APPENDIX I

Many aircraft tanker fleets exist in today's air forces. These are capable of carrying large payloads of liquids (specifically, Jet fuel) over long distances. Given the altitude of 43,000 ft hypothesized for the subpolar SAI deployment mission, an aerodynamic assessment of six different aircraft was conducted to determine their ability to carry a cargo load of liquid sulfur dioxide (a precursor of reflective sulfuric acid), release the cargo in a gaseous phase, and safely return. This appendix defines the parameters used to conduct the study, the methodology used in the assessment process, and the conclusions drawn from that study.

Basic Study Parameters and Assumptions

This study was conducted with a similar set of constraints applied to each configuration. These are:

1. The aircraft would fly from an airfield as close as is feasible to 60 degrees latitude, North or South.
2. The airfield would be close to the release point of the precursor, minimizing the fuel required.
3. Sulfur dioxide is the precursor of choice, and it can be expelled within 2 minutes from the onboard pressurized tank. It is expected to require a 49 psia pressurized tank for an airfield temperature of 71°F (Weather Atlas). At lower latitudes, the pressure could double, depending upon ambient temperatures.
4. The designated altitude is ~43,000 ft (13 km).
5. Precursor would be deposited during the late Spring and early Summer in one hemisphere and the fleet would then relocate to the other hemisphere for that Spring/Summer deployment. This requires a ferry capability of 4,000 NM.
6. These aircraft would be purchased new to meet the fleet needs. In their air-to-air refueler configuration, they would carry refueling booms, probe/drogue reels, additional tanks, pumps, plumbing, seats, and reinforced floors for alternate cargo missions. The newly purchased aircraft in SAI deployment configuration would not have this equipment installed, thereby decreasing the Empty Weight by 25,000 lbs.
7. In general, 2,700 lbs of new weight is added to the aircraft to account for the weight of the pressurized liquid Sulphur Dioxide Tanks. The weight of the tanks was calculated by engineers at VPE Aerospace Consulting, LLC.
8. All aircraft are assumed to be designed to an ultimate load factor of 4.5 g's (limit load of 3g's).
9. The flight performance of each aircraft is based upon a climb rate of 300 fpm at 43,000 ft.
10. A standardized commercial mission profile was used throughout the flight assessment. For safety, after the SAI release, it allows for a 200 NM diversion flight to an alternate airport as well as a 30 minute loiter, and a 5% fuel reserve upon landing.
11. Information regarding the aircraft was gleaned from Original Equipment Manufacturer (OEM) pages, United States Air Force (USAF) databases, and other internet sources. Information regarding the engines was retrieved from the OEM pages and Nate Meier's JET-ENGINE.NET (Meier).

Aircraft

The aircraft assessed are the following:

1. KC-135R Stratotanker– As shown in figure 1, this is a 4-engine aircraft built for the USAF by the Boeing Company. It is similar to the B707 commercial aircraft. It first entered service in 1957, and many are still flying today (USAF Fact Sheet KC-135). For the KC-135R, the earlier engines were replaced with the CFM56 turbofan engines. This is a 21,600 lb. sea level thrust engine. It has a crew of 3, a MTOW of 322,500 lbs., a fuel capacity of 200,000 lbs, and an operating Empty Weight of 124,000 lbs. It had a service ceiling of 50,000 ft.

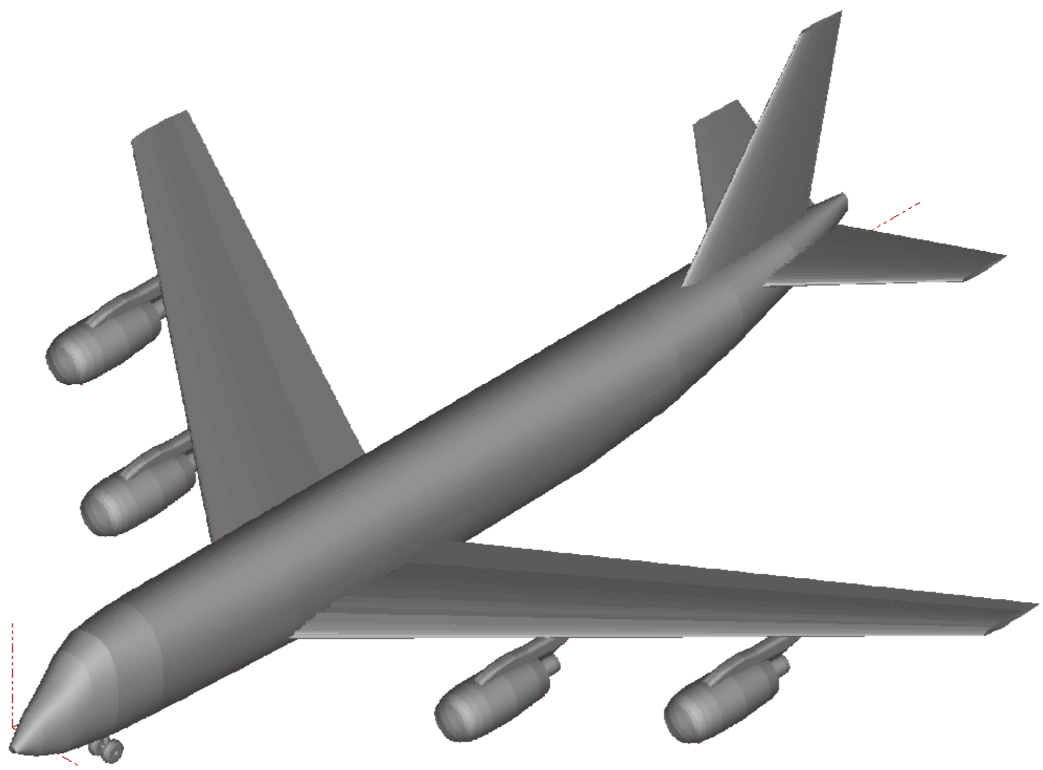

Figure 1. Solid Model of the KC-135R without refueling equipment

2. KC-10 Extender – As shown in figure 2, this is a 3-engine aircraft built for the USAF by McDonnell Douglas. It is derived from the DC-10 commercial aircraft. 60 aircraft were built for the US. It has both tanking and cargo capability. The Empty Weight is 241,027 lbs; it can carry up to 170,000 lbs of cargo; and has a MTOW of 590,000 lbs (USAF Fact Sheet KC-10 Extender). Its max fuel capacity is 365,000 lbs. Its service ceiling is 42,000 ft.

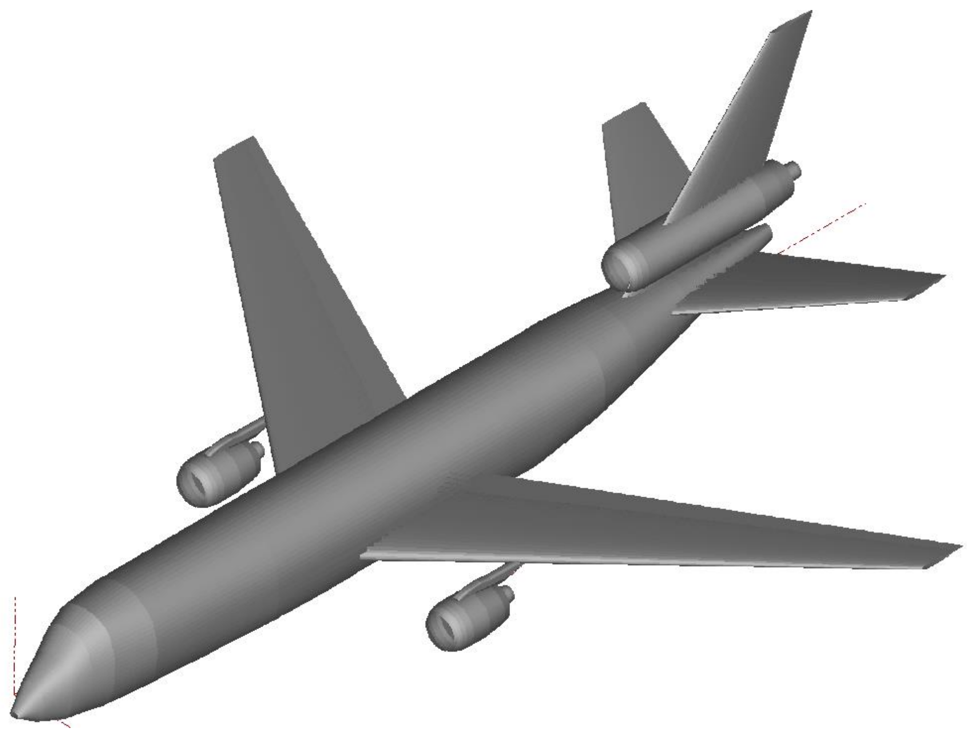

Figure 2. Solid Model of the KC-10 Extender without refueling equipment

3. KC-46A Pegasus – As shown in figure 3, this is a twin-engine aircraft built for the USAF by Boeing. It is derived from the B767 commercial aircraft. 179 aircraft are planned to be procured for the US. It has both tanking and cargo capability. The Empty Weight is 181,610 lbs; it can carry up to 65,000 lbs of cargo and 58 patients; and has a MTOW of 415,000 lbs. Its max fuel capacity is 212,299 lbs (USAF Fact Sheet KC-46A). Its service ceiling is 40,100 ft.

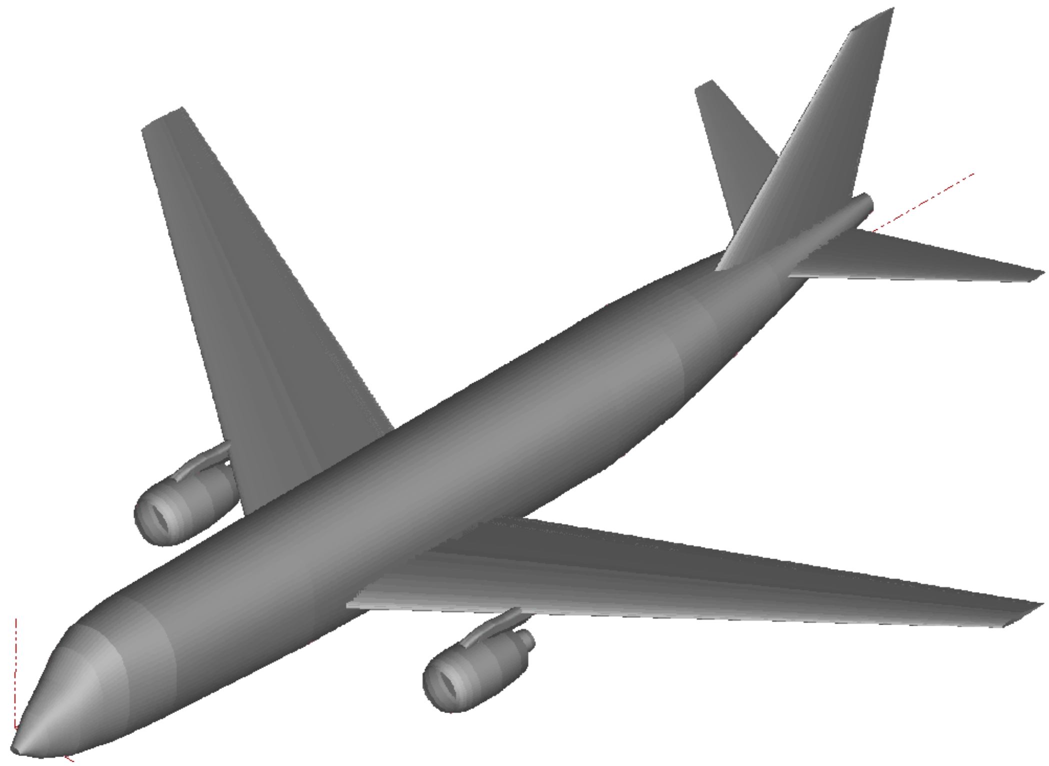

Figure 3. Solid Model of the KC-46A Pegasus without refueling equipment

4. A340-600 – As shown in figure 4, this is a 4-engine aircraft built by Airbus. It was built to compete with the B777-300 commercial aircraft. It can seat up to 380 passengers. The Operating Empty Weight is 384,000 lbs; it can carry up to 146,000 lbs of payload; and has a MTOW of 840,000 lbs (Airbus A340-600). Its max fuel capacity is 342,905 lbs. Its service ceiling is 41,450 ft.

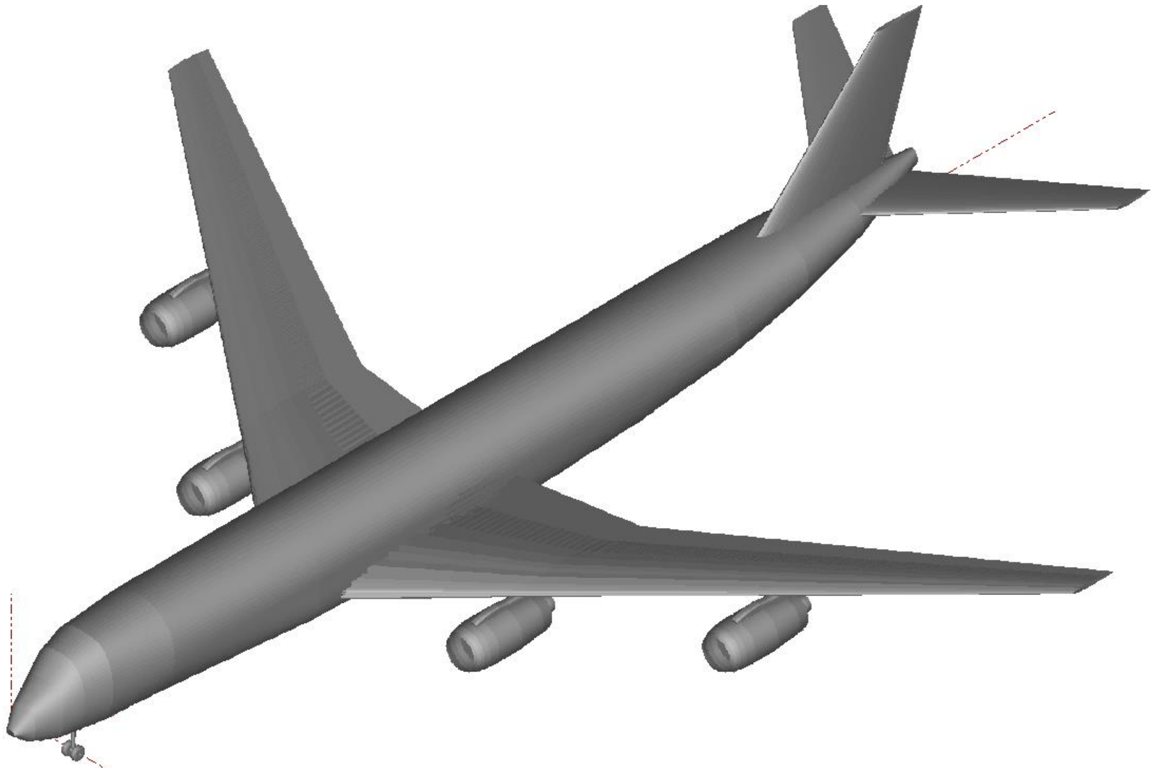

Figure 4. Solid Model of the A340-600

5. A330-MRTT – As shown in figure 5, this is a twin-engine refueling aircraft built by Airbus. It is derived from the A330 commercial aircraft. 60 aircraft are planned to be procured worldwide. It has both tanking and cargo capability. The Empty Weight is 275,600 lbs; it can carry up to 95,000 lbs of cargo; and has a MTOW of 514,000 lbs (Airbus Military). Its max fuel capacity is 245,000 lbs. Its service ceiling is 42,700 ft.

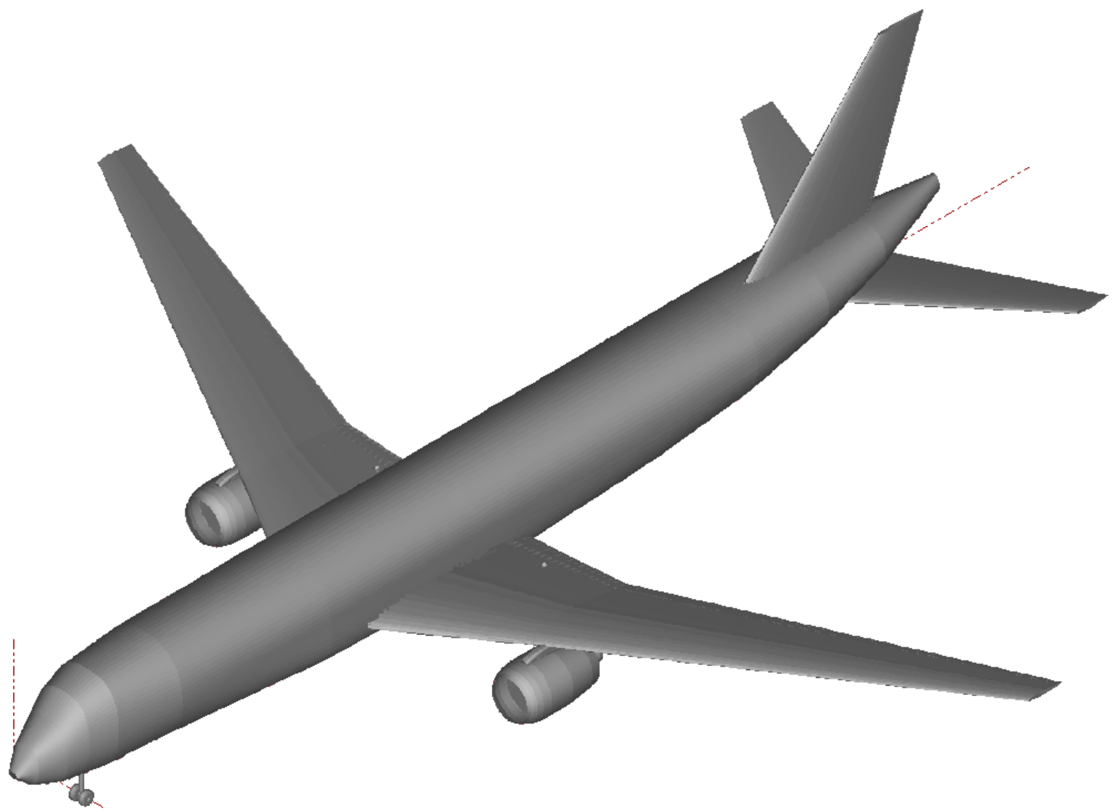

Figure 5. Solid Model of the A330-MRTT without refueling equipment

6. SAIL-43K – As shown in figure 6, the SAIL-43K is derived from a theoretical study performed in (Bingaman et al. 2020) to determine the viability of building a purpose-built aircraft for very high-altitude SAI injection. The SAIL-43K is redesigned from the original SAIL-01 for a load factor of 4.5 G's ultimate, as well as a larger internal tank capability for increased SO2 carriage. It has 4-engines. The Operating Empty Weight is 99,350 lbs; it can carry up to 167,971 lbs of payload at 43,000 ft; and has a MTOW of 299,397 lbs.

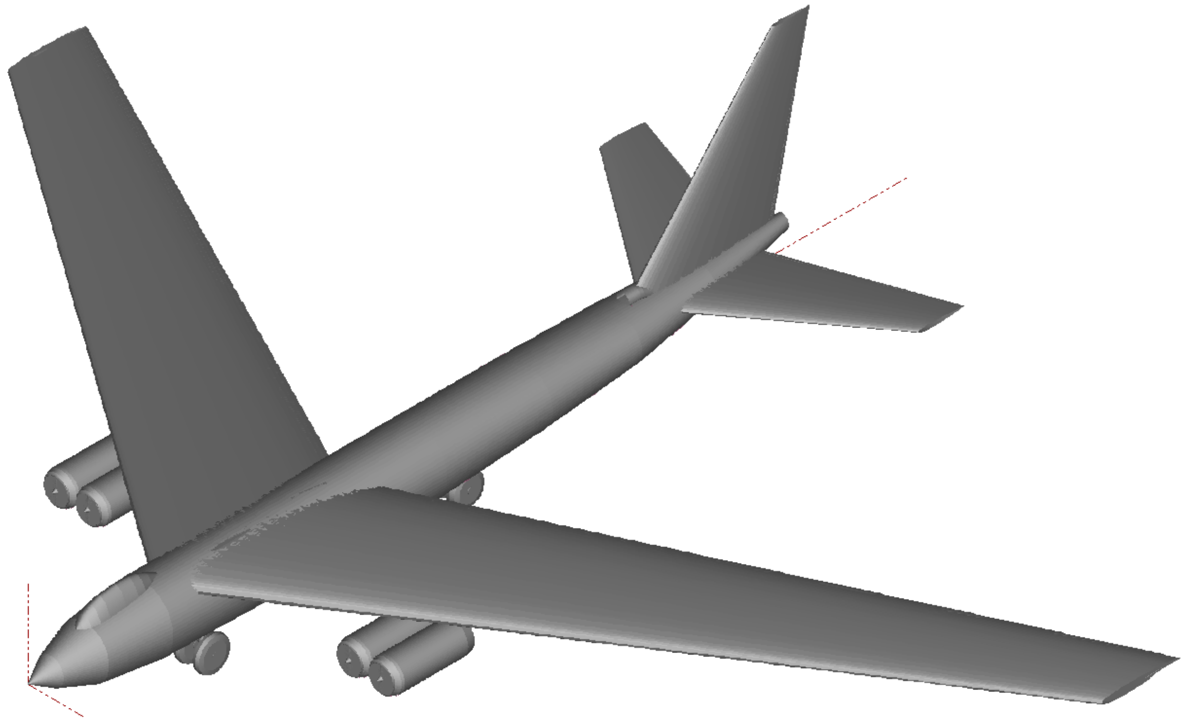

Figure 6. Solid Model of the SAIL-43K

Methodology

To make this assessment, the RDSWIN software tool was used. This tool was created by Dr. Daniel P. Raymer and is used in conjunction with his textbook (Raymer 2019). The following modules were used for the assessment to be made:

Geometry Module - All data was scaled and input based upon geometric data found online at the OEM site or from blueprint or 3 view images (Combat Aircraft; The Aviation Zone), in conjunction with dimensional data found at Wikipedia and open-source geometry image on the internet. This data is used to create an accurate scaled solid model of the aircraft. The output geometry from here is used in the other modules.

Weight Module – Weight is critical in assessing an aircraft capability. Therefore, a separate Excel program was created. Four different weight estimating methodologies were utilized from existing textbook or NASA documents. Formulae from noted authors Jan Roskam, Daniel P. Raymer, Egbert Torenbeek as well as from NASA Flight Optimization System (FLOPS) were utilized (Roskam 1999; Raymer 2019; Torenbeek). The outputs for each component weight estimations were then averaged and used in the weight module.

Aerodynamics Module - Geometric inputs from the geometry file are used to determine the lift, parasitic and wave drag, and lift induced drag for a variety of flight conditions. Laminar flow constraints and interference factors were added.

<u>Propulsion Module</u> – Each aircraft has a set of engines to deliver thrust at different altitudes and speeds. In addition, the specific fuel consumption needs to be known to determine the amount of fuel being burned during takeoff, climb, cruise, descent and landing. This data is known as the engine TAB data and can rarely be found in any documents. Most OEMs do not release this information however it is critical to assessing an aircraft performance. Since the performance for the TF39 engine can be found in Nicolai's textbook (Nicolai 1975), the basic thrust and SFC data are scaled and extrapolated from this information. This turbofan is similar to other large diameter turbofans of that era. Using JET-ENGINE.NET to locate thrust at the sea level static and cruise conditions provides enough data to make a reasonable estimate of thrust and SFC.

<u>Mission Sizing Module</u> – The data from the previous modules is used here to determine takeoff, climb, cruise, weight drop, descent, climb, loiter, descent, landing and fuel reserve. A standard commercial aircraft mission profile was used (Vedantham 1999). A climb rate of 300 fpm at 43,000 ft was used to assure the mission was achievable over different ambient conditions.

The aircraft were individually assessed in this manner. An initial determination of reaching the documented service ceiling was made. Following that, the payload weight was increased or decreased as required to reach 43,000 ft altitude with sufficient fuel to safely conduct the mission. Then, Weight was removed, if required, from the OEW to account for purchasing the aircraft without the onboard refueling equipment, and other gear, making it a single mission vehicle. This was uniformly 25,000 lbs of equipment removed. An additional 2700 lbs of weight were added back in the cover the weight of pressurized tanks for SO2. Note that added weight was included into the SAIL-43K to cover the external tanks.

Conclusions

In general, all the aircraft reach a limit of around 400,000 to 500,000 lbs of MTOW capability to 43,000 ft altitude. This is of course limited by the available thrust at 43,000 ft, as well as wing size. Although it is desired to fly faster at altitude to gain greater lift, some aircraft lacked sufficient thrust to overcome the increased drag. Note also that the OEW of some aircraft greatly limit its ability to carry large payloads. The fuel fraction is relatively low for this mission, with typical fuel loads in the 20,000 to 50,000 lb range. Again, the aircraft performs this mission essentially over the airport.

AIRCRAFT	MODIFIED OEW	PAYLOAD	MTOW @43K	THRUST @43K	MACH	FUEL
KC10	215,509	128,801	376,000	23,506	0.82	33,157
KC135R	95,593	105,200	219,400	12,675	0.81	18,607
KC46A	160,130	74,870	256,500	13,734	0.76	21,500
A340-600	359,638	102,761	492,000	28,371	0.67	29,600
A330-MRTT	237,341	88,300	357,105	19,892	0.71	31,464
SAIL 43K	99,350	167,971	299,397	21,209	0.82	32,076

Table 1. Aircraft Performance (*All weights are in pounds.*)

The SAIL-43K is the outstanding performer in this assessment. It was purpose built for this mission. With four engines, it can obtain high cruising speed. Its low OEW allows for substantial payload fraction.

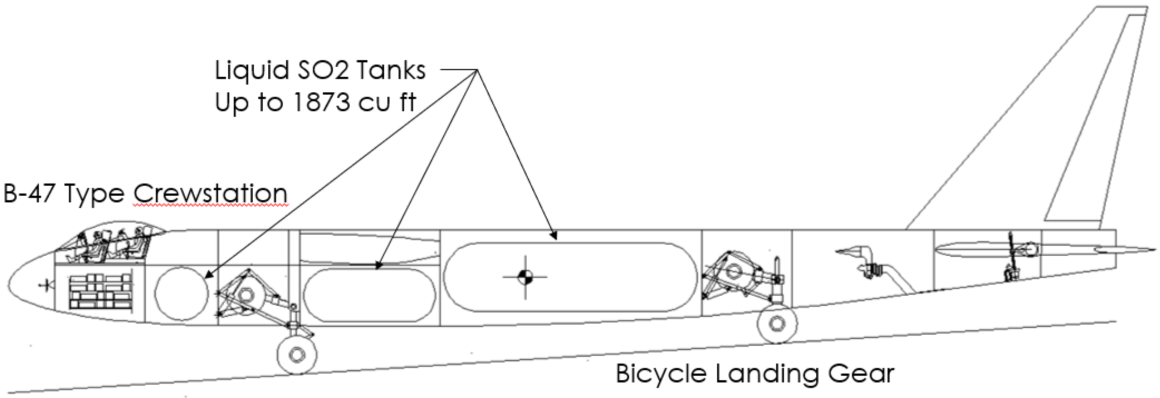

Figure 7. Inboard Profile of the SAIL-43K

Abbreviation:

FLOPS: Flight Optimization System

MTOW: Maximum Takeoff Weight

OEW: Operating Empty Weight

OEM: Original Equipment Manufacturer

SAI: Stratospheric Aerosol Injection

SAIL: Stratospheric Aerosol Injection Lofter

SFC: Specific Fuel Consumption

USAF: United States Air Force

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