximum payload, and fuel to bring the aircraft to maximum gross weight, (2) flight with maximum fuel, with payload weight set to bring the aircraft maximum gross weight, and (3) flight with maximum fuel and zero payload weight (e.g., ferry mission). An example of this calibration with these three missions modeled is shown in Fig. 5 for NASA's modified DC-8, as overlaid with data recreated from the publicly available DC-8 range-payload diagram.

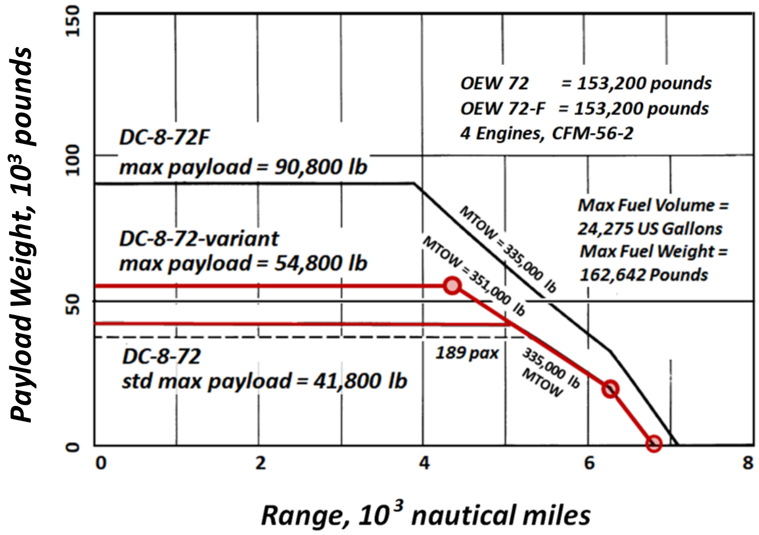

Fig. 5 DC-8 range payload results and calibration comparisons with values.

Results of the performance models were used to help differentiate the capabilities of the candidate replacement aircraft. Fig. 6 shows the calibration results as a range-payload diagram. Details of these calibrations are shown in the appendix to this paper. For the P-8, the necessary performance details were not publically available. Thus, the P-8 calibration involved the preliminary steps of calibrating a Boeing 737-900ER with a modified wing tip geometry and a maximum ramp weight of 188,200 pounds. That model was transitioned to a P-8 model by removing 7,500 pounds of passenger furnishings for an empty weight of 90,995 pounds, decreasing the maximum payload weight to 23,885 pounds, and increasing the maximum fuel weight from about 46,063 pounds to 73,320 pounds.

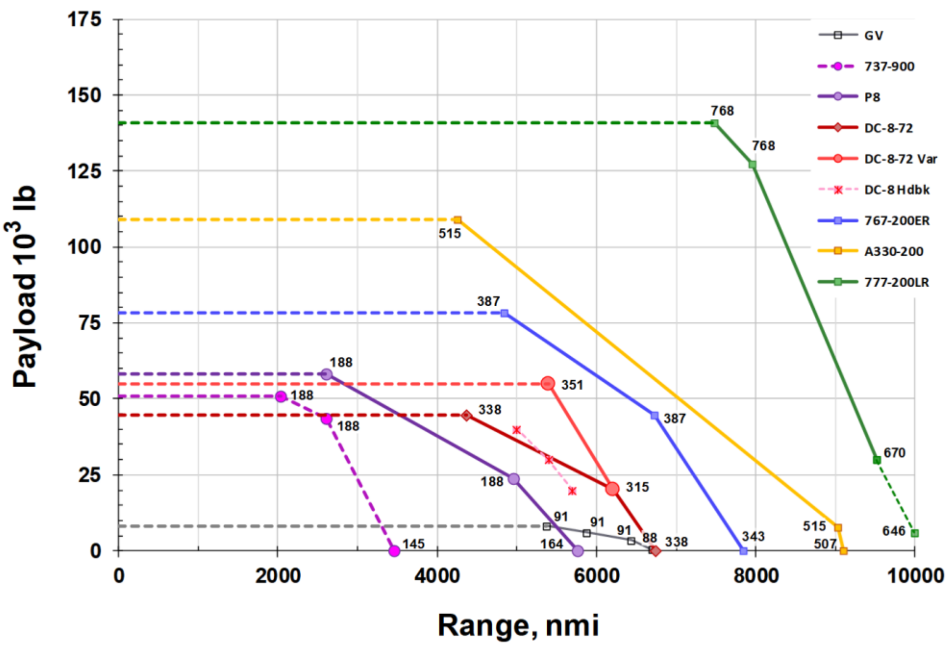

Fig. 6 Aircraft range-payload diagrams. Dashed lines, unless noted in legend, represent extrapolated values.

V. Analysis of Candidate Aircraft on Airborne Science Missions

The calibrated models of the candidate aircraft were utilized for predicting performance for selected airborne science missions. Three representative missions were selected based on features that were known to have stressed the capabilities of NASA's DC-8. These missions are shown in Fig. 7 and are described as follows:

- Santiago, Chile to Palmdale, CA: (SCEL-KPMD): Represents a nominal transport mission and demonstrates the effects of losing an engine mid-way through a long-range mission, while carrying a substantial payload of 46,000 pounds.
- Christchurch, New Zealand to Punta Arenas, Argentina (NZCH-SCCI): A vertical sampling science mission that features multiple repeating, consecutive climb-descend segments.
- Smoke Survey: A forest-fire particulate gathering study that required flying at low altitudes in the central U.S. for a flight duration of eight hours.

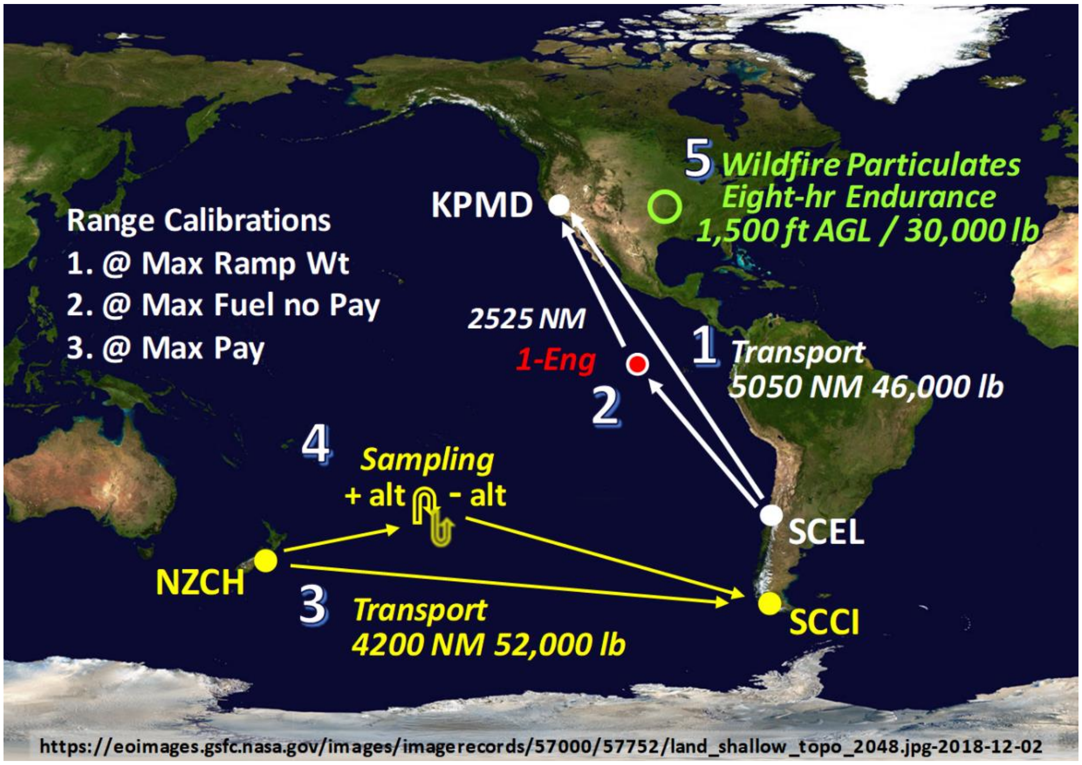

Fig. 7 Transport and science missions used for this study.

A. Science Mission Performance

The mission performance analyses considered variation in each of the aircraft's optimal operating characteristics given the different aerodynamic and propulsive efficiencies associated with each configuration. This is particularly noticeable during operations with a single engine inoperative. The only four-engine aircraft in the candidate comparison set is the legacy DC-8 – virtually all but the largest modern transport aircraft use fewer, larger engines than were available during the design of the DC-8. These larger, fewer engines enable a more efficient configuration, but of course result in greater loss in performance if a single engine were to fail. As such, the FLOPS mission models adjusted the speeds and altitudes of the SCEL-KPMD mission differently for each aircraft in response to a single engine failure. This is shown on the left column of Fig. 8.

The right column of Fig. 8 shows the speed and altitude differences for the candidate aircraft on the sampling mission. This science mission is a strenuous test on aircraft performance and involves multiple consecutive climb and descent flight profiles, which are neither traditional nor operationally efficient. As the aircraft burns fuel and gets lighter, it becomes capable of higher-altitude sampling. This is another bonus for the scientists: aircraft that can fly higher than the current DC-8 and/or climb and descend more rapidly can gather a wider range of sample data.

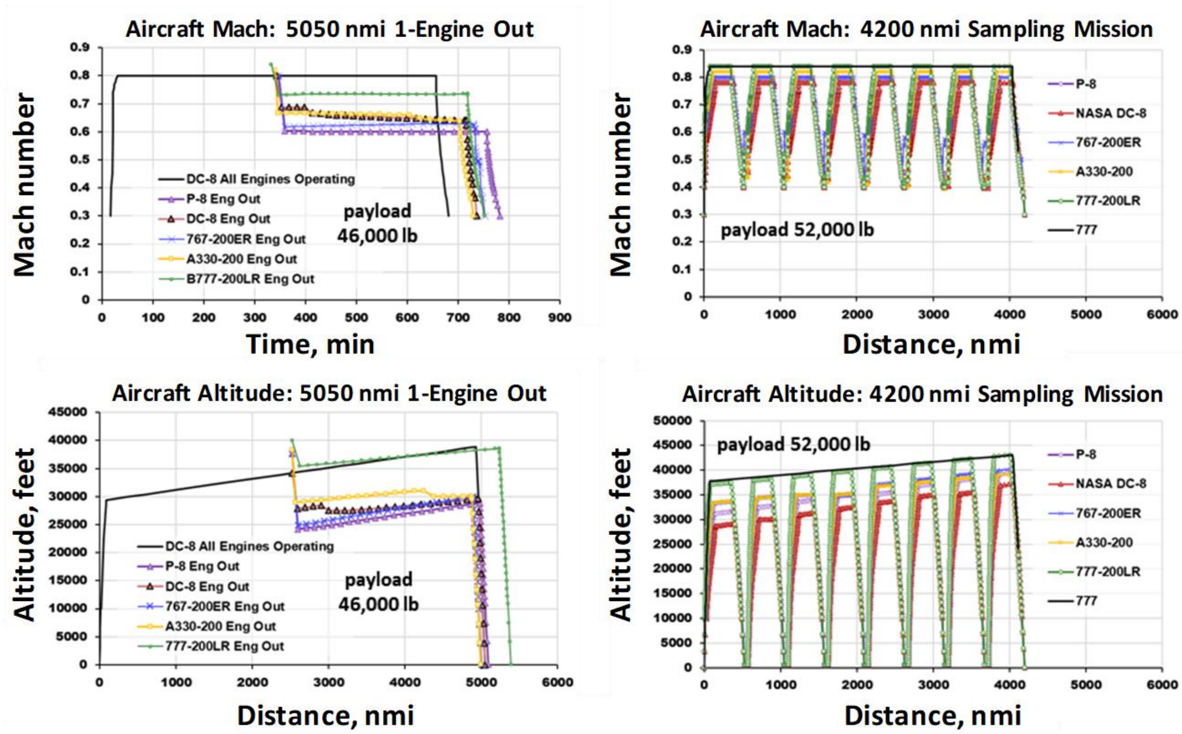

Fig. 8 Aircraft speed (Mach) and altitude vs. distance for the engine-out and atmosphere sample missions.

In all missions, the payload requirements were assumed identical to weights recorded during the previous DC-8 mission on which it was based. Required payload volume was not readily available and was assumed compatible for all aircraft. For aircraft without the capacity for carrying all the payload weight, it was assumed the payload could be equally subdivided and distributed, without adversely affecting experimentation, for transport within *n* aircraft such that group of *n* aircraft would offer the same aggregated mission payload capacity as the larger aircraft. This applied to only the G-V and P-8, as these were the smallest candidates in terms of payload capacity. The summary of weight constituents for all aircraft flying the three missions are shown in Fig. 9, which includes payload, fuel, reserve fuel, and operating empty weight. The G-V and P-8 values are repeated to show the values for each individual aircraft as well as the aggregate values for all aircraft.

B. Cost of Operation

Fuel weight is a strong predictor of operating costs. As seen from Fig. 9, assuming a constant payload, the fuel use varies significantly across the candidate fleet of aircraft. If one looks at only the aggregate use, the lowest fuel weight occurs with the 767-200ER for the SCEL-KPMD and NZCH-SCCI missions, whereas the P-8 can accomplish the Arkansas-Missori wildfire mission with the lowest aggregate fuel usage. This speaks to the challenge with "right-sizing" a candidate aircraft – the smaller aircraft obviously burns less fuel if the mission payload is within the payload limits of an individual aircraft, but when missions call for more range-payload capability than the aircraft has, it is more economical to use a single larger aircraft. If one must choose a single aircraft type as a replacement, the choice becomes a balance between the missions requiring large range-payload capability and those that need lesser capability.

The science payloads may require additional scrutiny. Given that new ASP aircraft are rare, the experimenters tend to fit their experiments to the capabilities of the current fleet. A cheaper-to-operate aircraft that has tighter payload constraints (size, weight, power) may provide an experimenter with more opportunities to gather data with smaller, lighter, less-power-hungry instrumentation. Conversely, a larger, more expensive aircraft with looser constraints may provide for more cross-instrument correlation for a richer data set. Such an exercise was beyond the scope of this study, hence why payload weight was fixed for these missions. However, a set of metrics with normalized range and payload weight were developed for all of the aircraft to aid decision-makers with this process. This included the fuel cost for *n* mission flights (where *n* is the number of aircraft required for single complete science mission, which is only >1 for the G-V and P-8), as well as the *fuel cost metric*, defined as the estimated fuel cost to carry 1,000 pounds of payload one nautical mile. The *fuel cost metric* and fuel cost estimates are compared in Fig. 10.

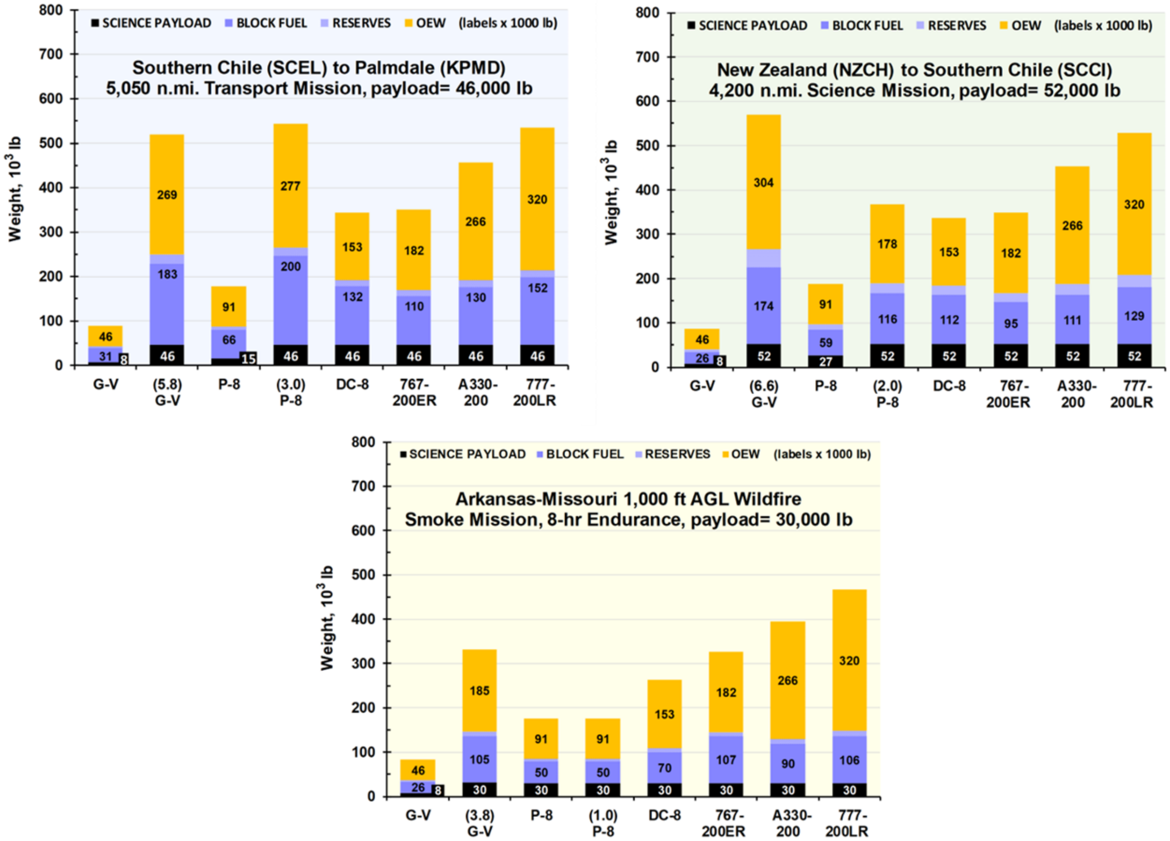

Fig. 9 Aircraft weight constituents for example science missions.

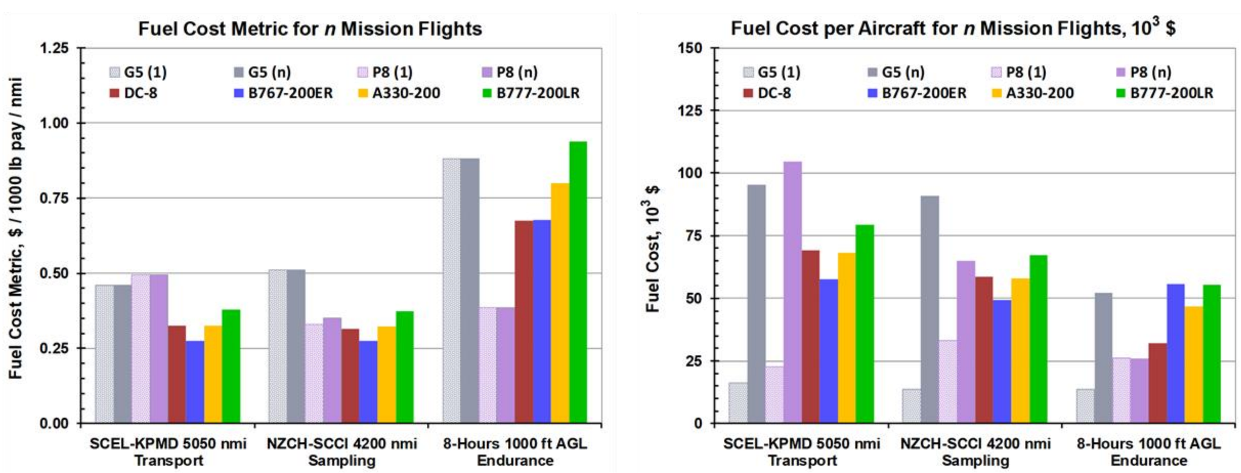

Fig. 10 Aircraft fuel costs and metrics for example science missions.

With the *fuel cost metric*, the 767-200ER ranks “best” for the SCEL-KPMD mission, and is essentially tied for “second best” on the smoke sampling mission. On the as-flown mission, the 767-200ER offers the lowest fuel cost (assuming *n* G-V and P-8 aircraft) for the first two missions, but is tied amongst the “worst” for fuel cost on the smoke sampling mission. In this case, it could be that a different, more complementary aircraft or set of aircraft should fly that mission. Across the board, a fleet of G-V aircraft does not appear to be a suitable replacement for the capabilities of the DC-8 on any of these sizing missions, though certainly is a strong candidate for missions requiring smaller range-payload capabilities or multiple, dispersed, simultaneous measurements with smaller payload requirements. The P-8 is not a great like-for-like replacement option, but the P-8 offers several advantages that should not be overlooked.

The P-8 is an extended-range variant of a late-model Boeing 737, designed to provide replace the U.S. Navy's P-3 Orion anti-submarine aircraft. Like the NASA airborne science missions, the P-8's missions requires performance capabilities that allow for loitering above remote oceans for extended periods at both high and low altitudes. Feedback from the NASA DC-8 crew indicated that good performance throughout the flight envelope is preferred in comparison to optimal performance in narrow bands of that envelope. The range of the P-8 is improved with use of a higher aspect ratio wing that features a swept wing tip to reduce induced drag. Other modifications include a reduction in the operating empty weight through removal of passenger accommodations, and an increase in fuel capacity to 73,372 lb in auxiliary fuel tanks. P-8 models developed for this study from publicly-available data indicates a range of 5,000 nmi with a 25,000 lb payload, both of which are in line with typical science mission requirements listed in the DC-8 Experimenter's Handbook. Features of the P-8 include enhanced floor strength, an over-sized aft fuselage door, and an installed dropsonde systems suitable for in-situ atmospheric data collection. Considering the full picture, a properly configured P-8 might offer a reasonable compromise for reducing costs while not substantially reducing the current experimental capabilities of the NASA DC-8. The P-8 falls short in this study only on the longest range (SCEL-KPMD) and most strenuous science (NZCH-SCCI) missions.

VI. Conclusion

NASA's DC-8 flying laboratory offers the airborne science community an unparalleled capability to host large, heavy payloads over long distances. As one of the first-generation jet transports, the DC-8 is getting harder to maintain and operate in the face of mechanical and crew considerations. As such, the airborne science community may lose a valuable asset if this capability is not sustained in ASP's portfolio of aircraft.

This paper includes the results of a 2018 study conducted by NASA to determine the metrics that make the DC-8 such a successful airborne science platform, and to consider future, more sustainable aircraft to maintain or enhance this capability with lower risk. The first step was to interview the DC-8 operators and science users to understand the unique features and requirements of this platform, which uncovered a variety of candidate metrics and features. Some of these were requests that seem unusual to traditional aircraft analyses, such as visibility over the rear of the aircraft with a t-tail, availably of a rear lavatory (so that the forward lavatory does not contaminate sensitive air data sensors), floor space and cabin access for installation of large instruments, and mission performance that includes multiple climbs and descents. These metrics led to the selection of several candidate aircraft platforms representative of size classes that could be of use to ASP users: the Gulfstream G-V, Boeing P-8 Poseidon (military variant of a late-model Boeing 737), NASA DC-8, Boeing 767-200ER, Airbus 330-200LR, and Boeing 777-200LR.

Calibrated performance models of these aircraft were developed to three transport missions at the extremes of each aircraft's range-payload capabilities. These models were used to analyze performance across three airborne science missions that represented some of the more strenuous use cases of the DC-8. The performance results for each aircraft were assessed by comparisons to each other and to the current capabilities of NASA's DC-8, while also considering defined metrics of scientific utility. The results indicated that an aircraft such as the 767-200ER aircraft could offer all of the DC-8 capabilities and more: additional experimenter floor-space, payload capacity, and range than the NASA DC-8, and generally a reduced operating cost. The P-8 emerged as a possible candidate offering marginally less of those items than the DC-8, while using substantially less fuel per mission. The P-8 may be very useful for those cases that do not require the full capabilities of the current DC-8, but are otherwise not accommodated within NASA's fleet of airborne science aircraft.

Appendix

Tabular data for the mission performance described in this paper are provided below. Table 3 provides aircraft model and reference ranges for calibration of the range-payload capabilities. Table 4 provides details for the nominal and one-engine inoperative performance on the SCEL-KPMD mission. Table 5 provides details for the NZCH-SCCI atmospheric sampling mission. Table 6 provides details for the Central U.S. smoke sampling mission.

Table 3 Aircraft Model and Reference Weights for the Range Payload Calibrations

Ramp, Taxi, Takeoff Weight, lb	G-V	737-900	P-8	DC-8-72	767-200ER	A330-200	777-200LR
Ref. Max Ramp Wt	90,900	188,200	188,200	338,000	388,000	515,661	768,000
Taxi Fuel (model, 15 minutes)	315	500	500	627	942	996	1,283
Δ Taxi Fuel (Ref.-model)	85	0	0	2,373	58	988	717
Ref. Max Takeoff Wt	90,500	187,700	187,700	335,000	387,000	513,677	766,000

Reference and Model Weight, lb	G-V	737-900	P-8	DC-8-72	767-200ER	A330-200	777-200LR
Max Payload plus Fuel Cal-1*	90,815	188,200	188,200	335,627	387,942	514,673	767,283
Max Fuel plus Payload Cal-2*	90,815	188,200	188,200	335,627	387,942	514,673	767,283
Max Fuel plus OEW Cal-3*	87,815	144,557	164,367	315,467	343,290	507,032	640,146
Max Fuel Volume (gal)	6,151	6,875	10,951	24,219	24,131	35,990	47,783
Max Jet A US Fuel Wt	41,215	46,062	73,372	162,267	161,680	241,132	320,146
Max Jet A1 Fuel Wt	40,533	45,300	72,158	159,582	159,005	241,132	314,849
Fuel Wt with Max Payload	36,315	46,062	38,900	127,627	127,942	139,887	306,283
Max Zero Fuel Wt, ZFW	54,500	149,300	149,300	208,000	260,000	374,786	461,000
Operating Empty Wt, OEW	46,200	98,495	90,995	153,200	181,610	265,900	320,000
Max Payload	8,300	50,805	58,305	54,800	78,390	108,886	141,000
Payload Wt with Max Fuel	3,400	43,643	23,833	20,160	44,652	7,641	127,137

Range Calibration Results *	G-V	737-900	P-8	DC-8-72	767-200ER	A330-200	777-200LR
Range 1: @ Max Payload plus Fuel	5371.0	2040.4	2601.6	4373.7	4849.2	4253.9	7476.7
Range 2: @ Max Fuel plus Payload	6439.6	2601.6	4960.7	6211.0	6725.4	9036.8	7953.7
Range 3: @ Max Fuel plus OEW	6703.0	3456.7	5767.0	6740.9	7838.6	9100.2	9513.8

Table 4 Transport Mission / 5,050 nmi / 46,000 lb / Santiago, Chile to Palmdale, CA (SCEL-KPMD)

Mission: SCEL-KPMD Transport	G-V	P-8	DC-8-72	767-200ER	A330-200	777-200LR
Range, nmi	5050	5050	5050	5050	5050	5050
SCEL-KPMD Science Payload, lb	46,000	46,000	46,000	46,000	46,000	46,000
Airplane Payload Capability, lb	7,900	15,094	46,000	46,000	46,000	46,000
Airplanes / Science Payload, n	5.8	3.0	1	1	1	1
Flight time, min	676	673	664	670	655	642
Ramp weight, lb	89,579	178,247	344,099	350,479	457,097	534,693
Mission Fuel weight, lb	35,079	72,158	144,899	122,869	145,197	168,693
Block Fuel weight, lb	31,371	65,631	132,182	110,371	130,493	151,749
n * Block Fuel weight, lb	182,667	200,015	132,182	110,371	130,493	151,749
Block Fuel Cost, $	$16,388	$34,285	$69,050	$57,656	$68,168	$79,272
n * Block Fuel Cost, $	$95,423	$104,485	$69,050	$57,656	$68,168	$79,272
(Fuel: 6.70 lb / gal, $3.50 / gal)						

1 Engine Out at 2525 nmi	G-V	P-8	DC-8-72	767-200ER	A330-200	777-200LR
2nd-half Range Capability, 1E, nmi	-	2,525	2,525	2,525	2,525	2,525
Δ 2nd-half Cruise Time, 1E / all E	-	1.31	1.19	1.25	1.23	1.15
Δ 2nd-half Cruise Fuel, 1E / all E	-	1.06	1.01	1.08	1.09	0.94
Δ Total Cruise Time, (all E + 1E) / all E	-	1.15	1.10	1.13	1.11	1.07
Δ Total Cruise Fuel, (all E + 1E) / all E	-	1.03	1.00	1.04	1.04	0.97
Δ Mission Block Time, (all E + 1E) / all E	-	1.12	1.08	1.11	1.10	1.07
Δ Mission Block Fuel, (all E + 1E) / all E	-	1.01	1.00	1.02	1.03	1.08

Table 5 Science Mission / 4,200 nmi / 52,000 lb / Christchurch, NZ to Punta Arenas, Chile (NZCH-SCCI)

Transport Mission: NZCH-SCCI	G-V	P-8	DC-8-72	767-200ER	A330-200	777-200LR
Range, nmi	4200	4200	4200	4200	4200	4200
NZCH-SCCI Science Payload, lb	52,000	52,000	52,000	52,000	52,000	52,000
Transport Payload Capability, lb	7,900	26,576	52,000	52,000	52,000	52,000
n, Airplanes / Science Payload	6.6	2.0 - 2.5	1	1	1	1
Transport Flight Time, min	564	558	553	559	547	536
Ramp weight, lb	86,973	188,200	337,018	349,065	453,316	528,532
Mission Fuel weight, lb	32,473	70,629	131,818	115,455	135,416	156,532
Block Fuel weight, lb	26,405	59,111	112,147	94,656	111,225	128,905
n * Block Fuel weight, lb	173,805	124,133	112,147	94,656	111,225	128,905
Block Fuel Cost, $	$13,794	$30,879	$58,584	$49,447	$58,103	$67,338
n * Block Fuel Cost, $	$90,794	$64,846	$58,584	$49,447	$58,103	$67,338
(Fuel: 6.70 lb / gal, $3.50 / gal)						
Sampling Mission: Climb-Descend	G-V	P-8	DC-8-72	767-200ER	A330-200	777-200LR
Sampling Payload Capability, lb	-	20806	52000	52000	52000	52000
Payload (Sampling / Transport)	-	0.78	1	1	1	1
Flight Time, min	-	660	672	620	653	640
Flight Time (Sampling / Transport)	-	1.18	1.22	1.11	1.19	1.19
Ramp weight, lb	-	188,200	343,890	367,463	475,514	548,534
Block Fuel weight, lb	-	65,075	119,014	112,056	133,336	148,897
Block Fuel (Sampling / Transport)	-	1.10	1.06	1.18	1.20	1.16

Table 6 Smoke Mission / 8 Hours / 30,000 lb / 1,500 ft Altitude / Arkansas-Missouri

Mission: Low Alt. 8h Endurance	G-V	P-8	DC-8-72	767-200ER	A330-200	777-200LR
Distance Covered, nmi	2171	2462	2051	2954	2163	2179
Smoke Sampling 1500 AGL w/ 30k lb	30,000	30,000	30,000	30,000	30,000	30,000
Science Payload weight / Airplane, lb	7,900	30,000	30,000	30,000	30,000	30,000
airplanes / science payload, n	3.8	1	1	1	1	1
Endurance, minutes	480	480	480	480	480	480
Mach, start of cruise	0.439	0.500	0.408	0.596	0.410	0.435
Mach, end of cruise	0.388	0.438	0.366	0.530	0.407	0.396
Ramp weight, lb	83,384	175,716	253,526	326,413	395,283	467,447
Mission Fuel weight, lb	28,884	54,721	70,326	114,803	99,383	117,447
Block Fuel weight, lb	26,338	49,797	61,261	106,592	89,518	105,932
n * Block Fuel weight, lb	100,018	49,797	61,261	106,592	89,518	105,932
Block Fuel Cost, $	$13,759	$26,013	$32,002	$55,682	$46,763	$55,338
n * Block Fuel Cost, $	$52,248	$26,013	$32,002	$55,682	$46,763	$55,338
(Fuel: 6.70 lb / gal, $3.50 / gal)						

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