Meeting Review

The Second NCAR Research Aircraft Fleet Workshop

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PREFACE

During the period 15-16 April 1987 a workshop was held at NCAR for the purposes of assessing the scientific needs for atmospheric research aircraft in the next 15 years, and recommending how the composition of the NCAR aircraft fleet should evolve to meet those needs. The workshop was attended by approximately 75 atmospheric and oceanic scientists and research managers representing all of the scientific areas served by the NCAR Research Aviation Facility (RAF). The NCAR group that planned this workshop recognized that the products of the meeting would be most credible and valuable if they reflected the viewpoints of a representative cross section of scientists from a broad spectrum of disciplines and interests, and accordingly prepared the invitation list to provide the needed balance and breadth.

This workshop followed up on a previous meeting (the First NCAR Research Aviation Facility Fleet Workshop) that was held in February 1982 with similar purposes. The major recommendation from the first workshop was to replace the Sabreliner with a mid-sized jet. This recommendation had not been implemented at the time of the second workshop.

One of the major reasons to convene a second workshop was that NCAR staff were considering the pros and cons of several different aircraft acquisitions. One possibility was to refurbish a used Gulfstream I mid-sized turboprop aircraft that had been acquired by the National Science Foundation as surplus government property. Significant interest also continued in a mid-sized jet, and additional platforms, such as a storm-penetration aircraft, were also proposed as important development needs. Background materials on three of these options were furnished to the participants prior to the workshop. From the discussions and recommendations that are reported herein, NCAR staff were able to gain a clear idea of the directions in which RAF fleet development should proceed in order to best serve the needs of the atmospheric and oceanic sciences during the remainder of this century and beyond.

During the workshop, four working groups were organized to discuss the relative merits of acquiring and developing four different types of aircraft. Meeting in these individual working groups and later in plenary session, the workshop participants reached consensus on several important recommendations. The NCAR staff has prepared planning documents for implementation of one of these recommendations, the acquisition of a mid-sized jet aircraft, and is seeking community-wide support of this important addition to the RAF Fleet.

Warren Johnson
Al Cooper
May 1989
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>PREFACE</td>
<td>iii</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>ix</td>
</tr>
<tr>
<td>1. Introduction</td>
<td>1</td>
</tr>
<tr>
<td>2. Opening Presentations</td>
<td>5</td>
</tr>
<tr>
<td>2.1 NCAR Perspective</td>
<td>5</td>
</tr>
<tr>
<td>2.2 Current RAF Fleet-Capabilities and Limitations</td>
<td>6</td>
</tr>
<tr>
<td>2.3 RAF Perspective on Science Needs for Aircraft Platforms</td>
<td>9</td>
</tr>
<tr>
<td>2.3.1 Need for increased total flight support</td>
<td>9</td>
</tr>
<tr>
<td>2.3.2 Need for payload and cabin space greater than provided by the</td>
<td>10</td>
</tr>
<tr>
<td>Sabreliner or King Air</td>
<td></td>
</tr>
<tr>
<td>2.3.3 Need for improved ability to withstand the hazards of icing,</td>
<td>11</td>
</tr>
<tr>
<td>lightning, and turbulence, and to work inside of or near</td>
<td></td>
</tr>
<tr>
<td>thunderstorms and hailstorms</td>
<td>11</td>
</tr>
<tr>
<td>2.3.4 Need for improved performance</td>
<td>11</td>
</tr>
<tr>
<td>2.3.5 Need for larger payloads to be carried to the upper troposphere</td>
<td>12</td>
</tr>
<tr>
<td>and lower stratosphere</td>
<td></td>
</tr>
<tr>
<td>2.3.6 Need to be able to conduct measurements on a global scale</td>
<td>12</td>
</tr>
<tr>
<td>2.3.7 Implications</td>
<td>13</td>
</tr>
<tr>
<td>2.4 RAF Program Plan for Aircraft Platforms</td>
<td>13</td>
</tr>
<tr>
<td>3. New Aircraft Platforms Under Consideration by the RAF</td>
<td>16</td>
</tr>
</tbody>
</table>
3.1 Mid-Sized Turboprop Aircraft ................................................. 16 
3.2 Mid-Sized Jet Aircraft ......................................................... 19 
3.3 Storm-Penetration Aircraft .................................................. 37 

4. Researchers’ Views of Science Needs for Aircraft Platforms ........ 49 
4.1 Boundary-Layer and Surface-Exchange Processes ....................... 49 
4.2 Air-Sea Interaction and Oceanography ..................................... 49 
4.3 Radiative Processes and Air/Ground Truth ................................ 50 
4.4 Cloud Physics and Weather Modification .................................... 50 
4.5 Mesoscale Convective Systems ................................................. 50 
4.6 Meso- and Synoptic-Scale Dynamics ........................................ 51 
4.7 Troposphere-Stratosphere Interactions ..................................... 51 
4.8 Gas-Phase Transformations of Atmospheric Chemicals ................. 52 
4.9 Conversion, Redistribution, and Removal of Atmospheric Gases and 

Aerosols ..................................................................................... 53 
4.10 Biological Sources and Global Distributions of Atmospheric Chemicals . 53 
4.11 Other Points Raised in the Group Discussion ............................ 54 

5. Summary of Working Group Discussions .................................... 58 
5.1 Charge to the Working Groups ................................................ 58 
5.2 Working Group 1—Mid-Sized Turboprop Aircraft ......................... 59 
5.2.1 Science needs served .......................................................... 59 
5.2.2 Role played by the aircraft in the RAF fleet .......................... 61
ABSTRACT

A workshop was organized and conducted by staff of the National Center for Atmospheric Research (NCAR) during April 1987 to assess the scientific needs for atmospheric research aircraft in the next 15 years, and to recommend how the composition of the NCAR aircraft fleet should evolve to meet those needs. The workshop was attended by approximately 75 atmospheric scientists and research managers representing essentially all of the atmospheric research areas in which NCAR instrumented aircraft are used. Spokespersons for ten of these research areas summarized current and future needs for research aircraft in their subdisciplines. The attendees discussed the capabilities of NCAR's current aircraft fleet (operated by its Research Aviation Facility, RAF), as well as prospective aircraft acquisitions to augment these capabilities. Four working groups were organized to discuss the pros and cons of acquiring and/or developing the following types of aircraft, respectively:

- A mid-sized turboprop (Gulfstream I) aircraft
- A mid-sized jet aircraft
- A storm-penetration aircraft
- Other aircraft, different from those above.

A majority of the workshop attendees agreed to the following recommendations:

- Electra aircraft flight time available to NSF-funded scientific investigators should be increased by 100 to 200 hours per year.
- As its top fleet-acquisition priority, NCAR should proceed to acquire a mid-sized jet aircraft to replace its existing Sabreliner.
- As a second priority, NCAR should acquire a storm-penetration aircraft, or arrange for joint use of such an aircraft with another agency.
- The existing Gulfstream I mid-sized turboprop aircraft owned by the NSF should not be renovated and developed as a research facility.
The consensus on the mid-sized jet was remarkable in that it was near-unanimous (only three negative votes). Although a few participants stated that they would prefer a larger jet aircraft, such as a Boeing 737 or a DC-9, the mid-sized jet emerged as the clear choice of the workshop. This type of aircraft was considered to be an excellent match to the needs of major studies of global climate, atmospheric chemistry, and mesoscale meteorology during the next two decades.

It was agreed that to meet these important needs, the new mid-sized jet should have a full-fuel scientific payload of 5,000 pounds, a range of greater than 4,000 nautical miles, an endurance of greater than 9 hours, and a maximum altitude near 50,000 feet with full payload. These capabilities are currently available in mid-sized jets of the Gulfstream IV class.
1. Introduction

The first NCAR Research Aviation Facility (RAF) Fleet Workshop was held in February 1982 to discuss scientific priorities for atmospheric research in the following 10 years, the types of new airborne instruments expected within the next decade, and the aircraft fleet that would be needed at NCAR to serve these requirements. The results of this meeting, which was attended by approximately 25 atmospheric scientists and research managers, were summarized by Hildebrand and McCarthy (1983).

Regarding the future composition of the RAF aircraft fleet, the workshop attendees made the following major recommendation:

"The aircraft that clearly were identified as having the highest priority for enhancement were the small-to-medium jet aircraft. The Sabreliner was endorsed as a very important aircraft that serves critical scientific needs. The weaknesses of the Sabreliner (its inability to operate in icing and its limited altitude and range capabilities) could be alleviated in large part by replacement with a medium twin-jet aircraft of the Gulfstream II or Canadair Challenger variety."

In the years following the workshop, however, funds were not available for the acquisition of additional aircraft. Accordingly, the above recommendation could not be implemented.

In late 1985 a used Gulfstream I (G-I) mid-sized twin-turboprop aircraft became available as surplus government property at the FAA facilities in Oklahoma City. Because this type of aircraft was viewed by NCAR and NSF personnel at that time as a useful general research platform for the NSF atmospheric science community, the necessary arrangements were accomplished in 1986 to transfer the FAA G-I aircraft to NSF for incorporation into the RAF fleet at NCAR.
Since the newly acquired G-I was not in flyable condition and, in fact, was rather completely dismantled,\textsuperscript{2} it was clear from preliminary estimates that a significant amount of funds would be required to (1) bring the aircraft back to airworthy condition, and (2) to modify and instrument it for research use. Because of budget limitations and the lack of a strong consensus that the G-I development should be given a high priority, no funds were made available to NCAR during FY 1986 or FY 1987 for initiation of this development.

In the meantime, significant interest continued in a mid-sized jet aircraft, and additional platforms, such as a storm-penetration aircraft, were also proposed as important development needs. To help sort this out, the Second NCAR Research Aircraft Fleet Workshop was held in April 1987 to obtain a detailed update of the views of the NSF atmospheric science community about the priorities of the various prospective research aircraft platform developments before proceeding with any of them.

NCAR staff hoped to gain from the discussions at this second workshop a clear idea of the directions in which RAF fleet development should proceed in order to best serve the needs of the atmospheric sciences during the remainder of this century and beyond. Accordingly, the following objectives were established for the second workshop:

- To assess the science needs for atmospheric research aircraft in the next 15 years, and
- To recommend how the composition of the NCAR aircraft fleet should evolve to meet those needs.

The NCAR group planning this workshop recognized that the products of the workshop would be most credible and valuable if they reflected the viewpoints of a representative

\textsuperscript{2} The FAA had done this in 1981 as part of a new project that required a major reconfiguration of the aircraft. This project was later cancelled after the aircraft had been dismantled.
cross section of atmospheric scientists from a broad spectrum of disciplines and interests. Thus the planning group took care to ensure that the list of invitees reflected the balance and breadth needed to represent the entire spectrum of those areas of atmospheric science in which research aircraft play a role. A total of 77 atmospheric scientists and research managers from a broad variety of disciplines attended the meeting, as shown in Appendix A.

As a point of departure for the discussions at the workshop, the participants were advised prior to the meeting about the then-current NCAR plans for fleet augmentation. There were no plans to replace the Electra or King Air, but the Sabreliner was a candidate for replacement because of its age and limited capabilities. Three documents were prepared by the RAF staff and mailed to the participants prior to the workshop for their use as information sources regarding three types of new aircraft platforms that NCAR was then considering:

- A mid-sized turboprop research aircraft (G-I) (Workshop Document 1)
- A mid-sized jet research aircraft (Workshop Document 2)
- A storm-penetration research aircraft (Workshop Document 3).

These documents contained information on aircraft characteristics and capabilities, science needs served, and prospective development plans and costs. The workshop attendees were asked to use this information, along with the other information provided in the workshop presentations, to recommend to NCAR how the developments of these and other research aircraft should be prioritized.
2. Opening Presentations

On the first day of the workshop, several speakers from NCAR gave presentations to provide background information and set the stage for the subsequent deliberations. These presentations are briefly summarized in this section.

2.1 NCAR Perspective

Richard Anthes, Director of NCAR, and Robert Serafin, Director of NCAR’s Atmospheric Technology Division (ATD), gave their views regarding airborne observational facilities and how they fit within the NCAR program. Anthes stated that the development of new facilities must keep pace with the needs of researchers for such facilities if atmospheric science is to progress. His view was that increased support for facility development such as new research aircraft is essential, but that such increased support for hardware should not take place at the expense of NSF funding for research. Anthes stated that increased funding of facility development should be accompanied by increased funding for atmospheric research to provide a balanced program. He then proceeded to briefly outline NCAR’s five-year plan for requesting incremental funds from NSF for research aircraft development and supplemental flight operations support.

Serafin reviewed the plans of the Atmospheric Technology Division for development of new research instrumentation and platforms, including the Electra Doppler Radar (ELDORA) system slated to be installed on the NCAR Electra aircraft in FY 90-91. He emphasized that research aviation is among the more important activities in which NCAR engages, and stressed the importance of careful and effective planning for the future in this area. Serafin’s view was that obtaining input from the atmospheric science community on research aviation needs, such as was being done with the current workshop, was essential to ensure that the flight facilities provided to the community remain state-of-the-art and capable of addressing the most important areas of atmospheric science investigation.
2.2 Current RAF Fleet—Capabilities and Limitations

At this point, Warren Johnson, Manager of the RAF, described the current RAF fleet, consisting of three aircraft: a twin-jet Sabreliner NA265-60 acquired in 1968, a four-engine turboprop Lockheed Electra L-188C acquired in 1972, and a twin-turboprop Beechcraft King Air B200T acquired in 1982. (In the immediate past the fleet also included a twin-prop Beechcraft Queen Air B80-88, but this aircraft was retired in 1986.) Illustrations (not to scale) of the three current aircraft are shown in Fig. 1. Details about these are provided in Appendix B.

Johnson summarized the most important features of the King Air, Sabreliner, and Electra aircraft in a table (Table 1). The King Air and Sabreliner are similar in size, but both are substantially smaller than the Electra. The Electra has a large payload and cabin volume, and is the longest-range aircraft in the fleet with a range of 2,400 NMi with IFR (instrument flight rules) fuel reserves. This range enables the aircraft to fly the long leg between San Francisco and Honolulu without ferry tanks (but only if the winds at flight altitude are not adverse). One limitation of the Electra for some applications is its maximum altitude (typically 25,000 feet). Also, its relatively high cost of operation (approximately $2,360 per flight hour in FY 88) can be considered a disadvantage.

Johnson stated that the King Air was a highly useful atmospheric research platform for single-investigator studies. This is the RAF's most modern aircraft, and also its most economical to operate at approximately $780 per flight hour (FY 88). The principal limitation of the King Air concerns the operational ramifications of a lightning strike to the aircraft. The King Air is no more susceptible to lightning strikes than any other aircraft, but when a strike to an engine or propeller occurs, manufacturer's directives require that the engine be torn down and inspected for possible bearing damage. This is an expensive ($25,000) and time-consuming (two- to three-week) procedure which can have serious effects on budgets and field programs. Consequently the RAF has had to develop operational procedures which limit the exposure of the aircraft to lightning strikes. This
Fig. 1. Current NCAR research aircraft (not to scale): Electra (top), King Air (center), and Sabreliner (bottom).
Table 1. Characteristics of the NCAR King Air (KA), Sabreliner (SL), and Electra (EL) aircraft.

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<tr>
<th></th>
<th>KA</th>
<th>SL</th>
<th>EL</th>
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<tbody>
<tr>
<td>Max. gross takeoff wt.</td>
<td>14,000</td>
<td>20,000</td>
<td>116,000</td>
</tr>
<tr>
<td>Max. payload w/full fuel</td>
<td>1,680</td>
<td>1,880</td>
<td>7,200</td>
</tr>
<tr>
<td>Max. payload</td>
<td>2,350</td>
<td>2,250</td>
<td>20,800</td>
</tr>
<tr>
<td>Exterior dimensions:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length</td>
<td>13.4</td>
<td>14.6</td>
<td>32.0</td>
</tr>
<tr>
<td>Wingspan</td>
<td>17.4</td>
<td>13.7</td>
<td>30.2</td>
</tr>
<tr>
<td>Height</td>
<td>4.3</td>
<td>4.9</td>
<td>9.8</td>
</tr>
<tr>
<td>Cabin volume</td>
<td>10.4</td>
<td>13.6</td>
<td>85.0</td>
</tr>
<tr>
<td>Baggage volume</td>
<td>0</td>
<td>0</td>
<td>15.0</td>
</tr>
<tr>
<td>Flight load limits</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Flight crew (persons)</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Max range w/reserves</td>
<td>1,800</td>
<td>1,300</td>
<td>2,400</td>
</tr>
<tr>
<td>Cruise speed</td>
<td>240</td>
<td>400</td>
<td>310</td>
</tr>
<tr>
<td>Maneuvering speed</td>
<td>170</td>
<td>360</td>
<td>203</td>
</tr>
<tr>
<td>Rate of climb (SL)</td>
<td>2,050</td>
<td>3,500</td>
<td>2,000</td>
</tr>
<tr>
<td>Single eng. service ceiling</td>
<td>17,000</td>
<td>24,000</td>
<td>N/A</td>
</tr>
<tr>
<td>Typical mission:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max. oper. altitude</td>
<td>33,000</td>
<td>43,000</td>
<td>28,400</td>
</tr>
<tr>
<td>Endurance</td>
<td>7.3</td>
<td>2.5</td>
<td>8.5</td>
</tr>
<tr>
<td>Operation in known icing</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
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in turn sometimes leads to undesirable flight constraints in certain types of measurement programs.

Finally, the strengths and shortcomings of the Sabreliner were reviewed. This is the only high-altitude jet aircraft in the fleet, and as such is needed for some types of atmospheric research. However, the aircraft is over 20 years old, is becoming increasingly more difficult to maintain, has too small a payload for many projects, has an endurance of only 2.5 hours with IFR reserves, and is not certified for flight into known icing conditions. These limitations pose severe operational constraints for many measurement programs. In addition, the Sabreliner’s typical maximum altitude (41,000 ft) is considerably lower than is desirable for many research applications.

Johnson stated that all of these considerations have led the RAF staff to conclude that the Sabreliner continues to be a prime candidate for replacement in the near future, as was recommended at the first RAF Fleet Workshop. There are no plans for replacement of either the Electra or the King Air, since these platforms are expected to be capable of serving RAF users well for many years to come.

2.3 RAF Perspective on Science Needs for Aircraft Platforms

The RAF perspective on scientific needs for research aircraft was addressed in detail in documents prepared for the workshop (Workshop Documents 1, 2, and 3). Several of these needs were highlighted in a workshop presentation by Al Cooper, RAF Deputy Manager for Research and Development, and are briefly summarized below.

2.3.1 Need for increased total flight support

The number of small aircraft in the RAF fleet is at its lowest level in more than ten years. Prior to 1981 a Sabreliner and two Queen Air aircraft were available. In 1983 the Sabreliner, one Queen Air, and 1-1/2 King Airs (including a 50% lease on the University
of Wyoming King Air) were available. Today the small-aircraft fleet consists only of the Sabreliner and one King Air.

RAF cannot currently offer the level of support provided in field programs like CCOPE,\(^3\) for example, in which the Sabreliner and two Queen Airs were operated. Future programs are likely to become larger and more complex, and will require enhanced capabilities for coverage of the phenomena being studied. An increase in the total requested flight hours must be anticipated because there is growing recognition of the need to bolster the observational component of atmospheric science; see, e.g., the report of the Joint NSF-UCAR Planning Committee.\(^4\)

Enhanced flight support on the Electra will be needed as well. This need will become particularly critical when the ELDORA Doppler radar becomes operational, because that radar will increase the demand for the Electra within the mesoscale research community at about the same time that atmospheric chemists will have greater need for that aircraft in the Global Tropospheric Chemistry Program and in other major programs. NCAR’s best estimate is that a doubling of Electra flight hours will be needed in the 1990’s.

2.3.2 Need for payload and cabin space greater than provided by the Sabreliner or King Air

New remote sensors and other complex new instruments are becoming important parts of the instrument complement of research aircraft, and the available cabin space and payload of the King Air and Sabreliner are increasingly limiting the instrument configurations that can be accommodated on those aircraft. This problem will worsen in the future as new remote sensors become available, as interdisciplinary studies requiring larger arrays

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\(^3\) CCOPE = Cooperative Convective Precipitation Experiment

of instruments are undertaken, and as studies in atmospheric chemistry receive greater emphasis and require more comprehensive instrumentation.

2.3.3 Need for improved ability to withstand the hazards of icing, lightning, and turbulence, and to work inside of or near thunderstorms and hailstorms

The Sabreliner cannot operate in icing environments, and is the only high-altitude aircraft in the RAF fleet. It also has quite limited endurance. The King Air is susceptible to expensive engine inspections if struck by lightning. Neither aircraft can be used as a storm-penetration aircraft. Thus there are significant observational needs in studies of mesoscale and severe storm systems that cannot be met by the current fleet, and studies of precipitation physics and storm structure suffer as a result. There remains a need for a storm-penetration aircraft such as the T-28 operated by the SDSMT (South Dakota School of Mines and Technology), but with improved performance and higher ceiling. In addition, many studies that are currently considered unacceptably hazardous or expensive could be conducted by an aircraft that, although unable to penetrate hailshafts, could work at high altitudes in icing environments and not be particularly susceptible to lightning damage. The limitations of the current aircraft were particularly evident in CCOPE and in GALE,\(^5\) where desirable missions could not be flown because of the above problems.

2.3.4 Need for improved performance

There are many high-altitude studies that the Sabreliner partially supports, including studies of cirrus, radiation balance, and in-situ verification of satellite observations, that need measurements at altitudes of 40,000-50,000 ft with substantial payloads and endurance. In addition, studies of ice development, cloud-top entrainment, and precipitation development could benefit from a higher rate of climb at middle altitudes (20,000-30,000 ft). If an aircraft could climb at rates comparable to the ascent rates of cumulus elements, it could support studies of the evolution of a cloud element with time. Increased speed would

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\(^5\) GALE = Genesis of Atlantic Lows Experiment
also be a benefit in planned future large-scale programs such as the STORM\textsuperscript{6} program, where rapid transit to features of interest would be of benefit, and where it would be useful to make a set of measurements fast enough so that the system does not evolve significantly during the period of measurements.

2.3.5 Need for larger payloads to be carried to the upper troposphere and lower stratosphere

The current fleet is limited in its ability to support atmospheric chemistry because the Electra is the only aircraft able to carry the large payloads often needed for comprehensive air chemistry experiments, and under most conditions that aircraft is limited to the lower troposphere (<25,000 ft). Higher altitude/larger payload capabilities are also needed for effective studies of jet-stream dynamics and of exchanges between the troposphere and the stratosphere.

2.3.6 Need to be able to conduct measurements on a global scale

Studies with a climatological orientation are increasing in frequency and importance. Examples of studies that have world-wide implications and require observations spanning substantial portions of the earth include the Global Tropospheric Chemistry Program, the FIRE\textsuperscript{7} project and other studies of radiation balance, studies of ocean-atmosphere influences (such as TOGA\textsuperscript{8} and EMEX\textsuperscript{9}), studies of global precipitation, and studies related to in-situ verification of estimates based on satellite or other measurements (as in FIRE, HAPEX\textsuperscript{10}, and TRMM\textsuperscript{11}). These projects require an ability to make measurements in

\begin{itemize}
\item \textsuperscript{6} STORM = STormscale Operational and Research Meteorology
\item \textsuperscript{7} FIRE = First ISCCP (International Satellite Cloud Climatology Project) Regional Experiment
\item \textsuperscript{8} TOGA = Tropical Oceans and Global Atmosphere
\item \textsuperscript{9} EMEX = Equatorial Mesoscale Experiment
\item \textsuperscript{10} HAPEX = Hydrologic Atmospheric Pilot Experiment
\item \textsuperscript{11} TRMM = Tropical Rainfall Measurement Mission
\end{itemize}
remote regions of the earth. Among the current NCAR aircraft, only the Electra is a truly intercontinental aircraft, and even it has a shorter range than would be desirable for this usage. It is difficult to conduct high-altitude studies in remote locations, or to fly the long legs that would be desirable in studies of climatological characteristics. These needs point to an aircraft with maximum range and speed considerably above that of the Electra.

2.3.7 Implications

The above needs are addressed to varying degrees by the prospective aircraft acquisitions discussed at the workshop. A Gulfstream I meets the need discussed in Sec. 2.3.1, partially meets that in Sec. 2.3.2, and provides improved ability to encounter the hazards of lightning (Sec. 2.3.3), but does not meet the last three needs. A mid-sized jet meets all needs except that in Sec. 2.3.3, where it provides some improvement (particularly in ability to encounter icing) but cannot serve as a storm-penetration aircraft. The storm-penetration aircraft meets the needs described in Sec. 2.3.3 and 2.3.4 very well, but (depending on the aircraft) probably does not address the other needs.

2.4 RAF Program Plan for Aircraft Platforms

Warren Johnson presented the then-current NCAR plan for requesting program funds from NSF for RAF flight support and research aircraft acquisition and development during the five-year period from FY 88 through FY 92. The FY 88 plan was simply an extension of the FY 87 budget with slight adjustments for inflation; no incremental funds for either flight support or aircraft platforms were expected. The budgeted RAF flight support levels for FY 88 are shown in Table 2. The total funds for flight support operations and maintenance amounted to approximately $1.14M, not including normal salaries and benefits for RAF staff. These funds cover the provision of 472, 175, and 212 flight hours for the King Air, Sabreliner, and Electra, respectively. These flight-hour quantities were unchanged from the previous two years.
Table 2. Budgeted RAF flight support levels (FY 88).

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<tr>
<td>Funds budgeted for operations</td>
<td>$368 K</td>
<td>$273 K</td>
<td>$500 K</td>
</tr>
<tr>
<td>and maintenance</td>
<td></td>
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<td></td>
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<tr>
<td>Nominal cost/flight hour</td>
<td>$779 K</td>
<td>$1,560 K</td>
<td>$2,359 K</td>
</tr>
<tr>
<td>Nominal flight hours available</td>
<td>472</td>
<td>175</td>
<td>212</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>(same as in FY87)</td>
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As of the date of the workshop, the NCAR program plan included $2M per year starting in FY 89 for the acquisition and development of additional or replacement aircraft for the RAF fleet, specifically either the NSF-owned G-I or a mid-sized jet, or possibly both. This plan also included additional funds for staffing and flight operations for these aircraft during the latter portion of the planning period. Sabreliner retirement was tentatively scheduled for FY 92, contingent upon a replacement aircraft becoming operational at that time. (The plan was deliberately left flexible regarding the type of aircraft to be developed, pending receipt of the recommendations from the fleet workshop.)

Another important element of the program plan was the inclusion of incremental funds for an additional 200 hours of Electra flight support, starting in FY 90. However, it was mentioned that this would probably be postponed until FY 91 because of a scheduled six-month period of downtime of the Electra during FY 90 for modifications required by ELDORA. In this case some of the FY 90 Electra flight support funds might be used for ELDORA development.

Johnson concluded his presentation by noting that the RAF was currently at an important crossroads in its planning for aircraft fleet development, and that the recommendations from the workshop would be timely and highly valuable in finalizing these plans.
3. New Aircraft Platforms Under Consideration by the RAF

3.1 Mid-Sized Turboprop Aircraft

Warren Johnson presented a summary of Workshop Document 1, which dealt with the subject of a mid-sized turboprop aircraft, specifically a Gulfstream I since a dismantled G-I was already in the NSF inventory. He first presented a table (Table 3) showing various characteristics of the G-I, including size, payload, and performance. Johnson then proceeded to review the reasons why NCAR was considering developing the G-I:

- With a maximum gross take-off weight of 36,000 lb, the G-I would fit nicely into the large payload gap between the King Air at 14,000 lb, and the Electra at 116,000 lb.
- The G-I would increase the RAF’s project support flexibility, simply because it would increase the size of the fleet to four aircraft.
- The aircraft would be useful for studies of tropospheric chemistry, cloud micro-physics, and boundary-layer processes, especially since it had features that would make it a good intermediate-sized platform for air chemistry instrumentation and remote-sensing systems (such as lidars and radars).
- The G-I development would probably be more affordable than other aircraft acquisition options.
- Gulfstream aircraft in general, and particularly G-I aircraft, are noted for their strength and durability; thus the G-I could be expected to be a “workhorse” aircraft that would stand up well under heavy use.

Johnson pointed out that adding a G-I to the RAF fleet would also have some significant disadvantages:

- The G-I would not provide any new performance capabilities not currently available with the existing three NCAR aircraft.
Table 3. Features of the Gulfstream I (G-I) aircraft.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value 1</th>
<th>Unit 1</th>
<th>Value 2</th>
<th>Unit 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. gross takeoff wt.</td>
<td>36,000</td>
<td>lb</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max. payload w/full fuel</td>
<td>2,740</td>
<td>lb</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exterior dimensions:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length</td>
<td>19.5</td>
<td>m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wingspan</td>
<td>23.8</td>
<td>m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Height</td>
<td>7.0</td>
<td>m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cabin volume</td>
<td>29.5</td>
<td>m³</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baggage volume</td>
<td>4.1</td>
<td>m³</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flight load limits</td>
<td>2.5</td>
<td>g</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flight crew (persons)</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max range w/reserves</td>
<td>1,800</td>
<td>NMi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cruise speed</td>
<td>308</td>
<td>ktas</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maneuvering speed</td>
<td>174</td>
<td>kias</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rate of climb (SL)</td>
<td>1,900</td>
<td>ft/min</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single eng. service ceiling</td>
<td>14,000</td>
<td>ft</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Typical mission:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max. oper. altitude</td>
<td>25,000</td>
<td>ft</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Endurance</td>
<td>6.6</td>
<td>hr</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operation in known icing</td>
<td>Yes</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
• The aircraft has a maximum altitude of only 20,000 to 25,000 ft, which would be a serious limitation for some studies.

• The G-I was already an old aircraft in 1987, and could develop into a major maintenance problem in 10 to 15 years.

• The G-I would not be a suitable replacement for the Sabreliner.

If the G-I were developed, it would likely be accomplished in two phases. The Phase-I development would result in a basic research aircraft with a data system, a drop chute for deployables, sensors for measuring primary meteorological state variables (temperature, humidity, radiation, and air motion), and air-sampling apertures for atmospheric chemistry measurements. Development of this basic research aircraft would take about 15 months and cost approximately $1.2M.

Further (Phase-II) development would produce an advanced research aircraft. In this configuration, the aircraft would have improved avionics, three 20-inch diameter viewports, additional air-sampling apertures, several external hardpoints for various sensors, leading-edge underwing pylons, a belly pod for large equipment such as radar antennas, a heated radome gust probe, sensor mount pads on the nose, and two engine-driven bleed-air venturis to furnish vacuum for chemistry equipment. This Phase-II development would cost approximately $2.0M and require an additional 18 months.

Finally, the estimated costs for operating a G-I for 400 flight hours per year were presented. Approximately $850K per year would be needed to cover the expenses of additional staff ($330K), and of operations and maintenance ($520K). The operational cost per flight hour would be approximately $1,300 per flight hour, which is about 1.7 times that of the King Air.
3.2 Mid-Sized Jet Aircraft

Detailed background information on mid-sized jet aircraft was included in Workshop Document 2, and was summarized for the workshop participants in a presentation by Al Cooper. As reflected in the recommendations from the First RAF Fleet Workshop held in 1982, the NCAR Sabreliner is a prime candidate for replacement because of its age and its limited size and performance capabilities. Cooper stated that, based on the results from the first workshop and other considerations, RAF's preliminary view was that the replacement aircraft should be a larger (mid-sized) jet with state-of-the-art performance capabilities.

Cooper reviewed the reasons why NCAR considers a mid-sized jet important and why NCAR has developed the plan contained in Workshop Document 2. There are important research areas that cannot be studied by use of the existing three aircraft in the RAF fleet, and others that are addressed only partially or awkwardly. The scientific objectives addressed in the document indicate that three general improvements over current capabilities are needed:

- Higher-altitude capabilities and increased endurance for better vertical and horizontal spatial coverage

- Larger payload and cabin space suitable for multi-investigator atmospheric chemistry and meteorology instrumentation, including large remote-sensing equipment

- Improved performance and suitability for measurements during cloud penetrations and in icing conditions.

A mid-sized jet aircraft would provide for new research opportunities in mesoscale meteorology, global tropospheric chemistry, and global climate. Efforts in these scientific areas are expected to increase in the coming decades. There is no alternative aircraft available to the NSF community that can meet these needs. The size and performance of this class
of aircraft are suited to community and NCAR priorities, and complement capabilities of the current fleet.

Another important feature of a modern mid-sized jet is that, with its high-bypass fanjet engines, it can also fly efficiently at low altitudes. Thus such an aircraft could provide significantly improved range and endurance for boundary-layer and other low-altitude studies.

Cooper then proceeded to discuss several of the research areas listed in Table 4 in which a mid-sized jet could be useful. In each of these areas, the limitations of the currently available aircraft and the advantages of a mid-sized jet were described.

In preparing the NCAR plan, the respective characteristics of commercially available mid-sized jet aircraft were reviewed, and were compared with a set of criteria based upon the perceived needs of relevant atmospheric research studies. To be seriously considered, an aircraft had to meet all or most of these desirable characteristics, which are listed below:

- Payload with full fuel of 5,000 lb or more
- Cabin volume of $34.0 \, \text{m}^3$ or more, and cabin floor area of $23.2 \, \text{m}^2$ or more
- Altitude capability of 45,000 ft or higher
- Turbofan engines (two or more) capable of operating efficiently at low as well as high altitudes
- Range suitable for overseas operations (3,000 nm or more, plus IFR fuel reserves)
- Takeoff weight less than 70,000 lb, so aircraft can be operated out of Jefferson County Airport, where the RAF is based
- Rate of climb of at least 1,000 ft/min at altitudes of 20,000 to 30,000 ft, to enable aircraft to follow vertical storm development
Table 4. Research categories in which a mid-sized jet would be useful.

- **Mesoscale and synoptic-scale meteorology**
  - Storm structure and dynamics
  - Jet-stream dynamics
  - Tropospheric/stratospheric interactions and exchange processes
  - Rainbands
  - Remote-sensing applications

- **Boundary-layer meteorology**
  - Turbulence and diffusion
  - Air pollution studies
  - Land/air interactions and fluxes
  - Sea/air interactions and fluxes
  - Terrain effects

- **Cloud physics and convective storm structure**
  - Ice origins and evolution
  - Precipitation formation processes
  - Cirrus studies
  - Cloud electrification

- **Climatology and global studies**
  - Radiative processes
  - Extended-scale atmospheric surveys
  - Polar meteorological and chemical studies
  - Remote ocean surveys

- **Atmospheric chemistry**
  - Global tropospheric chemistry
  - Stratospheric chemistry and aerosols
  - Fluxes and budgets of chemical species
  - In-cloud transport and aqueous-phase chemistry
• Oceanography
  – Sea/air interactions and fluxes
  – Surface and subsurface characteristics
  – Chemical sources and sinks
  – Ocean surface profiling
• Certification for flight into known icing conditions

• Electrical power of at least 25 KVA available for research equipment

• Endurance of six hours or more, plus IFR fuel reserves

• A manufacturer that is readily available to provide assistance with future modifications to the aircraft to fit NCAR's special needs.

Cooper stated that only five aircraft come close to or meet most of these specifications: the Gulfstream II, III, and IV (G-II, G-III, and G-IV); the Falcon 900; and the Canadair Challenger 601-3A. The characteristics of these aircraft are compared with those of the Sabreliner in Table 5. Aircraft and payload weights are compared in Table 6. Calculated performance figures for each aircraft for various typical research mission profiles were also presented.

The conclusions of the RAF analysis were as follows:

• The G-II might do the job, but has less range than desired, and is a 10- to 20-year-old aircraft.

• The Falcon 900 has insufficient electrical power available for research purposes (only 6 KVA), and the manufacturer has stated that there is no feasible way for this to be increased. The three-engine configuration would also be a handicap because it would be necessary to avoid mounting sensors on top of the fuselage where ice could be shed into the center engine. Another problem is that there is a fuel tank under the fuselage that would make it difficult to install downward-looking apertures or instruments.

• The Canadair Challenger 601 has a significant disadvantage in its relatively low ceiling. The certificated ceiling is only 41,000 ft, and the all-engine service ceiling is approximately 38,000 ft. These seem too low to meet community needs. In addition, the aircraft has the smallest payload and cabin size of the five examined.
Table 5. Comparison of mid-sized jet aircraft specifications with those of the NCAR Sabreliner.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Sabreliner</th>
<th>Falcon 900</th>
<th>Canadair 601</th>
<th>G-II</th>
<th>G-IIIB</th>
<th>G-III</th>
<th>G-IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. gross takeoff weight (lb)</td>
<td>20,000</td>
<td>45,500</td>
<td>44,600</td>
<td>64,800</td>
<td>69,700</td>
<td>69,700</td>
<td>73,200</td>
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<tr>
<td>Exterior dimensions:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length (m)</td>
<td>14.7</td>
<td>20.2</td>
<td>20.9</td>
<td>24.4</td>
<td>24.4</td>
<td>25.3</td>
<td>26.9</td>
</tr>
<tr>
<td>Wingspan (m)</td>
<td>13.6</td>
<td>19.4</td>
<td>19.6</td>
<td>21.0</td>
<td>23.7</td>
<td>23.8</td>
<td>23.8</td>
</tr>
<tr>
<td>Height (m)</td>
<td>4.9</td>
<td>7.6</td>
<td>6.3</td>
<td>7.5</td>
<td>7.5</td>
<td>7.4</td>
<td>7.6</td>
</tr>
<tr>
<td>Cabin dimensions:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length (m)</td>
<td>5.8</td>
<td>11.9</td>
<td>8.6</td>
<td>12.0</td>
<td>12.0</td>
<td>12.6</td>
<td>13.8</td>
</tr>
<tr>
<td>Width (m)</td>
<td>1.6</td>
<td>2.3</td>
<td>2.5</td>
<td>2.2</td>
<td>2.2</td>
<td>2.2</td>
<td>2.2</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.7</td>
<td>1.9</td>
<td>1.9</td>
<td>1.9</td>
<td>1.9</td>
<td>1.9</td>
<td>1.9</td>
</tr>
<tr>
<td>Volume (m³)</td>
<td>13.6</td>
<td>35.9</td>
<td>32.6</td>
<td>31.9</td>
<td>31.9</td>
<td>34.0</td>
<td>39.4</td>
</tr>
<tr>
<td>Baggage compartment volume (m³)</td>
<td>0</td>
<td>3.6</td>
<td>3.3</td>
<td>4.4</td>
<td>4.4</td>
<td>4.4</td>
<td>4.8</td>
</tr>
<tr>
<td>Max. fuel (lb)</td>
<td>7,122</td>
<td>19,003</td>
<td>16,665</td>
<td>23,300</td>
<td>28,300</td>
<td>28,300</td>
<td>29,500</td>
</tr>
<tr>
<td>Engines; no./thrust (lb each)</td>
<td>2/3,300</td>
<td>3/4,500</td>
<td>2/8,650</td>
<td>2/11,400</td>
<td>2/11,400</td>
<td>2/11,400</td>
<td>2/13,850</td>
</tr>
<tr>
<td>Certified ceiling (ft)</td>
<td>45,000</td>
<td>51,000</td>
<td>41,000</td>
<td>43,000</td>
<td>45,000</td>
<td>45,000</td>
<td>47,000</td>
</tr>
<tr>
<td>Max. range w/reserves (nmi)</td>
<td>1,300</td>
<td>3,800</td>
<td>3,200</td>
<td>2,560</td>
<td>3,500</td>
<td>3,728</td>
<td>4,245</td>
</tr>
<tr>
<td>Max. endurance w/reserves (hr)</td>
<td>3.5</td>
<td>9.7</td>
<td>9.0</td>
<td>6.3</td>
<td>7.8</td>
<td>8.1</td>
<td>9.4</td>
</tr>
<tr>
<td>Typical cruise speed (kt)</td>
<td>413</td>
<td>430</td>
<td>424</td>
<td>413</td>
<td>442</td>
<td>442</td>
<td>459</td>
</tr>
<tr>
<td>Stall speed at max. landing wt. (kt)</td>
<td>95</td>
<td>82</td>
<td>102</td>
<td>108</td>
<td>103</td>
<td>103</td>
<td>108</td>
</tr>
<tr>
<td>Climb rate at sea level, all engines (ft/min)</td>
<td>3,500</td>
<td>3,500</td>
<td>4,200</td>
<td>3,850</td>
<td>4,270</td>
<td>4,270</td>
<td>3,816</td>
</tr>
<tr>
<td>Climb rate at sea level, one engine out (ft/min)</td>
<td>1,500</td>
<td>1,480</td>
<td>1,380</td>
<td>1,400</td>
<td>1,470</td>
<td>1,470</td>
<td>1,278</td>
</tr>
<tr>
<td>Electrical generation units, no./power (KW or KVA)</td>
<td>2/11 (DC)</td>
<td>3/9 (DC)</td>
<td>2/30 (AC)</td>
<td>3/20 (AC)</td>
<td>3/20 (AC)</td>
<td>3/36 (AC)</td>
<td>3/36 (AC)</td>
</tr>
</tbody>
</table>

* Current certification is 45,000 ft; certification to 47,000 ft is planned by Gulfstream.

** With NBAA IFR fuel reserves: execute missed approach at destination airport, fly 200 NMI and arrive at alternate airport with 45 minutes of fuel remaining.

*** The third alternator is driven by an on-board auxiliary power unit (APU). In the case of G-IVs and late G-IIIIs, this APU can be operated in flight up to an altitude of 35,000 ft.
### Table 6. Comparison of mid-sized jet weights and payloads with those of the NCAR Sabreliner.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sabreliner</th>
<th>Falcon 900</th>
<th>Canadair 601</th>
<th>G-II</th>
<th>G-IIB</th>
<th>G-III</th>
<th>G-IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Max. gross ramp weight&lt;sup&gt;a&lt;/sup&gt;</td>
<td>20,000</td>
<td>45,500</td>
<td>44,600</td>
<td>65,300</td>
<td>70,200</td>
<td>70,200</td>
<td>73,600</td>
</tr>
<tr>
<td>B. Max. gross takeoff weight&lt;sup&gt;a&lt;/sup&gt;</td>
<td>20,000</td>
<td>45,500</td>
<td>44,600</td>
<td>64,800</td>
<td>69,700</td>
<td>69,700</td>
<td>73,200</td>
</tr>
<tr>
<td>C. Max. zero-fuel weight&lt;sup&gt;a,b&lt;/sup&gt;</td>
<td>13,500</td>
<td>28,220</td>
<td>31,000</td>
<td>42,000</td>
<td>44,000</td>
<td>44,000</td>
<td>46,500</td>
</tr>
<tr>
<td>D. Manufactured (bare) empty wt.&lt;sup&gt;c&lt;/sup&gt;</td>
<td>11,200</td>
<td>20,000</td>
<td>20,485</td>
<td>30,363</td>
<td>30,363</td>
<td>32,000</td>
<td>35,500</td>
</tr>
<tr>
<td>E. Outfitting and modifications to NCAR specifications&lt;sup&gt;d&lt;/sup&gt;</td>
<td>450</td>
<td>2,900</td>
<td>2,900</td>
<td>2,900</td>
<td>2,900</td>
<td>2,900</td>
<td>2,900</td>
</tr>
<tr>
<td>F. Operating empty wt. (D + E)</td>
<td>11,450</td>
<td>22,900</td>
<td>23,385</td>
<td>33,263</td>
<td>33,263</td>
<td>34,000</td>
<td>38,400</td>
</tr>
<tr>
<td>G. Max. research payload&lt;sup&gt;e&lt;/sup&gt; (C - F)</td>
<td>2,050</td>
<td>5,320</td>
<td>7,615</td>
<td>8,737</td>
<td>10,737</td>
<td>9,100</td>
<td>8,100</td>
</tr>
<tr>
<td>H. Max. fuel weight&lt;sup&gt;f&lt;/sup&gt;</td>
<td>7,122</td>
<td>19,003</td>
<td>16,665</td>
<td>23,300</td>
<td>28,300</td>
<td>28,300</td>
<td>29,500</td>
</tr>
<tr>
<td>I. Max. payload with max. fuel&lt;sup&gt;g&lt;/sup&gt; (A - F - H)</td>
<td>1,628</td>
<td>3,597</td>
<td>4,550</td>
<td>8,737</td>
<td>8,637</td>
<td>7,000</td>
<td>5,700</td>
</tr>
<tr>
<td>J. Fuel load with max. research payload&lt;sup&gt;h&lt;/sup&gt; (A - F - G)</td>
<td>6,700</td>
<td>17,280</td>
<td>13,600</td>
<td>23,300</td>
<td>26,200</td>
<td>26,200</td>
<td>27,100</td>
</tr>
<tr>
<td>K. Fuel load (% of capacity) with max. research payload (J x 100/H)</td>
<td>94%</td>
<td>91%</td>
<td>82%</td>
<td>100%</td>
<td>93%</td>
<td>93%</td>
<td>92%</td>
</tr>
</tbody>
</table>

<sup>a</sup> Manufacturers' airframe structural certification limitation.

<sup>b</sup> Maximum weight exclusive of fuel.

<sup>c</sup> This weight assumes a completely empty cabin with no interior furnishings and no research modifications or instrumentation.

<sup>d</sup> For any mid-sized jet added to the NCAR fleet, it is assumed that the weight of interior furnishings, airframe modifications, and supplemental (non-demountable) equipment would be kept to a minimum. This would allow substantial increases in payload over those normally quoted by the manufacturer. This weight also includes engine oil and unusable fuel.

<sup>e</sup> Research payload includes two pilots, scientific crew, demountable research instrumentation and equipment, supplies, baggage, and survival equipment, but excludes fuel.

<sup>f</sup> Maximum fuel weight at standard jet-fuel specific gravity; actual weight may vary, depending upon temperature and other factors affecting specific gravity of fuel.

<sup>g</sup> Maximum research payload which can be loaded when full fuel is carried.

<sup>h</sup> Maximum fuel which can be loaded when maximum research payload is carried.
• The two remaining aircraft, the G-III and G-IV, appear to be the most suitable, with the G-IV being the aircraft of choice because of its larger size and superior range and endurance.

The remainder of the presentation centered around the detailed characteristics of the G-IV aircraft, including its approximate cost, and preliminary plans for how the aircraft could be configured for research. The size of the G-IV relative to the NCAR Electra and Sabreliner can be judged from Figs. 2 and 3, which show photographs of scale models of the three aircraft. As indicated, the G-IV is clearly a large aircraft, closer in size to the Electra than to the Sabreliner. However, the G-IV could be operated out of Jefferson County (Jeffco) airport, the base used for the other RAF aircraft, without any restrictions on its takeoff weight.

The G-IV has been in production for only a short time. The aircraft incorporates advanced flight-management systems and other modern avionics instrumentation, and is designed for high efficiency and high performance. As shown in Table 7, the range guaranteed by the manufacturer, 4,245 NMi,\(^{12}\) is adequate to permit non-stop flight from Denver to London, Stockholm, or Frankfurt, or from Seattle to Tokyo, or from Punta Arenas to the South Pole and back. The capabilities of the aircraft for transcontinental flight were recently demonstrated by two record-setting flights around the world, the first of which was flown westbound against the prevailing winds in less than two days and with only four stops for fuel.

The RAF’s current long-range aircraft is the Electra. While it is clear that the G-IV could never approach the maximum load-carrying capability or floor space of the Electra (maximum payload of 20,800 lb versus 8,100 lb for the G-IV; cabin floor area

\[^{12}\text{Assumes NBAA IFR fuel reserves: execute missed approach at destination airport, fly 200 NMi and arrive at alternate airport with 45 minutes of fuel remaining. (This assumption is incorporated into all data presented in this section.)}\]
Fig. 2. Overhead views of scale models of Electra (top), Gulfstream IV (middle), and Sabreliner (bottom), showing relative sizes of the three aircraft.
Fig. 3. Side views of scale models of Electra (top), Gulfstream IV (middle), and Sabreliner (bottom), showing relative sizes of the three aircraft.
Table 7. Some potential G-IV long-range flight segments.\textsuperscript{a}

<table>
<thead>
<tr>
<th>From</th>
<th>To</th>
<th>Distance (NMi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seattle</td>
<td>Tokyo</td>
<td>4,162</td>
</tr>
<tr>
<td>Los Angeles</td>
<td>Pago Pago, Samoa</td>
<td>4,194</td>
</tr>
<tr>
<td>Honolulu</td>
<td>Brisbane, Australia</td>
<td>4,081</td>
</tr>
<tr>
<td>Punta Arenas, Chile</td>
<td>South Pole and return</td>
<td>4,307</td>
</tr>
<tr>
<td>Fairbanks, Alaska</td>
<td>North Pole and return</td>
<td>3,005</td>
</tr>
<tr>
<td>Denver</td>
<td>Frankfurt</td>
<td>4,255</td>
</tr>
<tr>
<td>Denver</td>
<td>Stockholm</td>
<td>4,237</td>
</tr>
<tr>
<td>Denver</td>
<td>London</td>
<td>4,082</td>
</tr>
<tr>
<td>Denver</td>
<td>Honolulu</td>
<td>2,906</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Assuming high-altitude cruise, no average wind (a reasonable assumption on non-stop round trips), and NBAA IFR fuel reserves.
of 58.4 m$^2$ versus 23.1 m$^2$), the research payloads for the two aircraft with full fuel are not that far apart: 7,200 versus 5,700 lb for the Electra and G-IV, respectively. It is instructive to compare the performance of the two aircraft as a function of altitude when carrying a full load of fuel, which is typical in the operation of research aircraft. This is illustrated in Fig. 4 for maximum endurance, and in Fig. 5 for maximum range. While at the lower altitudes the G-IV has only a slight advantage in endurance over the Electra, this converts to a significant advantage in range because of the G-IV's higher cruise speeds (Table 8).

For example, as indicated in Fig. 5, with zero-headwind conditions the G-IV could fly from San Francisco to Honolulu (2,100 NMi) at an altitude of 4,000 ft above the ocean, which is something the Electra cannot do. With favorable winds the G-IV could fly even lower, possibly within the boundary layer the entire distance. At these lower altitudes the G-IV's cruise speeds are in the range of 260-275 kt, only some 25 to 40 kt higher than those of the Electra. At higher altitudes (above 18,000 ft), the G-IV completely outperforms the Electra, as would be expected because of the G-IV's turbofan engines.

The G-IV's all-engine rate of climb, 3,800 ft/min or about 19 m/s, is adequate to provide climb capability to match the ascent rates of most cumulus clouds. The high maximum cruise speed (519 kts) and the slow stall speed (108 kts) provide a large range of possible operating speeds, so the aircraft can get to distant locations rapidly, but can still fly slowly when needed for atmospheric measurements.

The Tay Mk 610-8 turbofan engines on the G-IV feature a high by-pass ratio to enhance fuel economy and minimize noise. As a result, the aircraft can operate at noise-sensitive airports like Washington National or London without restrictions, while restrictions apply to many other aircraft, including the G-II and G-III. The efficient engines and wing have also reduced operating costs below those of the G-III, and far below those of the G-II.

While the current certificated operating altitude of the G-IV is 45,000 ft, the aircraft has been test-flown as high as 53,000 ft by the manufacturer. NCAR's goal would be to
Fig. 4. Maximum endurance of the Sabreliner, the Electra, and a G-IV as a function of altitude (assuming full fuel at takeoff, maximum-range cruise speed, a standard atmosphere, and NBAA IFR fuel reserves – see text).
Fig. 5. Maximum range of the Sabreliner, the Electra, and a G-IV as a function of altitude (same assumptions as in Fig. 4, plus assumption of no wind).
Table 8. Comparison of Electra and G-IV maximum-range cruise speeds at various altitudes (standard atmosphere).

<table>
<thead>
<tr>
<th>Altitude (ft)</th>
<th>True Air Speed (kt)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Electra</td>
</tr>
<tr>
<td>45,000</td>
<td>—</td>
</tr>
<tr>
<td>20,000</td>
<td>290</td>
</tr>
<tr>
<td>10,000</td>
<td>250</td>
</tr>
<tr>
<td>1,000</td>
<td>220</td>
</tr>
</tbody>
</table>
operate the aircraft at altitudes up to 51,000 ft. Although Gulfstream is planning to have
the aircraft certificated at a higher altitude, this is likely to be to only 47,000 ft initially
because of the expense of seeking a higher certification. However, NCAR and Gulfstream
staff have discussed the possibility of a cost-sharing arrangement under which Gulfstream
would pursue certification of the aircraft to 51,000 ft. Even if this proves not to be feasible,
a capability for sustained operation for several hours at 47,000 ft would still be a major
improvement over the Sabreliner’s ability to reach a maximum altitude of 41,000 ft only
briefly and only under ideal conditions.

Because the aircraft has just recently entered production, it is a modern aircraft
that likely could be easily maintained for 20 or more years. The maintenance records of
past Gulfstream aircraft have been excellent, and strong maintenance support is available
from the factory and around the country. At the moderate usage levels expected in NCAR
service (compared to that in commercial service), it is likely that the G-IV would be one of
the mainstays of the RAF fleet for at least 20 years. (The NCAR Electra and Sabreliner
are each more than 20 years old, but they still are maintainable and are providing good
service to the community.)

The estimated cost of a “green” G-IV (i.e., newly manufactured with bare interior
and no paint) is $18M. (This compares with an estimated $11–12M for a used G-III in good
condition.) This initial cost does not include the cost of interior outfitting and modification
to a research configuration (estimated at $4M), or of the instrumentation and data system
(estimated at $1M). These extra costs would bring the total cost of a research-ready G-IV
to an estimated $23M. Data on operating costs are not yet available. However, the costs
per flight hour of operating a G-IV are expected to be only slightly higher than those for
the Sabreliner.

To end his presentation, Cooper described the form that an NCAR G-IV aircraft
might take in its basic research configuration, as shown in Fig. 6. The advanced avionics
instrumentation would include a Global Positioning System (GPS), as well as a laser-based
Fig. 6. Prospective research configuration of Gulfstream IV (G-IV) aircraft.
inertial navigation system (INS). These would give major improvements in positioning accuracy compared with current systems. A radome gust probe would provide air-motion sensing via a five-hole pressure sensor\(^\text{13}\), but the radome would be kept as close to the standard shape as possible in order to minimize adverse aerodynamic effects. The radome would enclose a modern C-band weather radar with as large an antenna as possible, probably a 30-inch flat plate. To avoid the possibility of ice ingestion into the engines, sensor mounting locations around the radome would only be used when there is no chance of icing, and the radome would be anti-iced. Particle Measuring Systems (PMS) hydrometeor and aerosol spectrometer probes would be mounted on removable underwing pylons.

Other key features include overhead fuselage apertures for mounting of various specialized sensors; fuselage hardpoints on top, bottom, and forward fuselage for installation of radar antennas or other apparatus that must be located outside the fuselage; large viewports or optical apertures for use as lidar windows, camera ports, or radiometer windows; a tail boom that might be used for 360-degree rotation of sensors such as radiometers or field mills; window blanks for possible use as mounting plates or camera ports; a chute for deploying dropwindsondes or other expendables such as AXBTs;\(^\text{14}\) and (possibly) a cargo door to facilitate equipment loading.

For atmospheric chemistry measurements, several air inlets and exhaust ports would be installed on the aircraft. One main system might be a flow-through system bringing air into and out of the cabin, to which various devices could be attached as needed. The high and variable speed of a mid-sized jet will require that these inlets be designed to control losses and minimize contamination. (Because the G-IV engines are rear-mounted, there is

\(^{13}\) A possible alternative to a radome gust probe could be a Laser Air-Motion Sensing System (LAMSS). This instrument would measure three-dimensional air motions 10 to 100 m ahead of the aircraft using a laser Doppler technique, with either two crossed beams or a single conical-scanning beam. Preliminary design studies have shown that LAMSS appears to be feasible and could have significant advantages over existing gust probes. However, this instrument is not yet under development, and thus the technology may not be available at the time that the new mid-sized jet is instrumented.

\(^{14}\) AXBT = Aircraft Expendable Bathythermograph

36
little danger of contamination at any of these locations by the engines. The cabin floor area with convenient access to contaminant-free outside air on a G-IV actually exceeds that on the Electra because the G-IV engines are so much farther aft.) Engine-driven venturi systems would also be installed to provide vacuum sources for chemistry measurements.

Cooper stressed that one of the overriding concerns in configuring a G-IV would be to keep the aircraft as aerodynamically “clean” as possible so that performance degradation would be minimized. Toward this end, all equipment mounted on the exterior of the aircraft would be designed to minimize drag (perhaps with the aid of special wind-tunnel tests), and would be removable to the extent possible. In this way, each project could be flown with the aircraft in an optimum configuration for achieving maximum performance.

3.3 Storm-Penetration Aircraft

Byron Phillips, former RAF Manager, described the impetus behind the preparation of Workshop Document 3, and reviewed its contents. This document was prepared by an NCAR study group, chaired by Phillips in response to a request from the NSF that the storm-penetration category of research aircraft be reviewed at the workshop. NSF’s request, in turn, was motivated by one of the major recommendations from an NSF Special Advisory Panel, chaired by Stanley A. Changnon, which met in Rapid City, South Dakota in May 1985 to assess the needs of the atmospheric sciences and make recommendations regarding aircraft capable of penetrating convective storms. Among the resulting recommendations, which are listed in full in Appendix C, were two of particular importance:

- The T-28 storm-penetration aircraft owned and operated by the South Dakota School of Mines and Technology (SDSMT) should be upgraded over a two-year period, and flown as a national facility aircraft for an additional three-year period.

- Planning should begin immediately for the acquisition and development of a more capable storm-penetration aircraft for replacement of the T-28 within five years.
The second recommendation above was the basis for NSF's and NCAR's interest in including this category of aircraft in the current workshop.

Phillips next discussed the background of storm-penetration aircraft and traced their evolution. Many aircraft have been instrumented and used for cloud and meteorological research; however, only a few of these have been capable of surviving penetrations of thunderstorm cores. Today only the T-28, operated by SDSMT with base funding from the NSF, and the F-106, flown by NASA-Langley, have been hardened for storm penetration and are being used for storm-core research. The T-28 is armored for impacts of hailstones of up to three inches in diameter, and is used under ground-radar control for storms with radar reflectivities up to 55 dBZ. The NASA F-106 has been used for lightning-strike-to-aircraft research during ground-radar-controlled penetrations of storm cores with reflectivities up to 50 dBZ.

Penetration aircraft were also flown by NOAA during the 1960s and 1970s in conjunction with NASA-Langley and the USAF Aeronautical Systems Division. Radar-vectored storm penetrations were made using a variety of military-type aircraft. In addition, Colorado State University has used an F-11B aircraft for over five years in support of the National Hail Research Experiment (NHRE) and other research programs.

The SDSMT T-28 was armored and instrumented for hail research in the late 1960s. It has been in research use for nearly 20 years. Recognizing the age and flight limitations of the T-28, in 1985 the NSF convened the Special Advisory Panel mentioned earlier.

Stressing that the current workshop was a good opportunity for the participants to take another look at the science needs for a storm-penetration aircraft and to evaluate what type of aircraft would best fill these needs, Phillips went on to describe the assessments of the NCAR study group in this regard. Table 9 lists the various areas of atmospheric research in which a storm-penetration aircraft is needed, along with an appraisal of the
### Table 9. Research categories requiring storm penetration aircraft, and type of aircraft required.

<table>
<thead>
<tr>
<th>Research Category</th>
<th>Aircraft Type&lt;sup&gt;14&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation formation processes</td>
<td></td>
</tr>
<tr>
<td>Hail embryos</td>
<td>A</td>
</tr>
<tr>
<td>Hail growth</td>
<td>A</td>
</tr>
<tr>
<td>Mesoscale convective systems</td>
<td></td>
</tr>
<tr>
<td>Convective core precipitation</td>
<td>A</td>
</tr>
<tr>
<td>Stratiform rain</td>
<td>B</td>
</tr>
<tr>
<td>Ice trajectories through storms</td>
<td>B</td>
</tr>
<tr>
<td>Hail suppression issues</td>
<td>A or B</td>
</tr>
<tr>
<td>Ice origin and evolution</td>
<td>B</td>
</tr>
<tr>
<td>Lightning</td>
<td>B</td>
</tr>
<tr>
<td>Precipitation modification</td>
<td>B</td>
</tr>
<tr>
<td>Storm structure and dynamics</td>
<td></td>
</tr>
<tr>
<td>Hailstorms</td>
<td>A</td>
</tr>
<tr>
<td>Mesoscale convective systems</td>
<td>A</td>
</tr>
<tr>
<td>Isolated thunderstorms</td>
<td>A or B</td>
</tr>
<tr>
<td>Entrainment/mixing processes</td>
<td>B</td>
</tr>
<tr>
<td>Squall lines and tornadic outbreaks</td>
<td>A</td>
</tr>
<tr>
<td>Microbursts/strong downdrafts</td>
<td>A</td>
</tr>
<tr>
<td>Remote sensing verification</td>
<td>A</td>
</tr>
<tr>
<td>Electrification mechanisms</td>
<td>B</td>
</tr>
<tr>
<td>Cloud chemical processes</td>
<td>B</td>
</tr>
</tbody>
</table>

<sup>14</sup> See text for definition of aircraft type.
type of aircraft required. The aircraft type is broken down into two broad categories, defined as follows:

**Type A:** An aircraft hardened for lightning and penetration of large hail (two-inch diameter) and lightning, and stressed for maneuver loads of + 5, - 4 g or greater (e.g., a military aerobatic-type aircraft)

**Type B:** An aircraft capable of penetrating hail to one inch in diameter, tolerant of lightning, and stressed for maneuver loads of + 2-1/2, - 1 g (e.g., a standard civilian production aircraft).

Phillips stated that a storm-penetration aircraft is needed to take important measurements in the regions within storm cores where the reflectivity exceeds 35 dBZ, since the current NCAR aircraft do not normally operate in these regions because of the hazards of hail, severe turbulence, lightning, and heavy icing. He then described several types of aircraft requirements drafted by the study group, as follows:

- **Research requirements:**
  - Altitude: 40,000 ft in research configuration
  - Endurance: 3 hours plus IFR reserves
  - Scientific payload: minimum of 4,000 lb, plus crew
  - Penetration speed: less than 250 kt (indicated airspeed)

- **Operational design requirements:**
  - Stressed for + 5 g, - 3 g maneuver loads or greater (e.g., a military aerobatic-type aircraft).
  - Hardened for accidental encounters with flight into 2-in diameter hail.
  - Hardened for lightning.
- Engine reliability against loss due to hail, heavy rain, lightning, or ice ingestion.

- Flight-control-system reliability and proper performance at all altitudes and speeds during storm penetration.

- No aircraft structural damage from hail, gust loads, or lightning encountered in storms.

- Minimal aircraft skin damage from 2-in diameter hail impact at normal storm penetration speeds.

- Ready access to certified aircraft instruments, parts, and engines, and to overhaul and maintenance facilities necessary to maintain the aircraft. For a military-type aircraft, this requires that the aircraft should currently be in the active National Guard, Air Force, or Navy inventory and expected to remain on such inventory for the foreseeable future. Agreements and arrangements with the Department of Defense (DOD) will be required.

• Safety requirements:

  - Availability of an aircraft escape system (ejection seats/parachutes).

  - On-board crew limited to two to four persons (including scientific and technical personnel) who are properly trained for emergency procedures. (The aircraft escape margins within a severe storm can become marginal.)

  - On-board research/storm navigation radar.

  - Air-ground-air voice communication link of maximum reliability.

Next, the various candidate aircraft that might meet these requirements were discussed. The NCAR study group concluded that the requirements are so demanding that the choice should be restricted to an aircraft of military aerobatic design. Aircraft of this
type were surveyed, and four were selected as being the best candidates: the Grumman A-6, the General Dynamics F-111, the Lockheed S-3A, and the Convair F-106B. Of these, the first two were selected for detailed study, and were described briefly by Phillips.

The Grumman A-6 series is a two-place, twin-jet, mid-wing, subsonic aircraft originally designed in 1957 as a carrier-borne low-level attack bomber. It is in current fleet inventory (A-6E "Intruder" model) with several variants including a KA-6D tanker, and an EA-6B "Prowler" electronic countermeasures aircraft. The EA-6B includes the addition of two seats and will thus accommodate a total of four crew members.

The A-6E aircraft is equipped with two PWJ52-P-8B turbojet engines carried symmetrically in the lower fuselage. A primary fuel tank occupies much of the central fuselage. A large amount of electronic equipment (related to armament and counter measures) would need to be removed to convert the aircraft to research use. The wing span and length are 16.2 m and 16.7 m, respectively. The wings fold (span folded is 7.7 m). The aircraft has five attachment points – two on each wing and one centrally mounted on the fuselage – each capable of carrying 3,600 lbs. The empty weight is 26,660 lbs, and the maximum take-off weight is 60,400 lbs. The endurance on internal fuel is over three hours plus reserves. With maximum external fuel (an additional 10,000 lb in five tanks), the aircraft maximum range is 2,800 NMi. The service ceiling (without external pods) is 42,400 ft. The cruise speed of the A-6E is 420 knots, the flaps-up stall speed 142 knots. The aircraft is equipped with two 30-KVA electrical generators. A recent directive has been issued grounding part of the A-6E fleet due to wing cracks. This should be corrected within standard U.S. Navy practices.

The EA-6B variant is heavier, but has an increased service ceiling of 44,500 ft due to increased engine performance (the aircraft has J52-P-408 engines). Equipped with five external store pods (maximum drag), the EA-6B service ceiling is 38,000 ft. (The service ceiling in a research configuration with intermediate drag would likely be near 40,000 ft.)
The A-6 is a durable high-performance aircraft, currently in the active inventory of the U.S. Navy and Marine Corps, and is still in production. A support base of parts, maintenance facilities, and knowledgeable technicians will be available for the foreseeable future. Diagrams of the A-6 (two-place) and the EA-6B (four-place) aircraft are shown in Fig. 7.

Phillips then described the General Dynamics F-111. The F-111 is a two-place, twin-jet, supersonic fighter-bomber designed in the early 1960's under contract with General Dynamics, with Grumman Aircraft as an associate. The outer-wing sweep angle is variable in flight or on the ground from $16^\circ$ (spread) to $72^\circ$ (swept). The fuselage is constructed of aluminum alloy with a honeycomb-sandwich skin, and is designed with an internal weapons bay. The engines are after-burner-equipped PWTF300-P-100 turbofans (25,000 lb static thrust each). The wing span is 19.2 m (half this when swept), and the aircraft length is 22.4 m. Fuel tanks are internal in the wings and fuselage. The empty weight is over 47,000 lb, the maximum take-off weight 100,000 lbs. External stores can be carried on eight underwing attachment points. The service ceiling without external stores is 59,000 ft. Views of the F-111 in extended- and swept-wing configurations are shown in Fig. 8.

From the data now available, the F-111 appears to be a higher-performance but more complex aircraft than the A-6. Interest in the F-111 is derived in part because an F-111 is owned by NASA, and the NASA mission for the aircraft is winding down. The aircraft, therefore, could become available. NASA personnel have suggested that the variable-geometry wings would permit reasonably slow penetration speeds with the wings spread. Modifications which significantly change the aircraft’s aerodynamics may be difficult because of the aircraft’s maximum speed.

Phillips concluded that it was still too early to select one of these aircraft as best for use in storm penetrations. Too little is known of their respective characteristics, such as construction, size and access of electronic bays, de-modification and modification costs, need for armament against hail, and engine and flight-control reliability. The decision
Fig. 7. Pictorial views of two-seated Grumman A-6 “Intruder” (top) and four-seated Grumman EA-6B “Prowler” (bottom).
Fig. 8. Pictorial views of General Dynamics F-111 two-seated tactical fighter-bomber.
regarding which aircraft to acquire and modify for storm penetration should follow a careful examination of these factors.

In the end, aircraft availability may dictate which aircraft is acquired. The A-6 and F-111 series aircraft are both currently within the active DOD inventory, and both appear suitable for modification and use as penetration aircraft. These are both all-weather attack bombers designed to fly in adverse weather with large payloads, are both highly maneuverable with aerobatic qualities, and both have crew ejection systems. They are thus in high demand for use by the military. It is assumed that one aircraft of one of these types covered can be obtained on loan or bailment from DOD. This would require that use of the aircraft for storm research be given a high priority.

Phillips also described the preliminary development plan for a storm-penetration aircraft as prepared by the NCAR study group. Under this plan, the development program would consist of the following three phases, with estimated costs as indicated:

- Phase I–Aircraft selection and acquisition ($100K, assuming aircraft is acquired under a bailment or extended loan from a DOD agency)
- Phase II–Engineering and accomplishment of aircraft modifications ($600K to $900K)
- Phase III–Aircraft research instrumentation ($1.4M to $1.6M).

The total cost of bringing a storm-penetration aircraft up to operational research status in the NCAR fleet would thus be in the range from $2.1M to $3.6M.

Phillips stated that, since a penetration aircraft would be a special-purpose instrumentation platform with unique instrumentation requirements, the study group believed that all candidate sensors for the aircraft would need to be adapted for measurements at
high penetration flight speeds and in severe storm conditions. In addition, new sensor developments would need to be adequately funded and vigorously pursued.

Some of the research instrumentation systems that are expected to be flown on the penetration aircraft are as follows:

- GPS-INS navigation system
- Data acquisition, recording, and display system
- Differential-pressure air-motion sensor
- Hydrometeor spectrometer probes
- Radiometric sensors
- Near-field humidity sensor
- Total-water-content/liquid-water-content sensors
- Holographic camera
- Downward-looking mm-wavelength radar
- Electric field, conductivity, and hydrometeor-charge sensors
- Air-to-ground and ground-to-air data-telemetry link.

Sensor improvement or development would be needed for nearly every system listed. Addressing these needs would be essential to the success of the penetration aircraft effort.

Phillips closed his presentation by noting that interagency collaboration would be desirable and probably necessary for the development and operation of a storm-penetration aircraft. This activity would represent a major initiative for NSF. The operating facility would need to depend on DOD for parts, maintenance, and flight training. The sensor and system developments could benefit from the ideas, engineering skills, and funding resources of the entire community. NOAA clearly has interests in severe storm research.
that are parallel to those of the NSF community. The aviation hazards presented by thunderstorms are major concerns of DOD, FAA/DOT, and NASA. NASA is planning an atmospheric aircraft hazards program that would be carried forward with FAA and DOD cooperation. A storm-penetration aircraft is a requirement for this program.

For these reasons, Phillips suggested that the NSF community should examine the possibility of cooperative multiagency support and usage of a penetration aircraft. Clearly a cooperative program which includes NASA, NOAA, FAA, and DOD would provide additional scientific and engineering priorities that would help in the critical step of obtaining an appropriate aircraft from DOD, along with the continuing support necessary to keep the aircraft operational. Although working out the necessary multiagency arrangements for cooperative funding and usage of a storm-penetration aircraft might be difficult, the long-term benefits to each agency would justify these efforts.
4. Researchers’ Views on Science Needs for Aircraft Platforms

4.1 Boundary-Layer and Surface-Exchange Processes (Carl Friehe)

Carl Friehe discussed needed measurements for study of the atmospheric boundary layer and of exchange processes at the earth’s surface. He reviewed the measurement needs, which include requirements for routine measurement of dynamical and thermodynamical properties of the boundary layer, for measurements of turbulent fluxes, for remote determination of the height of the boundary layer, and for application of Doppler lidar, remote profiling of temperature, and terrain-following radar. A combination of local and remote sensors is attractive for boundary-layer studies because two data sets can be collected simultaneously, one in-situ and one extending above or below the aircraft. Two aircraft types are needed, a King Air or similar aircraft for single-investigator studies over land or coastal oceans, and a multi-engine aircraft with long range for boundary-layer measurements over remote portions of the ocean.

4.2 Air-Sea Interaction and Oceanography (John Bane)

John Bane discussed the needs for aircraft in the oceanography community. He mentioned the need for mapping of the ocean surface topography with positioning accuracies of centimeters in the vertical, and for measurement of wave structure and ocean color. He also discussed the needs for measurements of the interactions between the air and the sea and for study of surface stresses and fluxes. An important need of this community is to be able to deploy (drop) in-situ sensors from aircraft and to receive their telemetered measurements. While AXBTs are the prime example at present, further developments of other deployable, expendable sensors are needed and expected.

The needed aircraft include a long-range aircraft (of the P-3 or Electra class, although greatly extended range for mid-oceanic studies is also desirable), an aircraft such as a C-130 with large payload for deployment of expendable sensors, a medium-range aircraft (perhaps of the Gulfstream I class) for studies over the continental shelf, and a very
slow-moving aircraft for studies near the ocean surface and for water sampling. Aircraft usage within the oceanography community is likely to increase as scientists in this field become more familiar with the usefulness of aircraft in their research programs.

4.3 Radiative Processes and Air/Ground Truth (William Smith)

Some of the instrumentation needs for remote sensing and for measurements of radiation in the atmosphere were described by William Smith. He mentioned needs for pyranometers and pyrgeometers that cover full hemispheres, and for high-speed multispectral measurements to measure surface temperatures and other surface characteristics. Lower-resolution spectrometers, viewing infrared interferometers, microwave imagers and sounders, and other remote sensors were also discussed as desirable aircraft instruments. He suggested that the priority aircraft for these studies is a mid-sized jet because of its ability to carry appropriate payloads to high altitudes and over long flight segments.

4.4 Cloud Physics and Weather Modification (John Hallett)

John Hallett emphasized the high-altitude needs in cloud physics, and pointed out that we only cover lower levels of clouds effectively with the aircraft currently available. Time-on-station is also often a limiting factor, especially in studies of marine regimes and diurnal cycles. An aircraft resistant to lightning is essential, and an effective aircraft for studies in cloud physics must be able to work in environments where lightning, turbulence, icing, and hail pose hazards. He argued that there are significant opportunities for important studies in the upper troposphere, and that aircraft presently available cannot support the needed studies.

4.5 Mesoscale Convective Systems (Edward Zipser)

Edward Zipser suggested that large mesoscale programs need 3 to 10 aircraft to be able to cover the mesoscale storm systems effectively. There is a wide variation in the severity of mesoscale storm systems, but he suggested that many could be studied
effectively without need for a specially-hardened storm-penetration aircraft. Particularly at high altitude (>10 km), hazards are often low enough so that conventional aircraft can work safely, provided that they are able to detect or receive information on the severity of the elements they plan to penetrate. While a storm-penetration aircraft is needed for study of severe storms, he thought that such an aircraft might not be required in studies of most mesoscale convective systems. Particular needs include a high-altitude capability, good communications and transfer of information to and from the aircraft, a payload capability adequate to support extensive remote sensing, and an ability to work in environments where there is lightning, icing, and severe turbulence. Long range and endurance are also desirable characteristics for aircraft used in these studies.

4.6 *Meso- and Synoptic-Scale Dynamics (Carl Kreitzberg)*

Carl Kreitzberg pointed out that the domain of interest in these areas of research is large, with a scale size of order 3,000 km. It is difficult for aircraft to provide the comprehensive data sets needed by meteorologists who are studying cyclonic-scale systems. This need might be met better through automatic reports from instruments on commercial aircraft, and such aircraft might also be used to release “safe” dropwindsondes. He emphasized the need for good communications (both by voice and for data transmission), and suggested that in-situ and remote sensors need improvement particularly with regard to measurements of altitude, position, fluxes, and in-cloud and near-saturated humidity. He mentioned that a mid-sized jet (if it were available) would be very useful for the ERICA Project during the winter of 1988-89.

4.7 *Troposphere-Stratosphere Interactions (Ron Smith)*

Ron Smith discussed the need for airborne measurements at altitudes above those of the jet stream, and stressed that aircraft capable of achieving altitudes above 40,000 ft are essential in such studies. Aircraft measurements at such altitudes are also needed for
interpretation of measurements from satellites (e.g., ozone mapping by TOMS\textsuperscript{15}). He discussed the need for simultaneous measurements of several gaseous species and of aerosols, and therefore for an appropriate payload and cabin volume to support the needed complement of sensors. He also argued for development of airborne remote sensors for measuring potential vorticity, radiation, and temperature profiles.

Because the chemical composition of the atmosphere changes rapidly with height above the tropopause, it is important to be able to measure gradients and interactions among species in this region and to reach altitudes that are as high as possible. Also, because tropopause folds may cause important variations in properties on a scale of \(<10 \text{ km},\) the sensors need to have relatively fast response. Smith’s recommendations thus included not only a new aircraft with higher ceiling, increased payload and cabin space, improved all-weather capability, and longer range and endurance, but also new capabilities in instrumentation and real-time data processing and display.

4.8 Gas-Phase Transformations of Atmospheric Chemicals (Brian Ridley)

Brian Ridley discussed the need for a wide array of simultaneous measurements for studies in atmospheric chemistry. He argued that such goals as determination of oxidation rates and rates of production or depletion of ozone could not be achieved without using many instruments together on one aircraft. These needs point to a payload at least three times that of the Sabreliner, and for an ability to reach high altitudes to provide realistic data for tests of chemical models. The Global Tropospheric Chemistry Program may need 150 to 200 flight hours per year over the six-year (or longer) duration of the program. Because of these anticipated needs, he favored an increase in Electra flight hours over new acquisitions of aircraft if a choice must be made.

\textsuperscript{15} TOMS = Total Ozone Mapping Satellite
Other needs are for good air conditioning, sampling apertures adapted to the needs of each instrument, and UV sensors to document the radiation environment in which photochemical transformations occur. While an aircraft of the G-IV class could meet some of the high-altitude needs, Ridley suggested that the size of such an aircraft was marginal and that the real needs are for a still larger aircraft.

4.9 Conversion, Redistribution, and Removal of Atmospheric Gases and Aerosols (Barry Huebert)

Barry Huebert indicated that there is a set of needs common to many atmospheric chemistry programs: large cabin space and payload for multiple-investigator programs, adequate power for pumps and instrumentation, multiple unobstructed inlet locations, endurance of 6 h or more, range to cover such legs as California to Hawaii, and good air-motion sensing to support measurements of fluxes. It is also desirable to have a ceiling of >30,000 ft, good cabin-pressure control, and adequate air conditioning to handle the heat load from pumps and other equipment. He pointed out that some aspects of studies of conversion and removal processes are more difficult in a fast-moving aircraft. For example, cloud-water collection may become harder at high speeds.

He saw little use for a Gulfstream I in such studies because of its small cabin, and also considered the mid-sized jets to be marginal in size. He favored increasing the hours available on the Electra to support these studies, and suggested acquiring a second Electra if needed to support the demand for large aircraft.

4.10 Biological Sources and Global Distributions of Atmospheric Chemicals (Jarvis Moyers)

For these studies, Jarvis Moyers said that vertical profiles of chemical constituents in the atmosphere are needed, and such measurements need to be made frequently and routinely. Small aircraft are adequate in many cases, and are particularly well suited to exploratory studies. There are also needs to determine large-scale spatial and temporal
distributions and to make comprehensive sets of measurements, and these require a large aircraft of the Electra or C-130 class for the lower and middle troposphere and a mid-sized or larger jet for the upper troposphere. These studies need to obtain comprehensive measurements of the detailed chemical composition of the atmosphere, and so typically are large multi-investigator programs. They also require long-range flights to measure large-scale variations and to reach regions of interest. Moyers also emphasized the need for new instruments for measurements of fluxes of chemical species, particularly in studies of surface exchange processes.

4.11 Other Points Raised in the Group Discussion

The following are some questions and points raised in the group discussion following the presentations. Many of these were left as questions to be addressed in the working groups.

- How strong is the need for high-altitude (>40,000 ft) flight? A serious commitment to filling this need rules out many aircraft that are otherwise candidates, and increases the expense of the acquisition. Ron Smith was particularly strong in advocating the need for flight to altitudes of 40,000-50,000 ft, where vertical gradients of many variables are large and especially important to quantify.

- Can a mid-sized jet support the missions that have been proposed for the Gulfstream I? (A jet has disadvantages of greater speed and operating cost at low altitude, but it appears that a fanjet such as the Gulfstream IV could perform any mission that the G-I could do, at an acceptable airspeed and cost.)

- Is a military-class aircraft required for a penetration aircraft because of the stresses encountered? (The material prepared for the workshop indicated that this is a requirement.)
• How important is the need for penetrations of severe storms at high altitude, and what is the maximum altitude at which cloud penetrations are needed? (This affects the choice among the candidates for a storm penetration aircraft.)

• To what extent are mesoscale convective systems and other severe storms amenable to study by non-penetrating aircraft?

• There were a number of comments to the effect that real performance values for a research-configured aircraft are needed, not just “book” values from the manufacturer.

• John Hallett commented that important chemical processes are associated with clouds and especially with precipitation, and that the upper half of the troposphere is quite important in precipitation formation. Some atmospheric chemists responded in agreement that the upper half of the troposphere cannot be ignored, but also commented that most reactive elements of interest are emitted at the earth’s surface so most chemistry studies focus on the lower troposphere.

• Alan Bandy questioned the cost-effectiveness of developing the Gulfstream I. He argued that the expense of that development would be better spent in increasing flight hours on the Electra, and pointed out that the G-I is not a particularly efficient aircraft to operate.

• Brian Ridley and others raised the possibility of NCAR acquiring a DC-9 or other large jet. RAF responded that, because of runway weight limits, such an aircraft could not be operated from the Jeffco airport where NCAR is currently based. Therefore, such an acquisition would mean major changes in the ways that RAF operates and maintains aircraft, and would force a move to another airport. It was agreed that the DC-9 deserves further consideration, however, because a used DC-9 can be acquired at a cost comparable to that of the more expensive mid-sized jets.
• There was some discussion of the real need for atmospheric chemists to fly such large instruments, and a segment of the audience suggested that “they should miniaturize as we have.” In response, Alan Bandy and others pointed out that a continuing challenge is to increase the sensitivity of the instruments, and so new instruments being developed for this purpose are inherently state-of-the-art prototypes. These instruments are large of necessity, and in fact would be larger in many cases if their size were not limited by the aircraft platform. The size of the instruments is likely to increase, not decrease, since more sensitive instruments are needed to address the developing scientific questions.

• There was a brief discussion of the need for NCAR to develop aircraft types similar to those operated by NASA (e.g., DC-8 and ER-2). Some commented that, while it was possible for investigators to gain access to those aircraft, such usage had to be in a NASA-sponsored program addressing NASA aims. It is difficult for university investigators to design a program and obtain the DC-8 for participation in that program. Bob Serafin commented that it seemed to be more appropriate for NCAR to develop facilities that complemented rather than duplicated other facilities. Some NOAA scientists commented that the NOAA P-3s are also available to the community, and further use of those aircraft seemed to be more efficient than acquisition of a second Electra by NCAR. The mid-sized jet, however, would offer new capabilities not now available through either NOAA or NCAR.

• There were many comments, within and following the presentations, that indicated the need to consider aircraft instrumentation as well as aircraft platforms. Many of the speakers mentioned instrumentation needs, and there was some sentiment for the idea that instrumentation development should be given priority over the acquisition of new platforms. The NCAR position (as stated by Bob Serafin and...
Warren Johnson agreed with the need for instrumentation developments, but advocated a broader approach in which the platforms and instrumentation would be developed together to result in integrated new measurement systems.
5. Summary of Working Group Discussions

5.1 Charge to the Working Groups

Following the presentations and discussions on the science needs for research aircraft, four working groups were established. Each of the first three working groups was asked to evaluate how well a specific type of aircraft would satisfy the science needs expressed earlier. Working Groups 1, 2, and 3 were assigned the evaluation of (1) a mid-sized turboprop aircraft, (2) a mid-sized jet aircraft, and (3) a storm-penetration aircraft, respectively.

Working Group 4 was asked to determine if any other aircraft types might be serious candidates for acquisition. Each workshop participant was given free rein to join the working group in which he/she had the most interest, rather than being arbitrarily assigned to one of the groups.

The specific charge to the working groups was to develop answers to the following questions:

1. What is the science served? What role does the aircraft play in the fleet?

2. How should the aircraft be configured? Should the configuration be similar to the current RAF aircraft? What improvements should be made in:
   - Sensing systems?
   - Navigation/positioning systems?
   - Data processing systems?
   - Communications systems?

3. How important is this aircraft to the atmospheric science community in relation to the other aircraft being considered at the workshop?
(4) Are there acceptable alternatives to acquiring this aircraft?

Brief summaries of the discussions, conclusions, and recommendations of each of the four working groups are provided in the following sections.

5.2 Working Group 1—Mid-Sized Turboprop Aircraft (John Winchester, Chair)

5.2.1 Science needs served

It was decided that this discussion should be broadened to include various sizes and types of turboprop aircraft (e.g., G-I, Electra, King air, etc.), since each type of aircraft serves particular science needs. The science community is generally pleased with the present fleet, but some deficiencies were noted with the existing aircraft. For example, the King Air is too small for many chemistry studies, is too slow for some mesoscale boundary-layer programs, and cannot take lightning strikes without requiring expensive inspections. The existing RAF aircraft are frequently oversubscribed, and increasing the flight hours available would allow the aircraft to serve more of the science community. However, this step would obviously require additional funds in the RAF budget. The participants agreed that an additional aircraft was clearly desirable to help satisfy the many outstanding needs of the atmospheric science community.

The capabilities of various types of aircraft were then discussed with the purpose of matching these capabilities with the needs in particular areas of atmospheric science, especially the following:

- Boundary-layer meteorology
- Mesoscale meteorology
- Cloud physics and atmospheric electricity
- Atmospheric chemistry (regional and global)
• Oceanography and air-sea interaction.

Much of the discussion centered around how well a mid-sized turboprop aircraft, such as a Gulfstream G-I, would fill these needs compared with other types of aircraft.

It was pointed out that currently, for mesoscale and cloud convection studies, there is a shortage of aircraft that can fly into active convective regions. A G-I might be a suitable aircraft for this. It would be useful to employ two aircraft at different altitudes since convective evolution occurs rapidly.

The group discussed in depth the concept that a mid-sized jet aircraft might be able to cover many of the science needs as well or better than a mid-sized turboprop. For example, low-altitude boundary-layer studies could be handled satisfactorily with a Gulfstream G-IV jet aircraft because of its high-bypass fanjet engines.

The oceanographic and air-sea interaction community expressed a desire in acquiring access to a long-range aircraft that could participate in the large field programs currently being planned. This aircraft would need to fly at low to medium altitudes, and would need to be able to acquire turbulence measurements and to deploy expendable probes. This aircraft would be expected to be versatile enough to serve boundary-layer and air-sea interaction experiments, FASINEX\(^6\)-type mesoscale meteorology experiments, as well as larger-scale studies of cyclogenesis developments.

The atmospheric chemistry representatives also recommended acquisition of a large aircraft having a payload capacity adequate for large chemistry packages and pumps, that would be suitable for participating in multiple aircraft programs, and that also had the capability to provide remote-sensing measurements for boundary-layer studies.

\(^6\) FASINEX = Frontal Air-Sea INteraction EXperiment
5.2.2 Role played by the aircraft in the RAF fleet

One of the points brought out in this discussion is that the G-I mid-sized turboprop aircraft has severe altitude limitations that would compromise its usefulness. On the other hand, the G-IV jet aircraft could work well at both low and high levels, has a good range, could fly boundary-layer experiments as well as many other types of studies, and probably would be more cost effective than the G-I if only operational costs were considered. Other factors are that a G-IV could take pressure off the oversubscribed King Air, and would serve as a logical replacement for the almost-obsolete Sabreliner.

The working group agreed that more flight hours are necessary on the Electra. An alternative could be to acquire another Electra or perhaps a P-3, and go to a four-aircraft fleet. The atmospheric chemists expressed their concern that the ELDORA airborne Doppler radar development might adversely effect the space and weight available on the Electra for their chemistry programs, as well as make scheduling of the aircraft more difficult. Some of the NCAR staff present suggested that the impacts of ELDORA will be considerably less than what the chemists believe they will be. Concerns were also raised regarding the amount of floor space available on a G-IV aircraft for the extensive instrumentation required for chemistry experiments.

The suggestion was made that other aircraft are available at other institutions, and that more use should be made of these platforms. This raised concerns regarding the difficulties encountered in sharing aircraft, especially aircraft configured with different instrumentation. Also, funding arrangements would have to be identified for operating these other aircraft that did not adversely impact RAF’s ability to continue to operate its current fleet.

5.2.3 Recommendations

Consensus was reached on the following recommendations, which are presented in order of priority:
- Instead of a turboprop, a mid-sized jet aircraft should be acquired. (The existing NSF-owned G-I should not be developed.) A modern fanjet aircraft such as a G-IV or a Falcon 900 offers long range, low- and high-altitude capability, long flight duration, adequate payload, and good fuel economy.

- Increase the availability of the Electra. This means that more funds need to be made available for flying additional hours, and for the additional RAF staff necessary to do this. The Electra is critical to the needs of the atmospheric chemistry community, but also is the only aircraft in the RAF fleet capable of serving as a platform for ELDORA. It is important that the ELDORA system be designed to be as completely and easily removable as possible, to minimize any adverse impacts on the usefulness of the aircraft for atmospheric chemistry (in terms of space, weight, and scheduling). The Electra is also considered very important to the oceanographic community, and will be even more useful as capabilities are added for deployment of additional expendable oceanographic probes.

- Increase the utilization of other aircraft operated by other institutions. Some of the science needs for smaller aircraft can be met by existing aircraft, such as the University of Wyoming King Air and the Battelle Pacific Northwest Laboratory G-I. Realistic and workable agreements should be arranged among NSF, NCAR, and these other institutions to provide funds for staffing and operations, and to provide for allocation of flight time.
5.3 Working Group 2—Mid-Sized Jet Aircraft (Ron Smith, Chair)

5.3.1 Science needs served

The initial discussion of science needs centered on the prospective research application of a mid-sized jet aircraft, using Workshop Document 2 as a guide. Performance characteristics of specific aircraft in this category were reviewed. Early in the discussion, a strong opinion was expressed, primarily by the atmospheric chemists, that a larger aircraft was required, such as a Boeing 737 or a DC-9.

The working group attached considerable importance to the improved altitude capability which a new mid-sized jet would provide to the atmospheric sciences community. Better altitude capability with improved endurance would allow higher profiling, better jet-stream studies (ability to get sufficiently above the jet and associated tropopause folds), better dropsonde capability (more data from higher levels), more complete cloud top data from mesoscale systems, and higher-altitude anvil penetrations (with adequate radar support). The group also thought that, coupled to the need for an improved altitude capability, any aircraft considered would need to have good or at least adequate low-altitude performance, particularly with respect to over-ocean operation.

Based on the specified science needs, the group felt that the Gulfstream G-IV has the best overall characteristics of all the mid-sized jet aircraft considered, especially with regard to endurance and altitude capabilities. In addition, the military version of the G-IV (designed for use in anti-submarine warfare) has good low-level and loiter capability. With regard to altitude capability, resource people from NCAR/RAF informed the group that experience has shown that there is typically a 5-10% degradation in performance when an aircraft is modified for atmospheric research (because of drag from inlets, sensors, etc.). However, with any new mid-sized jet that is added to the fleet, NCAR personnel expect to keep performance degradation well below this value for most research configurations. This
will be accomplished by using demountable sensors and inlets whenever possible, as well as by improving the aerodynamic design of any external hardware that must be added.

As the discussion of the performance characteristics of the G-IV aircraft continued, it was pointed out that this size of aircraft was marginal for some research applications in terms of payload and space available for the user. This limitation could be a problem when dealing with multi-investigator atmospheric chemistry experiments. Several members of the working group felt that a larger aircraft would be required by the atmospheric chemistry community and that perhaps ten to fifteen years in the future the G-IV-type aircraft would not turn out to be the best choice. Resource people from NCAR/RAF pointed out that the altitude ceiling for most of these larger jet aircraft was under 40,000 feet, and thus opting for these aircraft would sacrifice the desired altitude capability in favor of increased payload capability. Others present argued that the G-IV-type aircraft had the advantage of being cost-effective to the single investigator, whether an atmospheric chemist or a meteorologist. It was acknowledged in this discussion that the atmospheric chemistry community would also benefit from the improved altitude capability afforded by the G-IV-type aircraft.

5.3.2 Aircraft configuration

The group members suggested that efforts be made to define and utilize a standard configuration on a G-IV-type aircraft which would minimize drag and performance degradation typically associated with modifications to aircraft for atmospheric research purposes. Such an effort was judged to be important in order to get the maximum performance and altitude from the aircraft. (Of course, the standard configuration could be modified for projects where altitude was not the highest priority.) Several suggestions were made regarding this standard, “low-drag” configuration, including the provision of detachable pylon mounts and the use of common air inlets (however, some chemists present said that using common inlets for their work was not feasible most of the time).
5.3.3 Importance of the aircraft to the community

It was agreed that acquisition of a mid-sized jet aircraft would fill an important gap in the fleet of instrumented aircraft presently available to the atmospheric research community. Such an aircraft would give the community improved altitude capability, improved endurance, and longer range. The only significant sacrifices with this aircraft relative to a larger jet aircraft, e.g., a Boeing 737 or DC-9, are those of payload and cabin volume. With these larger jets the high-altitude capability is sacrificed.

5.3.4 Recommendations

The working group supported the acquisition of a G-IV-type aircraft because of its valuable attributes. However, the group recognized that such an aircraft might not meet all of the payload and cabin volume specifications desired by the atmospheric chemists. In light of this, the group also recommended that improved NSF-community access to the NASA DC-8 would be highly desirable and should be pursued through interagency collaboration on sharing of aircraft facilities.

Although the final group recommendation is in support of acquisition of a G-IV-type aircraft, the group recognized the valid concern regarding payload voiced by several of the atmospheric chemists in attendance.

5.4 Working Group 3—Storm-Penetration Aircraft (Steve Nelson, Chair)

5.4.1 Science needs served

Steve Nelson opened the discussion with a review of the science needs listed in Workshop Document 3 (see Table 9). The group accepted this list as a good summary of the science needs for a storm-penetration aircraft, with only a few (but important) amplifications. In-situ storm-core measurements were considered to be essential for ground-truthing remote sensors and for providing validation of convective models. General agreement was
reached on this point. In addition, it was believed that too narrow a range of applications was being placed on this aircraft by the workshop organizers. Group members believed that many of the tasks listed for the mid-sized jet could be handled more comfortably by the storm-penetration aircraft. Particular emphasis was placed on the investigation of mesoscale convective systems. There was concern that, in normal operation, the mid-sized jet would not be used for routine penetrations of the 30-dBZ regions in storms, as had been indicated in Workshop Document 2. On the other hand, it would be straightforward for the storm-penetration aircraft to cover this type of operation.

V. N. Bringi was given ten minutes for a brief presentation of radar data from the MIST\textsuperscript{17} program. The data pointed to the 6-10 km height range as being an area of critical concern in the development of hail within severe storms. These altitudes are outside the operational range of the SDSMT T-28, and represent a large gap in current aircraft capabilities. He stated that in-situ ground-truth measurements are needed to evaluate the new-generation radar systems which have been specifically designed to differentiate between hydrometer states.

5.4.2 Aircraft configuration

Rather than trying to select a specific aircraft, the working group concentrated instead on defining the desired characteristics for a storm-penetration aircraft. The necessary capabilities of 40,000-ft ceiling; 3- to 4-hour endurance; 2-man flight crew (pilot and trained science officer); and airframe hardening for lightning and large-hail protection clearly limited the choices to a military aircraft. The scientific payload would have to include both research and hazard-avoidance radar, a very accurate GPS navigation system, a high-rate data system, accurate cloud-temperature and supersaturation sensors, and upgraded PMS-type particle-sampling probes. Good air-to-ground communications would also be essential.

\textsuperscript{17} MIST = MIcroburst and Severe Thunderstorm
All of the prospective military platforms have a relatively large payload capacity. A fair amount of instrument development would be needed, however, because these aircraft typically are severely limited in internal cabin space. The instrumentation packages probably would have to be rugged, stand-alone systems that could be mounted in large external wing pods.

5.4.3 Importance of the aircraft to the community

A storm-penetration aircraft with the capabilities described would fill a major gap in the existing research facilities available to the international atmospheric science community. The SDSMT T-28 is getting old and cannot reach the altitude range at which measurements are essential for the understanding of severe storms. Drones are not feasible operationally and no other facility maintains such an aircraft. The group thought that a collaborative effort with other agencies, such as NASA or DOD, should be investigated, but recognized the difficulties involved in developing an adequate arrangement. However, some form of support from DOD will be essential in any case considering that a military-type aircraft is required.

Since the development of any new aircraft platform will affect the airborne sciences well into the future, the use of such a platform should be extended into much broader applications. The improvement and miniaturization of many key dynamic and air chemistry measurement systems would greatly expand its capabilities.

5.4.4 Recommendations

The group recommended that RAF actively pursue the acquisition or the cooperative development of a military-type storm-penetration aircraft. The group would like to see the funding for such an aircraft included in NCAR's near-term budget planning.
5.5 Working Group 4—Other Aircraft (James Dye, Chair)

5.5.1 Characteristics of other potentially useful aircraft

Several types of aircraft were discussed in terms of the roles they might fill in airborne science and their advantages and disadvantages. The aircraft discussed were long-range, long-endurance P-2/P-3 types; motor gliders; “flying box” types of platforms; small aircraft such as Cessna 180s; instrumented remotely piloted vehicles (RPVs) or drones; and lighter-than-air aircraft such as blimps.

Long-range, long-endurance (~15 hours) aircraft would be useful for studying evolutionary atmospheric processes, such as diurnal variations of stratiform clouds over the Pacific. Such aircraft would also have applications in radiation, cloud physics, and chemistry studies. Dirigibles would also be useful for long-duration studies and have the advantages of being able to perform true Lagrangian-type studies. They could also act as instrumented platforms that could be used for comparison of measurements with other aircraft. It was recognized, however, that blimps are extremely expensive to purchase and operate, and that this factor would probably prevent their use.

Motor gliders, which are being used extensively in European countries, were also discussed. Their slow speed, maneuverability, and low cost are significant advantages. Miniaturized data acquisition systems and inertial navigation systems have been installed on some of these aircraft, rendering them capable of making flux measurements. It was agreed that these types of aircraft could provide university departments with an inexpensive platform for making useful measurements, as well as for training students.

Drones or RPVs were discussed as appropriate vehicles for penetration of severe storms. Their most severe limitation is that they can only fly over restricted test ranges. It was also pointed out that drones would become relatively expensive after being instrumented and therefore probably would not be considered expendable. In spite of these
limitations, however, it was agreed that drones or RPVs might still fulfill a need for testing of cloud physics instruments.

One of the participants felt that there was a need for a "flying-box" type of aircraft that could act as a basic platform and be easily modified for instrument testing. This was perceived to be a less-expensive and perhaps more appropriate platform for this type of activity than a fully equipped pressurized aircraft.

An important theme that ran throughout the discussions was that there is a need in the community for smaller, low-cost, accessible aircraft such as Cessna 172s or 182s or motor gliders for small, individual experiments. These aircraft would also be useful for training graduate students and other personnel in airborne instrumentation and observations. It was suggested that NCAR host a workshop to discuss these needs and propose ways to satisfy them.

Another concern that surfaced in these discussions was the lack of coordination between agencies and institutions that operate research aircraft and the difficulty that university scientists have in obtaining access to some of these facilities. It was felt that this concern needs to be addressed, but it was not clear at what level or by whom.

5.5.2 Recommendations

The working group agreed upon the following recommendations:

- NCAR should host a workshop in the near future to discuss the needs for and approaches for obtaining small aircraft.
- There should be an expansion of efforts regarding interagency cooperation in the area of research aircraft.
- There should be an increased effort by the community in the education of students and scientists regarding instrumentation and observational techniques.
6. Results and Recommendations From Workshop

Following the presentations of recommendations from the four working groups, Warren Johnson moderated a general discussion aimed at reaching consensus on the relative priorities of the various recommendations. To facilitate this process, the participants were asked to vote (by show of hands) on various answers to each of seven multiple-choice questions that were presented serially. To ensure that the results of this procedure were a true reflection of science needs, rather than of programmatic or other needs, the voting was restricted to those who considered themselves "working scientists." Each of the seven questions is reproduced below, along with the number of votes received for each answer. (Because not everyone voted on every question, the total numbers of votes on the various questions were not the same.)

(1) Without regard to the issue of adding aircraft to the NCAR fleet, do you favor augmentation of the NCAR Electra flight operations budget, which currently supports 212 flight hours per year, so that additional Electra flight hours are made available?

(a) Yes 34
(b) No 1

(2) If such augmentation is undertaken, how many additional Electra flight hours should be made available each year?

(a) < 100 0
(b) ~ 100 16
(c) ~ 200 7
(d) > 200 5
(or maximum possible)
(3) What is your choice for the first aircraft to be added to the RAF fleet, if selection is limited to the following?

(a) G-I turboprop 1
(b) Mid-sized jet 35
(c) Storm-penetration aircraft 2
(d) Would opt for no aircraft rather than any of the above 0

(4) What is your choice for the first aircraft to be added to the RAF fleet, if selection is broadened to the following?

(a) Second King Air 2
(b) G-I turboprop 1
(c) Second Electra 1
(d) Small jet 0
(e) Mid-sized jet 27
(f) Medium-large jet (e. g., DC-9, 737) 5
(g) Storm-penetration aircraft 2
(h) Other 0

(5) Which mid-sized jet would you prefer?

(a) G-II class 0
(b) G-III class 0
(c) G-IV class 31
   (includes Falcon 900)
(d) Other 0
(6) Should two aircraft be added to the NCAR fleet within the next five years, assuming that the Sabreliner is retired?

   (a) Yes  28
   (b) No   1

(7) What is your second-choice aircraft (i.e., after G-IV class)?

   (a) Storm-penetration aircraft  16
   (b) Medium-large jet           7
   (c) Mid-sized turboprop        2
   (d) Large turboprop            1
   (e) King-Air class             2
   (f) Other (e.g., Skyvan)       2

After additional discussion about the implications and relative importance of the results from the voting, a majority of the participants reached agreement on the following four major recommendations:

(1) Electra aircraft flight time available to NSF-funded scientific investigators should be increased by 100 to 200 hours per year.

(2) As its top fleet-acquisition priority, NCAR should proceed to acquire a mid-sized jet aircraft to replace its existing Sabreliner.

(3) As a second priority, NCAR should acquire a storm-penetration aircraft, or arrange for joint use of such an aircraft with another agency.

(4) The existing Gulfstream I mid-sized turboprop aircraft owned by the NSF should not be renovated and developed as a research facility.
In closing the meeting, Warren Johnson and Bob Serafin of NCAR thanked the workshop participants for their highly useful inputs, and assured them that their recommendations would be considered very seriously in NCAR's planning for future research aircraft facilities.
Acknowledgments

Planning, conducting, and reporting on a workshop of this type require the dedicated efforts of a large number of people. The authors express their appreciation to their many NCAR colleagues who assisted them in these activities. The Workshop Organizing Committee got the project off to a good start. The members of this committee, in addition to the authors, were Ralph Cicerone, Richard Friesen, Greg Kok, Donald Lenschow, Robert Serafin, Paul Spyers-Duran, Peggy Taylor, John Wyngaard, and Edward Zipser. Peggy Taylor also served as the Workshop Administrator, and her careful, effective work in this capacity contributed materially to the success of the meeting.

Byron Phillips, who was kind enough to come out of his then-recent retirement from NCAR to help with the workshop, did a fine job in preparing Workshop Document 3 and in chairing the NCAR Study Group on a Storm-Penetration Aircraft. The members of this study group, in addition to the authors, were James Dye, James Fankhauser, Wayne Sand, Gilbert Summers, and Norman Zrubek. Phillips also played a major role, with the assistance of Norman Zrubek, in preparing Workshop Document 1 on development plans for a mid-sized turboprop research aircraft (Gulfstream I).

Gilbert Summers, James Ragni, and Norm Zrubek made key contributions to Workshop Document 2 on a mid-sized jet aircraft.

Karen Bowie processed the text for the workshop report in her usual highly competent manner, and Diana Hargett helped with the workshop documents and arrangements. Peggy Taylor, Erik Miller, Allen Schanot, and Richard Friesen served well as reporters for Working Groups 1, 2, 3, and 4, respectively.

In addition to the assistance provided by the above NCAR staff, Dennis Musil of SDSMT and Peter Sinclair of Colorado State University contributed valuable advice and information about storm-penetration aircraft.
Finally, the authors are grateful to all of the workshop participants, especially the presenters of science needs for research aircraft (Carl Friehe, John Bane, William Smith, John Hallett, Edward Zipser, Carl Kreitzberg, Ron Smith, Brian Ridley, Barry Huebert, and Jarvis Moyers) and the working group chairs (John Winchester, Ron Smith, Steve Nelson, and James Dye), who gave freely of their time and energy to share their views with the NCAR and NSF staffs in this important endeavor.
Reference

Appendix A

LIST OF WORKSHOP PARTICIPANTS

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Larry Mahrt, Oregon State University
William Mankin, NCAR-Atmospheric Chemistry Division
John Marwitz, University of Wyoming
John McCarthy, NCAR-Research Applications Program
Erik Miller, NCAR-Research Aviation Facility
Mitchell Moncrieff, NCAR-Micro/Mesoscale Meteorology Division
Adair Montgomery, National Science Foundation
Jarvis Moyers, National Science Foundation
Steve Nelson, National Science Foundation
Richard Pearson, Colorado State University
Byron Phillips, NCAR-Research Aviation Facility (retired)
Joseph Prospero, University of Miami
Charles Purdy, NCAR-Research Aviation Facility
James Ragni, NCAR-Research Aviation Facility
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Wayne Sand, NCAR-Research Applications Program
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Mel Shapiro, NOAA-Environmental Research Laboratories
Peter Sinclair, Colorado State University
Paul Smith, South Dakota School of Mines and Technology
Ron Smith, Yale University
William Smith, University of Wisconsin
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Graeme Stephens, Colorado State University
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Edward Zipser, NCAR-Micro/Mesoscale Meteorology Division
Norman Zrubek, NCAR-Research Aviation Facility
Appendix B

DETAILED CHARACTERISTICS OF CURRENT NCAR AIRCRAFT

A. NCAR Electra (L-188C)

Description:
- Crew: Two Pilots + Flt. Engineer + 16 Seats
  Available for Project Participants
- Length: 32.0 m; Wingspan: 30.2 m
- Gross Weight: 116,000 lbs max.
- Engines: Four Allison 501-D13, 4000 SHP each
- Base: Jefferson County Airport, Broomfield, Colorado

Performance:
- Altitude: 28,400 ft. (operating)
- Range: 2,400 n mi (at 22,000 ft cruise)
- Endurance: 8.5 hrs max. with IFR reserves
- Speed: 310 KTAS (typical cruise)
- Payload: 20,800 lbs max.; 7,200 lbs with full fuel

Sensors:
- Atmospheric State Parameters
- Gustprobe Instrumentation for Turbulent Flux Measurements
- Cloud Physics Instrumentation
- Radiometers (Short-Longwave and Ultraviolet)
- Remote Radiometric Surface Temperature
- Video Photography
- Dropwindsonde Dispensing-Acquisition
- Oceanographic Dropsonde Dispensing-Acquisition
- LIDAR—Vertical Profiles of Aerosols and Clouds
- Atmospheric Trace Gas Sampling

Applications:
- Multi-Investigator Experiments Requiring Large Payloads
- Measurements in Remote Regions Requiring Long Ranges
- Boundary-Layer Studies, Turbulence/Flux Measurements
- Oceanographic Investigations
- Air-Sea Interaction Measurements
- Cloud Physics Studies
- Tropospheric Profiling
- Radiometric Measurements, Satellite Ground Truth
- Atmospheric Chemistry Measurements
- Aerosol Measurements

Chronology:
- Manufactured in 1959
- Acquired by NCAR in 1972
B. NCAR King Air (B200T)

Description: One Pilot + 2 to 3 Seats Available for Project Participants
Length: 13.4 m; Wingspan: 17.4 m
Gross Weight: 14,000 lbs max.
Engines: Two Pratt and Whitney PT6-42
Base: Jefferson County Airport, Broomfield, Colorado

Performance: Altitude: 33,000 ft. (max.)
Range: 1,800 n mi (at 33,000 ft cruise)
Endurance: 7.3 hrs max. with IFR reserves
Speed: 240 KTAS (typical cruise)
Payload: 2,350 lbs max.; 1,680 lbs with full fuel

Sensors: Atmospheric State Parameters
Gustprobe Instrumentation for Turbulent Flux Measurements
Cloud Physics Instrumentation
Radiometers (Short–Longwave and Ultraviolet)
Remote Radiometric Surface Temperature
Video Photography
Dropwindsonde Dispensing-Acquisition
Oceanographic Dropsonde Dispensing-Acquisition
Atmospheric Trace Gas Sampling
Electric Field Strength Sensing

Applications: Boundary-Layer Studies, Turbulence/Flux Measurements
Oceanographic Investigations
Air-Sea Interaction Measurements
Cloud Physics Studies
Tropospheric Profiling
Radiometric Measurements, Satellite Ground Truth
Atmospheric Chemistry Measurements
Aerosol Measurements

Chronology: Manufactured in 1982
Acquired by NCAR in 1982
C. **NCAR Sabreliner (NA265-60)**

**Description:**
- Crew: Two Pilots + 2 to 4 Seats
- Length: 14.6 m; Wingspan: 13.7 m
- Gross Weight: 20,000 lbs max.
- Engines: Two Pratt and Whitney JT12A-8
- Base: Jefferson County Airport, Broomfield, Colorado

**Performance:**
- Altitude: 43,000 ft. (max.)
- Range: 1,300 n mi (at 37,000 ft cruise)
- Endurance: 3.5 hrs max. with IFR reserves
- Speed: 400 KTAS (typical cruise)
- Payload: 2,050 lbs max.; 1,628 lbs with full fuel

**Sensors:**
- Atmospheric State Parameters
- Gustprobe Instrumentation for Turbulent Flux Measurements
- Cloud Physics Instrumentation
- Radiometers (Short–Longwave and Ultraviolet)
- Remote Radiometric Surface Temperature
- Video Photography
- Dropwindsonde Dispensing-Acquisition
- Atmospheric Trace Gas Sampling

**Applications:**
- Upper Tropospheric Dynamics Studies
- Stratospheric-Tropospheric Exchange Measurements
- Cloud Physics Studies
- Tropospheric Profiling
- Radiometric Measurements, Satellite Ground Truth
- Atmospheric Chemistry Measurements
- Aerosol Measurements

**Chronology:**
- Manufactured in 1968
- Acquired by NCAR in 1968
Appendix C

SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS
FROM THE NSF SPECIAL ADVISORY PANEL MEETING
IN RAPID CITY, SOUTH DAKOTA, ON 13-14 MAY 1985

The NSF Special Advisory Panel conclusions and recommendations were:

1. That the T-28 has had wide usage for storm core penetration in both national
   and international programs.

2. That major advances have been made in our knowledge of storm processes
   as the result of T-28 data in combination with other observational field data
   analysis. The storm penetration in situ data has been critically important to
   these analyses.

3. That the study areas for application of a storm penetration aircraft include:

   - Precipitation mechanisms. The major part of thunderstorm precipitation
     growth occurs in the > 35 dBZ radar reflectivity regions.
   - Storm structure and dynamics.
   - Atmospheric chemistry and trace gas-aerosol particle transport, especially
     in storm updrafts/downdrafts.
   - Storm electrification.
   - Remote sensing verification for improved analysis and interpretation of
     ground-based remote sensing measurements.

Stanley A. Changnon, Chair
4. That measurements made from penetrating aircraft in the > 35 dBZ volume of storms are essential to interpret and understand the precipitation and dynamical processes occurring.

5. That the T-28 penetration aircraft has flight capability limitations which cannot be improved – altitude, endurance, payload, etc. The T-28 should be upgraded for support of the atmospheric sciences for the near term (5 years) and a more capable storm penetration aircraft be acquired and developed for T-28 replacement.

6. That the operational research requirements for a replacement aircraft specify:
   - A twin-engine aircraft stressed for aerobatic flight.
   - The capability for flight into regions of large hail.
   - Engine reliability in regions of heavy rain, hail, icing, and lightning.
   - A research altitude capability to 45,000 ft, flight endurance of 4-5 hrs.
   - Multiple crew.

7. That the cost of the replacement aircraft development is in the range of $3 to $4 million.

8. That development and operation of the replacement aircraft involve a need for committed scientific leadership and staff skilled in the technical aspects of research aircraft. This and the need to share overhead costs, give argument for developing and operating the aircraft at a larger aircraft facility.