upGREAT Cryocooler System Concept of Operations

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upGREAT Cryocooler System Concept of Operations

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Revision History

REV	DATE	DESCRIPTION	APPROVAL
Draft 0.1	11/25/2013	Draft for Science Project and upGREAT stakeholder review.	
Draft 0.2	1/23/2014	Updated draft incorporating comments from upGREAT Project Engineer C. Risacher, SOFIA Science Project SE&I lead D. Kozarsky, and USRA SE&I lead E. Burgh, for wider SOFIA Program, Platform Project and (non-decisional) Science PCB review.	
Draft 0.3	2/4/2014	Updated draft incorporating comments from Science PCB review and Platform SE&I, for Cryocooler SRR review.	
Draft 0.4	6/10/2014	Updated draft reflecting descope of cryocooler system to omit 400 Hz to 60 Hz FC and be more upGREAT-specific, as well as discussions and RFAs / RFIs from 4/17/2014 Cryocooler SRR, and follow-up discussions at 5/12/2014 and 5/22/2014 Face-to-Face TIMs with GREAT PI and upGREAT Project Engineer.	
Draft 0.5	7/15/2014	Updated draft incorporating comments from USRA SE&I Lead and NASA Cryocooler System development PM.	
-	7/23/2014	Initial Release (OCCB) per OCCB-CCR-0159 (JIRA # SOF-2390)	OCCB

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1. INTRODUCTION

1.1. Purpose

The purpose of this document is to describe the concept of operations for a Closed-Cycle Cryocooler (CCC) system to support the upGREAT Science Instrument (SI) for the Stratospheric Observatory for Infrared Astronomy (SOFIA). It outlines use cases and expected operational scenarios that will drive the requirements for the system and indicates the relevant responsibilities of the various stakeholders.

1.2. Scope

The upGREAT Cryocooler System will be used in lieu of expendable liquid cryogens to cool the upGREAT cryostats to liquid Helium (LHe) temperatures. The upGREAT cryostats, part of the German Receiver for Astronomy at Terahertz Frequencies (GREAT) instrument developed by the Max Planck Institut für Radioastronomie (MPIfR), are the first such receivers that will use CCC systems to achieve the necessary cryogenic temperatures.

The first CCC-cooled upGREAT channel / cryostat will be the Low Frequency Array (LFA), a 2 x 7 pixel array able to detect 1.9 ~ 2.5 THz frequencies. This channel is expected to arrive @ AFRC Bldg. 703 in late-CY2014, with commissioning flights in late-Feb. 2015. The upGREAT LFA will be integrated with the GREAT instrument in the lab, and will initially fly next to one of the earlier single-pixel receivers with liquid cryogen dewars.

Accordingly, Phase I of the upGREAT Cryocooler System will include a single He compressor and associated infrastructure needed to service a single Pulse Tube cold head and cryostat.

About 1 year after the arrival and commissioning of the upGREAT LFA, the upGREAT High Frequency Array (HFA) is expected, this being a 7 pixel array that can detect at 4.7 THz.

It is anticipated that an increasing number of 3rd and next generation SIs will use CCC systems to achieve the necessary cryogenic temperatures without need of expendable Liquid Nitrogen (LN2) and LHe cryogens. There are several reasons driving this migration, which will be summarized within this Concept of Operations (ConOps) document.

CCC systems do use He, but rather than relying on the heat of vaporization associated with the phase change from liquid to gas, they use a relatively small quantity of He gas as a refrigerant in a pressurized closed loop, using a compressor to generate a pressure difference between a supply and return line connected to a cold head, which includes one or more heat sink(s) that remove heat from cold plates within the SI cryostat.

There are several cold head technologies, as well as other key design and operational considerations, but generally all CCC systems include a compressor, a cold head, and interconnecting He line components. Figure 1.2-1a depicts a generic CCC system.

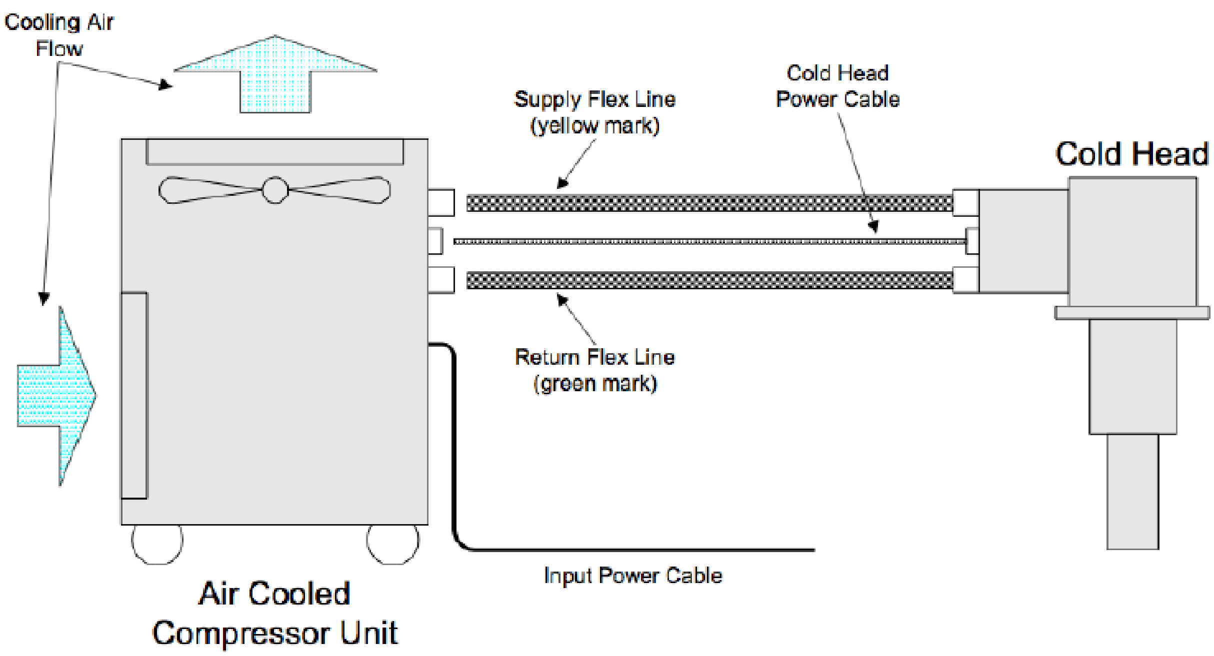


Figure 1.2-1a: Generic Closed-Cycle Cryocooler system, showing major components. Note that an air-cooled compressor is depicted here; water-cooled systems are also available.

For astronomical infrared instrumentation applications, the cold head is integral to an SI assembly cryostat, and is connected to the powered compressor via a pair of compressed He gas lines, a portion of which are flexible and routed through a "cable wrap", to accommodate relative motion between the compressor and the instrument on the telescope focal plane. The upGREAT developer has selected the Pulse Tube cold head technology, due to the absence of moving parts within the cold head itself, and the relatively low vibration levels.

Cold heads also generally require a power source to operate. Pulse Tube cold heads include a rotary valve, which converts the static pressure differential (between the supply and return He lines) generated by the compressor to a pulsating flow. Typically, the power to operate the cold head is provided by the compressor, using a power interconnect cable, but in the upGREAT application, this power is provided by an ancillary power supply (an external variable frequency drive for the rotary valve) to support further optimization of the thermal performance. Except in specific maintenance operations, the rotary valve is "slaved" to the compressor via a discrete signal line from the compressor to the variable frequency drive, such that the valve operates only when the compressor is on.The upGREAT Cryocooler System will include the necessary cabling and interfaces routed through the CLA to support this synchronization of compressor and rotary valve operations.

The Pulse Tube cold head selected for use with the upGREAT channel cryostats have a rotary valve that is not integral to the cold head itself, allowing the rotary valve to be installed remotely on a vibration-isolating mount. This is beneficial for astronomical instrumentation as it allows vibrations from the rotary valve (the only component with moving parts in a Pulse Tube cold head) to be mechanically isolated from the cryostat with its optical components. The rotary valve is interfaced to the cold head via a single, relatively short (70 ~ 75 cm) compressed He line, and to the compressor with the much longer (~40 meter) supply and return lines. For the upGREAT receivers, each cold head is serviced by a single, dedicated compressor. Figure 1.2-2b depicts the Phase I Cryocooler System, and reflects some of the upGREAT-specific adaptations discussed above and elsewhere within this document.

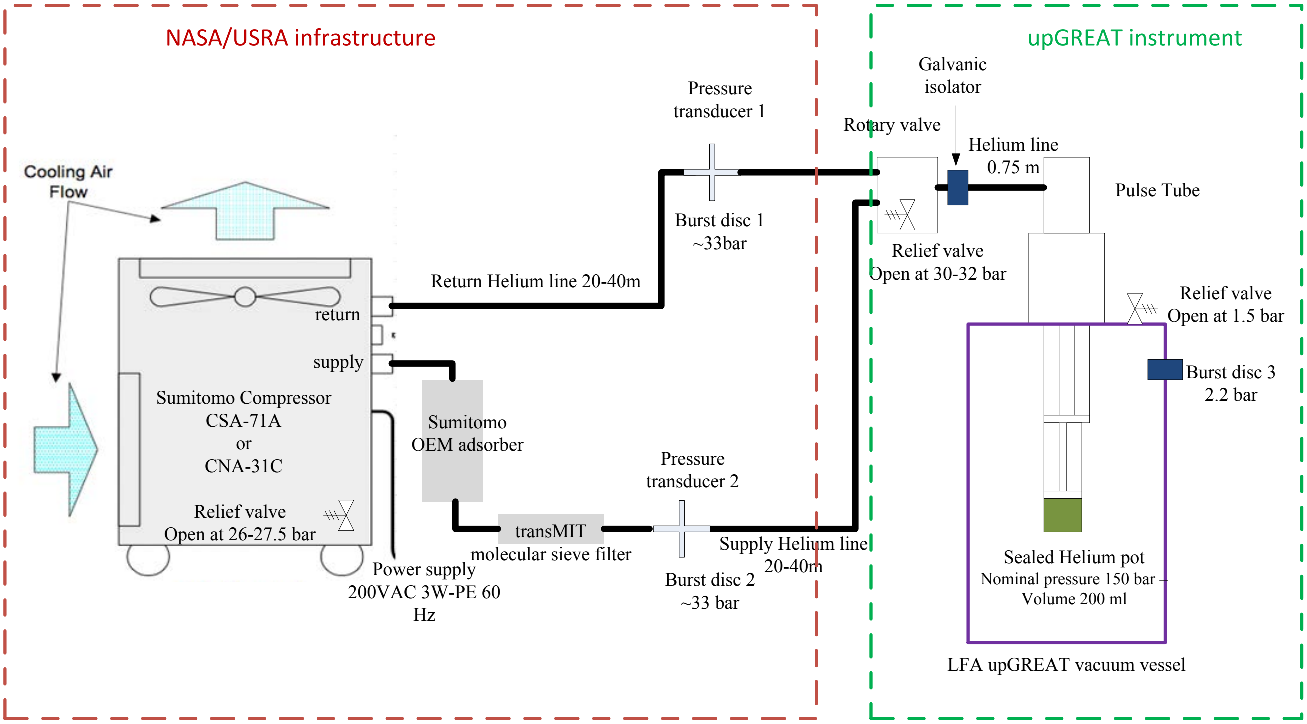


Figure 1.2-1b: upGREAT CCC system, showing major components needed to support one (1) upGREAT channel cryostat. Ultimately, two (2) such systems will be needed to support upGREAT LFA + HFA configurations, or other SIs that require two (2) cold heads.

The upGREAT channel cryostats require CCC systems for cooling, both aboard the SOFIA observatory as well as when they are in a laboratory environment on the ground. The cold heads themselves are incorporated into the upGREAT cryostats as tightly integrated components. As a consequence of this, the same physical cold head(s) will be used for upGREAT in both the airborne and ground laboratory environments.

There are several practical issues related to repositioning the same large, heavy compressors for use in both the airborne and ground laboratory environments, so the more likely scenario involves provision and use of separate GSE CCC compressors and associated infrastructure for use in the laboratories, including the Instrument Readiness Rooms (IRRs) and Preflight Integration Facility (PIF) at AFRC Bldg. 703, the facility formerly known as the Dryden Aircraft Operations Facility (DAOF).

The scope of this Concept of Operations document includes both the airborne and ground segment aspects of upGREAT Cryocooler System usage and operations, as special care must be taken to ensure that in both environments, the systems are designed and configured such that they will deliver the required thermal performance with adequate margins. However, the system requirements for the airborne and ground segment Cryocooler Systems will be captured in two separate System Specification documents.

The GREAT SI is a modular, multi-channel instrument that can accommodate two concurrent heterodyne receivers via two distinct cryostats. The CCC-cooled upGREAT LFA and HFA channel cryostats, each independently serviced by a distinct 2-stage cold head driven by a dedicated compressor, will augment the already-commissioned receivers and are expected to provide a 10 times gain in observing efficiencies, relative to the existing single-pixel channels, when mapping extended sources. The SOFIA Program has committed to supporting upGREAT with the necessary cryocooler system infrastructure, integrated, verified and certified airworthy, aboard the SOFIA observatory.

In order to both accommodate the upGREAT "point design" as well as optimize flexibility for future 3rd generation SOFIA SIs that use CCCs, the SOFIA Cryocooler System will ultimately include two (2) compressors, which will be connected to two (2) cold heads via two (2) supply/return pairs of compressed He lines, routed through the Cable Load Alleviator (CLA) "wrap". The "phased" delivery of the upGREAT channels, with the HFA cryostat arriving about one year after the LFA cryostat, will allow the initial implementation of the upGREAT Cryocooler System to have a single He compressor.

The development, integration and operations of this Phase I upGREAT Cryocooler system will provide invaluable experience and act as a "pathfinder" for the development of a more capable Phase II system with two (2) compressors that will service both upGREAT channels. It is hoped and expected that the operational experience with such systems gained during Phase I will also support implementation of a less upGREAT-centric Phase II SOFIA Cryocooler System, which will represent a more permanent facility-class SOFIA mission system, with a more optimal compressor location with respect to aircraft weight and balance, capable of supporting a variety of CCC-cooled next-generation SOFIA SIs. Though the initial implementation of the upGREAT Cryocooler System need only support the upGREAT LFA channel cryostat, the Cryocooler System will ultimately comprise two (2) He compressors, permanently or semi-permanently affixed to the aircraft and associated compressed He lines, Quick Disconnect (QD) fittings, instrumentation such as valves, pressure monitors, as well as additional inline external adsorber canisters and molecular sieve filter units.

The Cryocooler System will be implemented and maintained by the SOFIA Program, as part of the observatory's infrastructure. SI developers are responsible for provision and necessary restraints for the compressed He lines from the Cryocooler System connections located on or near the Telescope Assembly (TA) Counterweight Plate (CWP) to the SI cryostat(s) and cold head(s), likely with support from the USRA Mission Operations (MOPS) team. SI developers will also be responsible for any ancillary equipment or other SI-specific configurations, e.g., cold head variable frequency drive power supplies, supplemental filters required to protect cold heads that are especially sensitive to contamination, etc.

A pair of context diagrams depicting the scope of the upGREAT Cryocooler System and the relevant interfaces to other subsystems (and identifying the applicable ICDs) are provided as Figure 1.2-2a (Airborne system per SE01-2076, upGREAT Cryocooler System Spec.) and Figure 1.2-2b (Ground segment per SE01-2081, DAOF Cryocooler and Accommodations Spec.).

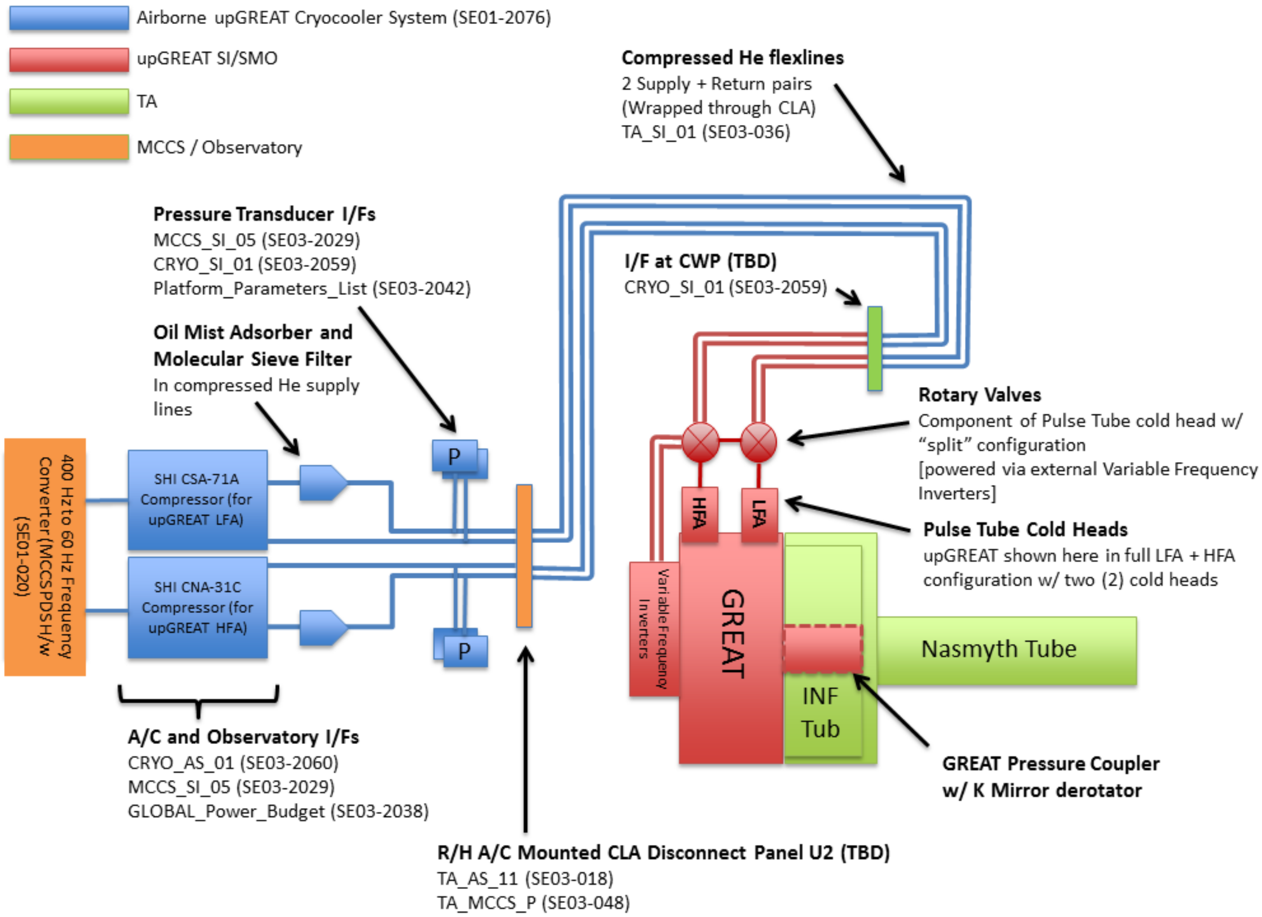


Figure 1.2-2a: Contextual diagram for the SOFIA Airborne upGREAT Cryocooler System. Blue items indicate elements of the Cryocooler System, including compressed He lines wrapped through the CLA, while red indicates upGREAT SI elements, not within the scope of the Cryocooler System. Relevant interfaces for the Cryocooler He lines are indicated. Not shown are the discrete signal lines, also routed the CLA cable wrap, that will keep the Pulse Tube cold head rotary valve operations "synchronized" with the compressor operations.

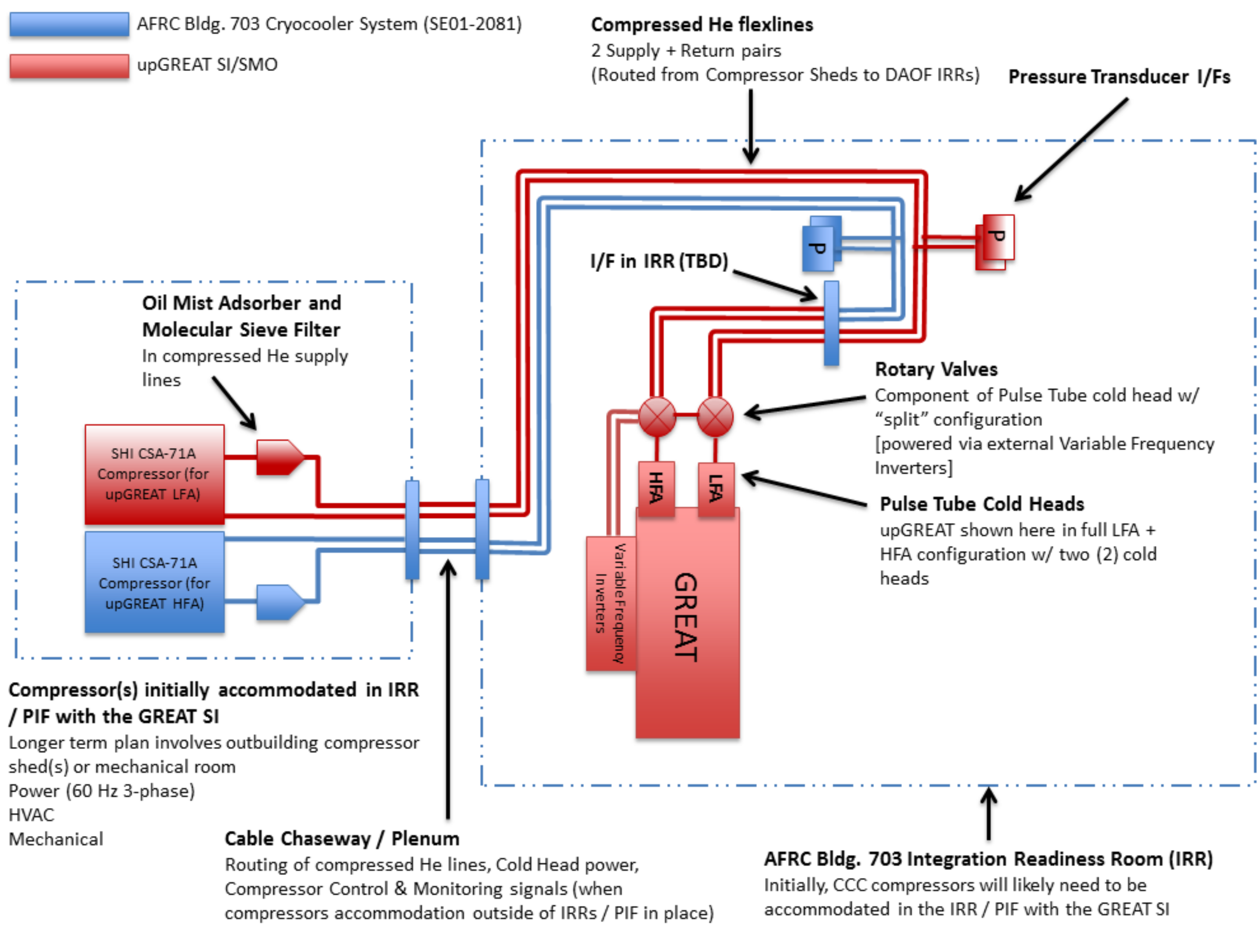


Figure 1.2-2b: Contextual diagram for the SOFIA laboratory Cryocooler System for use at AFRC Bldg. 703. Blue items indicate elements of the Cryocooler System, while red indicates upGREAT SI elements, not within the scope of the Cryocooler System. Though SE01-2081 anticipates a more comprehensive facility-level installation, it seems likely that the initial implementation will need to accommodate upGREAT / MPIfR provided compressors and He lines within the Instrument Readiness Room (IRR) / Preflight Integration Facility (PIF). Not shown are the discrete signal lines that will keep the Pulse Tube cold head rotary valve operations "synchronized" with the compressor operations.

1.3. Referenced Documents

SOF-DF-SPE-SE01-003	SOFIA System Specification
SOF-DF-SPE-SE01-004	SOFIA Airborne System Requirements
SOF-NASA-SPE-SE01-2076	upGREAT Cryocooler System Specification
APP-DA-SPE-SE01-2081	DAOF Cryocooler and Accommodations Specification
SOF-DA-ICD-SE03-036	Cable Load Alleviator Device / Science Instrument Cable Interface (TA_SI_01)

SOF-DF-ICD-SE03-037	Telescope Assembly/Science Instrument Mounting Interface ICD (TA_SI_02)
SOF-DF-ICD-SE03-048	Telescope Assembly / Mission Controls and Communications System (MCCS) Physical Interface (TA_MCCS_P)
SOF-NASA-ICD-SE03-2059	upGREAT Cryocooler System to upGREAT Science Instrument ICD (CRYO_SI_01)
SOF-NASA-ICD-SE03-2060	upGREAT Cryocooler System to Aircraft System ICD (CRYO_AS_01)
SOF-AR-ICD-SE03-2029	Principal Investigator Patch Panel to Principal Investigator Equipment Rack(s) Interface (MCCS_SI_05)
APP-DF-ICD-SE03-2038	Global Power Budget Interface Control Document
APP-DF-LIS-SE03-2042	Platform Parameter List
APP-DF-PLA-PM23-2000	SOFIA Airborne Platform Logistics Plan
SCI-US-PLA-PM17-2065	SOFIA Facility Science Instrument Maintenance Plan
APP-DA-PLA-PM17-2078	"24/7" Power and Network Connectivity between Flights Concept of Operations
APP-DF-PLA-PM17-2068	SOFIA External Observatory Connections Subsystem (SkyNet) Concept of Operations
UGA-2200-004	upGREAT Closed-Cycle Coolers Feasibility Study
UGA-2200-006	upGREAT Closed-Cycle Coolers Specification
N/A (white paper)	Cryocoolers for Future SOFIA Science Instruments, Ennico-Smith, K. (5/16/2011)
SPIE 7104, 70147G-1	Gemini Helium Closed Cycle Cooling System, Lazo, M. et al, (2008)
SPIE 7733, 77333V	Low-vibration high-cooling power 2-stage cryocoolers for ground-based astronomical instrumentation, Jakob, G. & Lizon, J.L. (2010)
ISBN: 978-0-309-14979-2	Selling the Nation's Helium Reserve, Committee on Understanding the Impact of Selling the Helium Reserve, National Research Council of the National Academies, National Academy Press (2010)

1.4. Background and Motivation

For the SOFIA Early Science and Basic Science missions, as well as the early portions of Segment 3 operations leading up to the Full Operational Capability (FOC) program milestone, all of the (first-generation) SIs have relied on expendable liquid cryogens, LN2 and LHe, for cooling of their detector arrays, cold optics and electronics. There are a number of operational, safety and cost issues surrounding this instrument cooling approach, particularly with LHe.

Operationally, the use of liquid cryogens requires cryogen servicing at regular intervals, and often at times that are inconvenient or not well-aligned with standard work shifts for staff support (e.g., weekends, nights, holidays, etc.). Whenever the cold SI is being accommodated at AFRC Bldg. 703, this support needs to be carefully coordinated with Science Mission Operations and S&MA. When the SI is installed on the SOFIA Telescope Assembly (TA) for hangar ops, line ops or flights, there are additional aircraft access considerations that require coordination with Flight Operations. These staffing and shift coverage requirements are significant cost-drivers.

Potential hazards surrounding the use of liquid cryogens include cryogenic "burns" to the skin due to spills during servicing, asphyxiation if cryogen boil-off displaces air resulting in O_2 levels below safe levels, as well as over-pressurization of LHe cryogen reservoirs resulting from a vacuum leak and resulting rapid boil-off event.

Cryogenic transfers and servicing are routinely and safely performed with adequate training programs and Personal Protective Equipment (PPE). That said, differences between the various S&MA jurisdictions involved have led to protracted discussions and implementation of procedural and equipment changes.

The importance of mitigating any asphyxiation hazard related to displacement of air (and therefore oxygen) due to venting of evaporated liquid cryogens drives analyses that generally make extremely conservative assumptions for the relevant enclosed volumes and SOFIA cabin air exchange rates. It is notable that these considerations tend to limit the maximum SI cryogen load, which has the potential to impact operations by decreasing the cold hold times and the cryogen servicing interval.

Analytical models and testing both show that in the event of a breach of the vacuum jacket surrounding an SI LHe cryogen reservoir, the entire volume of LHe can boil off very suddenly, in a matter of seconds. Also, icing of condensates around the non-return relief valves that vent the nominal boil-off can lead to less rapid, but nonetheless catastrophic over-pressurization. These are known hazards that are mitigated by design, analysis and testing, to ensure that there are redundant and independent flow paths and certified pressure relief devices, that the cryogen reservoir neck tubes are sized adequately to minimize the pressure rise from a rapid boil-off event, and that the cryogen reservoir qualification and acceptance test programs envelope the analytically determined pressure rise with a safe margin.

As with the other safety considerations surrounding the use of liquid cryogens, the hazard mitigations considered prudent and necessary are costly and have evolved over time with changes in the organization of the SOFIA program and the applicable airworthiness certification authority.

In addition to these operational and safety related considerations and their attendant costs, there is another more direct cost associated with the use of expendable liquid cryogens: the recurring cost of the cryogen itself. This is especially and acutely true for LHe, due to market conditions for this limited, non-renewable resource. As outlined in detail within “Selling the Nation’s Helium Reserve” (2010), recent and ongoing changes in the role of the Federal Government in the regulation and sale of the Federal Helium Reserve have already resulted in market instabilities, both in price and availability, and this is projected to get significantly worse within the timeframe of SOFIA’s nominal 20 year mission.

Because the use of CCC systems as an alternative to the use of expendable liquid cryogens addresses many of these operational, safety and cost-related concerns, their use has become ubiquitous in many industries and scientific research endeavors requiring such cryogenic temperatures, and several of the cold head technologies have reached industry standard maturity levels. Indeed, CCC installations have become quite commonplace as facility-provided systems at most world-class astronomical observatories, and, as a result most modern astronomical instruments that require cryogenic cooling for use at such observatories are now being developed to use CCC systems in lieu of expendable LHe.

The costs associated with the development, airworthiness certification and use of CCC systems for SOFIA are not insignificant but are largely dominated by non-recurring, up-front development and procurement costs, while the continued use of expendable liquid cryogens is a recurring expense of a limited and unstable resource that is prone to cost "spikes" and availability issues, posing unscoped programmatic cost and schedule risks to the SOFIA program.

A number of trade studies related to the use of CCC systems for SOFIA SIs have been conducted, by the SOFIA Science Instrument Development group, the Standard New Astronomy Cryostat for SOFIA (SNACS) effort, and by the upGREAT team. These are summarized in Appendix B. The details of each trade study are not presented herein; however, important conclusions, updates to reflect information learned subsequent to the initial study, and implications to the specification and implementation of the SOFIA Cryocooler System are discussed in the relevant sections of this document.

2. CONCEPT FOR THE SOFIA CRYOCOOLER SYSTEM

2.1. System Overview

At the time of the development of this Cryocooler Concept of Operations and the associated SOF-NASA-SPE-SE01-2076, *upGREAT Cryocooler System Specification*, the Level 1 and 2 requirements for SOFIA support of cryocoolers have not yet been baselined within SOF-DF-SPE-SE01-003, *SOFIA System Specification*, or SOF-DF-SPE-SE01-004, *SOFIA Airborne System Requirements*. However, the SOFIA program has clearly indicated a commitment and intent to do so in a timely manner to support integration and commissioning of the upGREAT channels, which will be the first to utilize CCCs in lieu of expendable liquid cryogen baths.

As part of the MCCS Power Distribution System (PDS) upgrades implemented during the Segment 3 downtime, a power budget to operate the cryocooler compressors aboard SOFIA, above and beyond the power budget already allocated to SIs, was established. In addition, the ground segment aspects of cryocooler support of SOFIA SIs were initiated with the development and baseline of APP-DA-SPE-SE01-2081, *DAOF Cryocooler and Accommodations Specification*, and a corresponding Facility Requirements Document (FRD) for upgrades that will ultimately support CCC operations within any of the five (5) DAOF Instrument Readiness Rooms (IRRs) as well as the Preflight Integration Facility (PIF).

Though the specifics of the CCC operations are likely to be somewhat dependent on the thermal design of individual SI cryostats, it is anticipated that once an SI has been cooled down in preparation for cold functional checks and observations, quasi-continuous CCC operations will be needed to maintain cryostat temperatures for the duration of the observing cycle. This includes operations in the AFRC Bldg. 703 IRRs, as well as aboard the SOFIA observatory. The specifics of the relevant operational scenarios and use cases are described in Section 2.4.

This Concept of Operations document references the need for quasi-continuous "24 / 7" power to CCC systems and potentially SIs, including operations between flights during an observing cycle, and addresses some of the associated Operations Engineering staffing impacts and implications. This is the subject of APP-DA-PLA-PM17-2078, *"24/7" Power and Network Connectivity between Flights Concept of Operations*, which will address in more detail how SOFIA will meet this need.

Various operating parameters, including compressed He supply and return line pressures, will be measured and monitored during CCC operations. CCC compressors also typically provide various Control and Monitoring signal functionality via digital and/or analog data connections, and these will be leveraged to provide additional insight into the Health and Status of the system, though the details of this will of course be dependent on the functionality provided by the selected compressor(s). Ultimately, it is envisioned that the Cryocooler System will interface with the SOFIA MCCS Data Acquisition Subsystem (DAS) for monitoring and archival of these housekeeping parameters, however the initial Phase I implementation of the system will provide such signals only to the SI, which will be responsible for processing and recording these parameters.

On the SOFIA observatory, compressed He lines will be passed through the cable load alleviator (CLA). Although this necessitates the use of long lines between the compressors and cold heads, this is unavoidable due to the size, mass and vibration levels associated with the compressors, which will be mounted to the airframe. At AFRC Bldg. 703, the use of long lines will ultimately allow the compressor(s) to be located outside the laboratory to reduce the noise levels to which personnel would otherwise be routinely exposed, as well as heat rejection to the ambient laboratory environment, which would likely overwhelm the capacity of the AFRC Bldg. 703 HVAC systems that maintain temperature control of the lab facilities.

2.2. Operational Environments and Interoperability Considerations

Because SIs are operated in both the lab environment as well as aboard the SOFIA observatory, the SOFIA Cryocooler System spans multiple segments of the SOFIA system.

The cold heads themselves are integral to the SI cryostat, and as such are provided by the SI developer. Removal and replacement of a cold head generally requires “breaking configuration” of the SI cryostat (i.e., warm-up, venting and opening of the vacuum dewar).

One very important aspect of this is the crucial importance of ensuring that the SI cold head(s) are fully compatible with both the ground-based CCC systems in the laboratory environment as well as the airborne CCC systems aboard the SOFIA observatory, and will provide the requisite thermal performance when operating in both environments.

Typically, CCCs are engineered and procured as fully integrated, “turn-key” systems, in which the He compressor, cold head, and interconnecting He lines and power lines are all designed, built and tested by the same manufacturer / vendor. Indeed, it is not uncommon for such vendors to publish disclaimers and caveats regarding the performance of hybrid “mix and match” systems, in which a cold head from one vendor is paired with a compressor from another vendor. In some cases, the vendor will go beyond this and annotate quotes with stronger warnings that state that they cannot guarantee the performance or be held responsible for malfunctions of the integrated system, and/or that doing so will render the factory warranty null and void.

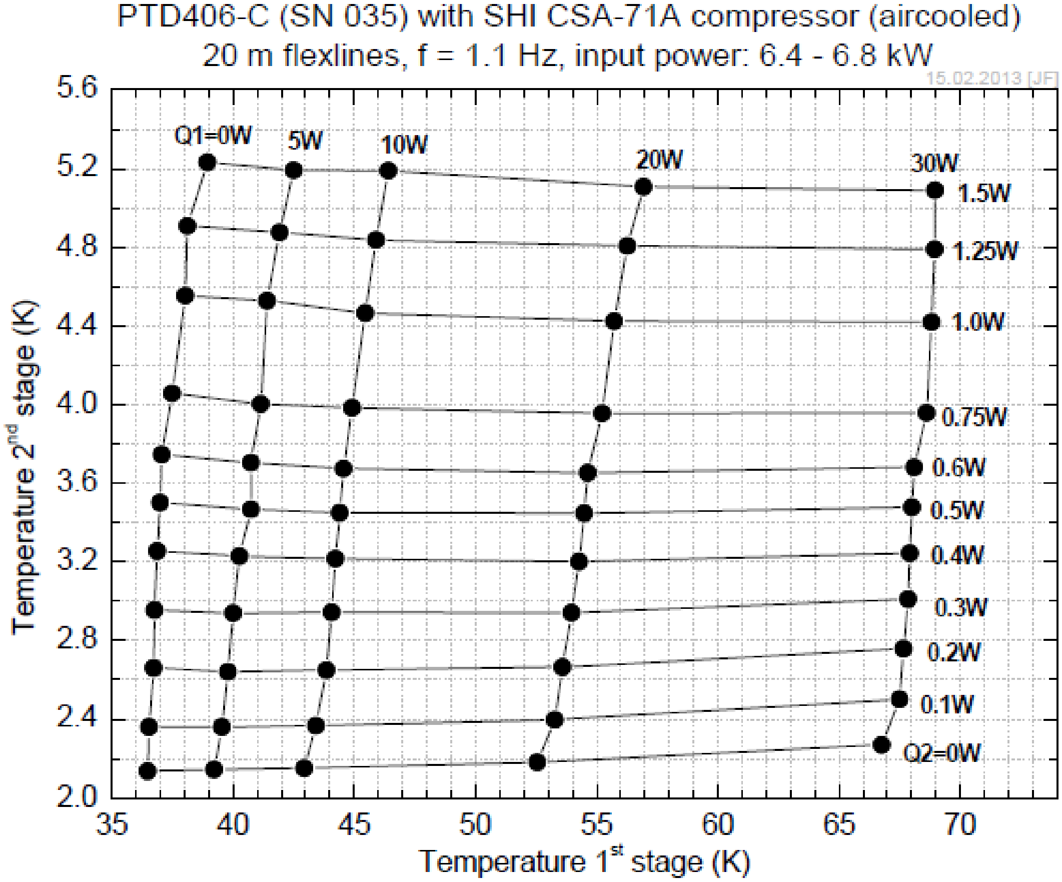
While such warnings and disclaimers do complicate the specification as well as the formal Verification and Validation (V&V) approach for such systems, it is worth noting that it is not at all uncommon (at least within the world of astronomical instrumentation) for instrument developers to select cold heads that meet their specific thermal and mechanical requirements when paired with the facility-provided compressors available at the target observatory.

Figures 2.2-1a and 2.2-1b are representative thermal performance "maps" showing the heat sinking capacity vs. temperatures at the 1st and 2nd stages of the cold heads, in both cases characterizing the measured performance of a "hybrid" system that has been specified for use by the upGREAT team, using two different air-cooled CCC compressors by Sumitomo Heavy Industries (SHI) Cryogenics operating from 3-phase, 50 Hz power, each driving a transMIT PTD406-C Pulse Tube cold head. This cold head is a variant of a commercially available Pulse Tube, modified per customer specifications to include a small (~0.2 liter) LHe "pot" on the 2nd stage heat sink. This dampens temperature fluctuations that are intrinsic to Pulse Tube operations, from 300 mK peak-to-peak to ~20 mK peak-to-peak at the 2nd stage heat sink, and also mitigates temperature rises during any brief interruptions in CCC compressor operations.

While each pairing of CCC compressor and cold head will result in a different thermal performance map, and other factors such as length and diameter of the He lines and frequency of the rotary valve drive also come into play, these all share the characteristic that the thermal pumping performance (heat sinking capacities) of the two stages are interrelated and dependent on the temperatures and heat loads of both stages.

Note that while these He compressors can be operated using 50 Hz and 60 Hz input power, use of 60 Hz input power results in higher thermal performance of the integrated system.

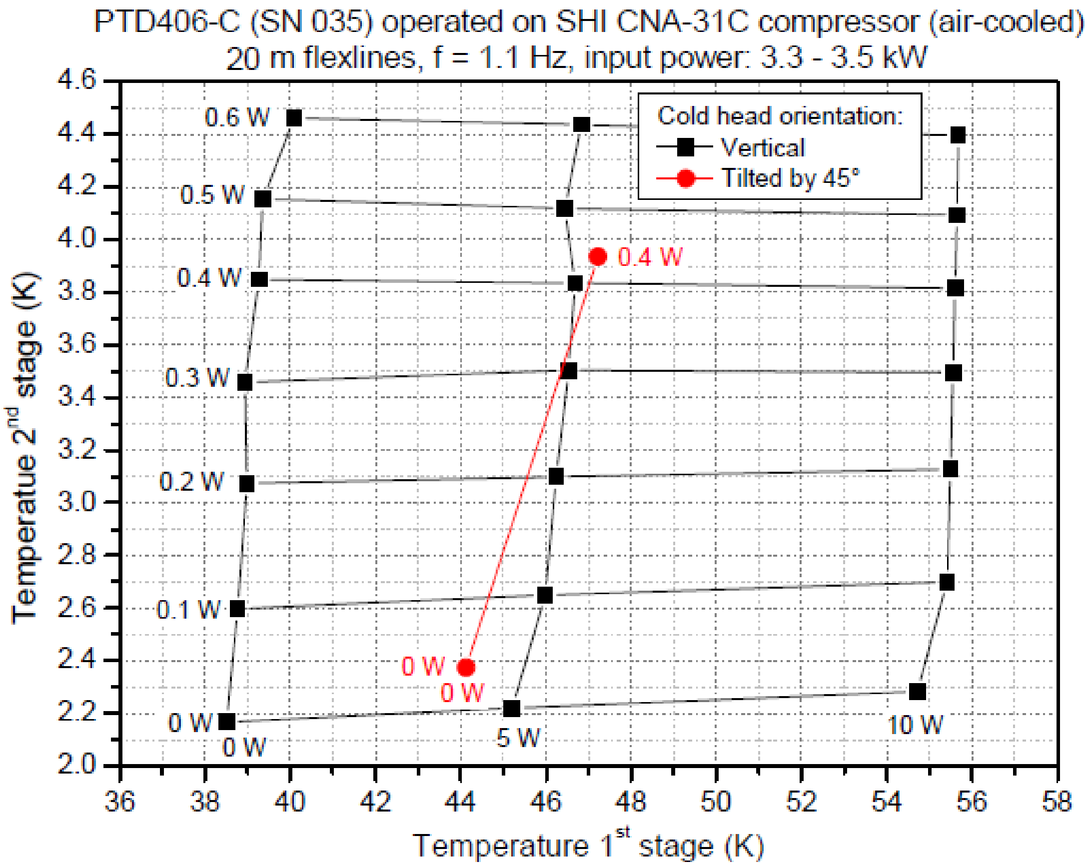
Operation of PTD406-C with air-cooled SHI compressor CSA-71A



Minimum temperature at 2nd stage	< 2.4 K
Cooling power 2nd stage	≥ 0.75 W @ 4.2 K
Cooling power 1st stage	≥ 20 W @ 57 K
Cool down time to 4.2 K	< 75 minutes *(no additional heat load)*
Input power in steady state	6.4 – 6.8 kW
Length of split line to rotary valve	75 cm
Weight of cold head with rotary valve	20 kg without vacuum vessel and radiation shield
Frequency controller for rotary valve mains supply	220 V / 50 Hz, ≤ 40 W el. power consumption

Figure 2.2-1a: Thermal performance map of transMIT PTD406-C Pulse Tube cold head driven by an air-cooled SHI CSA-71A He compressor via 20 m He flexlines (rotary valve powered via Toshiba VFS11S-2004PL-WP Variable Frequency Drive inverter set to 1.1 Hz)

Operation of PTD406-C with air-cooled SHI compressor CNA-31C



Minimum temperature at 2nd stage	< 2.4 K
Cooling power 2nd stage	≥ 0.45 W @ 4.2 K
Cooling power 1st stage	≥ 10 W @ 56 K
Cool down time to 4.2 K	< 90 minutes *(no additional heat load)*
Input power in steady state	3.3 - 3.5 kW
Length of split line to rotary valve	75 cm
Weight of cold head with rotary valve	20 kg without vacuum vessel and radiation shield
Frequency controller for rotary valve mains supply	220 V / 50 Hz, ≤ 40 W el. power consumption

Figure 2.2-1b: Thermal performance map of transMIT PTD406-C Pulse Tube cold head driven by an air-cooled SHI CNA-31C He compressor via 20 m He flexlines (rotary valve powered via Toshiba VFS11S-2004PL-WP Variable Frequency Drive inverter set to 1.1 Hz)

Figure 2.2-1a characterizes the measured thermal performance of the transMIT PTD406-C Pulse Tube cold head with the (larger) SHI CSA-71A compressor. The thermal performance map shown in Figure 2.2-1b represents the performance of the same transMIT PTD406-C Pulse Tube cold head with the (smaller) SHI CNA-31C compressor, and also shows the measured performance degradation of the cold head when tilted from the optimal vertical orientation to 45 degrees, reflecting a measured 2nd stage temperature rise of about 0.1 K.

Pairing a cold head to a compressor is a non-trivial activity that involves optimization of a fairly large parameter space, including several adjustable orifices within the cold head and/or the associated rotary valve, expansion volumes, the compressor static He charge pressure, and in some cases varying the frequency of the rotary valve drive. This often involves iterative test runs and suitable test lab infrastructure, and is generally performed by the cold head vendor (or system integrator) within their own facilities, and not “in the field” by the end user.

As a consequence, it is generally impractical to re-tune (or replace) an SIs cold head(s) when the SI is relocated between the laboratory and the SOFIA observatory, i.e., to achieve the necessary thermal performance with both the ground-based and airborne CCC compressors and associated compressed He lines.

The transportation and installation of an SI aboard the SOFIA observatory is a labor-intensive and time-constrained operation. The details of this are somewhat specific to the mechanical and thermal designs of each SI, but generally speaking, it is important to minimize the temperature rise of the SI detectors and/or readout electronics during the transportation and installation, leading up to cold functional checkout of the SI (i.e., hangar ops and line ops.) and especially the inflight astronomical observations.

Initial testing of the upGREAT LFA cryostat indicates that the total time between switch off and disconnection from the lab CCC system to the connection and activation of the airborne CCC system aboard SOFIA will need to be kept to < 2 hours total. Therefore, it is considered operationally impractical to physically relocate and integrate the CCC compressors aboard SOFIA such that the same physical compressor units can be used in both environments.

This scenario provides the basis for the derived requirements that the CCC compressors and associated systems in these two operational environments be distinct, functionally equivalent (if not identical), and fully compatible with the SI-provided cold head, from both physical interface and thermal performance envelope points-of-view.

2.2.1. Laboratory Environment (AFRC Bldg. 703)

When upGREAT is operating cold within the laboratory environment, the cold heads will be serviced by compressors that will ultimately be accommodated outside the laboratories, e.g., in one or more mechanical rooms or within air-conditioned enclosures (potentially sheds external to the AFRC Bldg. 703 structure). These compressors will interface with the SI cold heads via compressed He lines up to 40 meters in length, which will be routed from the compressor locations to the labs, where necessary via cable chaseways or plenums.

During the implementation phase for the required AFRC Bldg. 703 facility upgrades, as well as during any deployments to remote operating sites, it will likely be necessary for the compressors to be located within the SI laboratory itself. This will result in additional acoustic emissions and heat load into the laboratory environment, and possibly require mitigations such as the mandatory use of PPE hearing protection, and possibly portable air conditioning units.

Compressor operations manuals and data sheets specify ambient temperature ranges. As an example, the SHI compressors selected for use with upGREAT specify that operation between 4 - 28 C is recommended, with 5% capacity loss at ambient temperatures in the range of 28 - 38 C. Above 38 C, there will likely be further degradation in thermal performance and a risk of unplanned over-temperature conditions leading to compressor shutdown. Since temperatures in the high desert summer months can easily reach the range of 38 - 48 C, it is clear that the compressors will need to be operated in a conditioned environment.

In developing the SE01-2081 specification for the AFRC Bldg. 703 laboratory CCC accommodations, a survey of commercially available CCC systems was conducted, with particular focus on the physical, power and thermal performance envelopes of the compressors. The results of this survey informed the functional, physical and interfaces sections of SE01-2081, supporting our goal of outfitting the AFRC Bldg. 703 with CCC systems that will meet the initial need (i.e., upGREAT, ca. Dec. 2014) without unnecessarily constraining future (3rd generation) SIs to the same models, vendors or CCC technologies.

The AFRC Bldg. 703 laboratory environment is considerably less constraining than the SOFIA airborne environment (not burdened with very stringent power allocations and frequency conversion inefficiency, mass budget, crash loads, physical envelope, tilt, etc.). This affords some flexibility with respect to the selection and use of laboratory compressors that likely provide additional performance margin relative to the airborne compressors.

For operations in the laboratory environment, there will be no losses associated with input power Frequency Conversion; however, with reasonably conservative estimates of Power Factor (PF), each compressor will require a 200 VAC (+/- 10%), 3-phase (3W + PE), 60 Hz power circuit, with a 35 A minimum service ampacity, and maximum fuse or CB rating of 60 A.

2.2.2. SOFIA Airborne System Environment

Unlike the laboratory CCC systems, the airborne segment of the SOFIA Cryocooler System will be required to meet airworthiness and environmental (vibration, emergency "crash" load factors, etc.) requirements.

2.2.2.1 Physical Accommodations and Fluidic Compressed He interfaces to SI

Aboard SOFIA, the compressors will be mounted within the cabin, with the compressed He lines wrapped through the CLA and connections being made to the cold heads servicing the SI cryostats. The routing of the He lines through the CLA is such that this subsystem will be considered a permanent installation, even if the compressors themselves are pallet-mounted such that they could be considered semi-permanent or temporary in nature.

The compressed supply and return He lines will need to be wrapped through the CLA. The thermal performance of the interfaced cold head(s) are affected by the cross-section and length of these lines and, therefore, the determination of the physical location of the compressors should consider these factors as well as access considerations.

While SOF-DA-ICD-SE03-036 (TA_SI_01) indicates a nominal cable length of ~15 meters through the CLA, with additional lengths needed for connects between the Cryocooler compressors to the CLA Disconnect Panel, and between the CWP and the SI cryostat(s), minimum total line lengths of 30 to 40 meters for each of the supply and return lines are likely.

Such He line lengths are longer than in a typical CCC installation (the standard length for a 4.2 K CCC system is typically 10 to 20 meters); however, runs over 100 meters have been used successfully in ground-based observatory applications.

The line lengths and diameters (and resulting pressure drop) do affect the integrated system performance. For example, 4.2 K CCC systems typically use He lines with an ID of ¾ inch (19 mm); however, characterization testing using flex lines with a 25.1 mm ID showed significantly better performance. Also, though concerns have been raised regarding the length of the He lines in the SOFIA airborne application, testing of the Sumitomo compressor and transMIT Pulse Tube cold head reflected in Figure 2.2-1a but using a more representative 40 meter He line length actually showed a ~5% improvement cooling performance with respect to the 20 meter line used in the earlier testing. This is of course an encouraging result.

Because the two (2) pairs of compressed He lines will be routed through the CLA, it is important that this portion is tolerant of repeated flexing cycles and has an appropriately small minimum bend radius. The static charge pressure, as well as the high (supply) and low (return) pressures, will be dependent on the specific pairing of compressor and cold head; however, as this portion of the installation will be considered permanent, the selection of the lines through the CLA should envelope the most stringent application with respect to pressure rating and diameter. Due to the pressurized He application, such tubes need to be of seamless construction and will be an annularly- or helically-corrugated stainless steel flexible line with a braided stainless steel overwrap. Typical CCC lines have a Maximum Design Pressure (MDP) of 2760 kPa (400 psig) and a Maximum Normal Operating Pressure (MNOP) of 2410 kPa (350 psig).

2.2.2.2 Power Interface

The compressors and the associated supply and return He lines, fittings, transducers, and control circuitry operate as an aircraft subsystem. They will be mechanically mounted to the aircraft and supplied electrical power via the Power Distribution Subsystem (PDS). APP-DF-ICD-SE03-2038 and SOF-AR-ICD-SE03-2029 para. 3.2.1.4 presently define a 20 kVA allocation of 115 VAC, 400 Hz, 3-phase power from Observatory Bus 4. Some consideration was given to providing two 10 kVA power interfaces (i.e., one for each of the two CCC compressors and associated frequency converters), but it was determined that providing a single 20 kVA interface would provide additional flexibility in system implementation, and result in higher power conversion efficiencies.

A Circuit Breaker (CB) at the Observatory Power Panel (OPP) will be used to protect the 2 AWG platform PDS power feed wires and to control the application of power to the CCC compressor power interfaces. This CB will not be used for routine on/off control of the CCC compressors.

During discussions at the Cryocooler SRR, it was agreed that the Frequency Converter(s) needed to operate the cryocooler He compressor(s) aboard SOFIA would be provided by the SOFIA observatory within the scope of the MCCS PDS, and therefore removed from the scope of the Cryocooler System. This decision has been reflected within the contextual diagram provided within this Concept of Operations document as Figure 1.2-2a, but the SE03-2038 and SE03-2029 ICDs have not yet been updated via the Configuration Change Request (CCR) process to reflect an allocation of 17 ~ 18 kVA of 115 VAC, 60 Hz, 3-phase power (20 kVA @ 400 Hz reduced by the 85% ~ 90% efficiencies typical of modern solid-state Frequency Converters).

The technical instructions and manuals for the SHI compressors include several warnings regarding the use of inverters to power the He compressors. Discussions with SHI technical staff have indicated that these warnings reflect concerns associated with compressor motor winding overheating resulting from the poor quality of the AC waveform from certain solid-state inverters, i.e., high Total Harmonic Distortion (THD). SHI has acknowledged that they do have “inverter duty” compressors in their product line, however none that are air-cooled at this time or in the foreseeable future.

The Cryocooler Project development team has pointed out that in our airborne application, the use of a Frequency Converter (i.e., inverter) to convert 400 Hz aircraft power to 60 Hz power is unavoidable, but a power quality specification that could be levied upon the Frequency Converter(s) is not available. This has been tracked as a potentially significant threat, but further discussions with the MPIfR upGREAT project team have revealed that they have been operating their SHI CSA-71A and CNA-31C compressors with a solid-state 50 Hz to 60 Hz Frequency Converter for many months with no observed overtemperature conditions or other ill effects noted. In addition, the aircraft Frequency Converters that are being considered for the MCCS PDS power interface to the Cryocooler System have a specified THD level that compares favorably with that of 60 Hz utility power sources.

There has been some discussion surrounding the possibility of protecting the CCC compressor power source with an Uninterruptible Power Supply (UPS). This could prove beneficial to the overall reliability of both the airborne and laboratory operations. A UPS is essentially a Frequency Converter with a backup battery that maintains power at the output for some specified period of time after a lapse in the input power feed. While 20 kVA is a relatively large load to protect with a UPS, the objective would be to help isolate the CCC compressors from short-duration transients, such as the switchover from ground cart power to aircraft power. Since the battery back-up durations for reasonable size and mass UPSs tend to be in the range of 8 ~ 10 minutes, it probably isn’t practical to consider the use of UPSs to keep the CCC systems active for longer-duration power outages, such as during an aircraft tow-out from the hangar to the flight line, or vice versa.

UPS use in both the SOFIA observatory and in the SI laboratories would have the additional benefit of supporting an annunciation or alert function that could interface to SI computers (e.g., to help “safe” the SI) or even send a page or SMS text message to offsite staff in the event of a CCC power interruption.

It is acknowledged that a UPS for the airborne Cryocooler System may be larger and heavier than can be accommodated aboard SOFIA, and would need to interface with the Emergency Power Disconnect (EPD) discrete signal from the SOFIA decompression relay (28 VDC signal on U401 J3) and immediately disable the battery back-up function in the event of a signaled decompression event.

2.2.2.3 Power Budget Constraints on Airborne CCC Compressor Selection and Operations

The upGREAT Cryocooler System will ultimately be required to accommodate SIs with 2 cold heads. This provides flexibility with respect to both the physical and thermal design of SIs. The first SOFIA SI that will use CCC cooling is GREAT, which features 2 modular cryostats allowing it to make concurrent measurements in 2 different wavelength bands. The newer cryostats (known as upGREAT) will support multi-pixel observations at 1.9 ~ 2.5 THz (Low Frequency Array) and at 4.7 THz (High Frequency Array), which is expected to yield a 10-fold increase in observing efficiency as compared with the original single pixel GREAT receiver cryostats. Each of these 2 new upGREAT cryostats will require a dedicated 2-stage cold head for CCC cooling. Other SIs may opt to use two cold heads in parallel within a single cryostat to increase the heat pumping capacity at both the 1st and 2nd stage cold plates.

One characteristic of many CCC systems is that when initially started up with a warm thermal load and cold head they draw a higher "maximum" input power level, which is reduced to a somewhat lower "steady-state" input power level once the thermal load and cold head reach a certain temperature. The timing of this change in the power profile is of course dependent on the specific CCC system as well as the thermal mass of the SI cryostat being cooled, but it is typically in the range of 30 ~ 60 minutes.

Depending on the actual "maximum" input power levels, Power Factor of the CCC compressors and the efficiency of the Frequency Converter, concurrent operation of both the upGREAT LFA and HFA channel cryostats and two He compressors will likely involve a phased start-up (i.e., "stagger starting") of the compressors. This will ensure that they are not concurrently drawing their "maximum" input power levels, in order to stay within the presently allocated 20 kVA SOFIA power budget from Observatory Bus 4.

2.2.2.4 Cryocooler System Housekeeping, Monitoring and Control

A variety of Cryocooler System housekeeping (HK) parameters will be obtained, including supply and return He line pressure measurements and various compressor and gas temperatures. This may involve the routing of transducer excitation power from the MCCS Data Acquisition System (DAS) Instrumentation Excitation rack, either via patch panel and cable interfaces defined in SOF-AR-ICD-SE03-2029 (e.g., U401 J52) or potentially (and preferably) via existing instrumentation cabling.

It is envisioned that the Cryocooler System HK parameters will ultimately be routed to the MCCS DAS for enhanced visibility into system performance and archival. However, for the initial Phase I implementation to support the upGREAT LFA channel, it has been agreed that these signals will be routed only to the SI, which will be responsible for any conditioning, digitization, monitoring and archival. The GREAT SI will also be responsible for any remote monitoring of Phase I Cryocooler System performance.
Control and monitoring functions of the Cryocooler compressors will need to be accessed during operations by SI team personnel and/or Mission Operations crewmembers. Because such access may be needed during inflight astronomical observations, these controls must be accessible to flight crew

without the need to cross boundaries or cage the telescope. Any personnel accessing the Cryocooler System, either for operation or maintenance, should be trained in Cryocooler operations.

The Cryocooler System will include a variety of "interlocks", some intrinsic to the COTS He compressor and some added by the Cryocooler project team, which will monitor operating pressures, temperatures, tilt angles and accelerations, and will shut down the compressor if any of these parameters go outside of established nominal operating conditions. Such a shut-down will display a fault indication light on the Cryocooler System control panel and sound an audible alarm, but manual intervention will be needed to silence the alarm, clear the fault condition, reset the interlock, and restart compressor operations.

For at least the Phase I implementation of the upGREAT Cryocooler System, it will be the responsibility of the GREAT SI team to monitor the proper function of the Cryocooler System (via the GREAT data acquisition systems and interfaces), and respond as needed with any corrective action.

2.2.2.5 Cryocooler System Cooling and Heat Rejection to SOFIA Cabin

The Cryocooler compressors will be air-cooled, using cabin air conditioned by the nominal Boeing 747-SP air handling systems. The compressors have internal cooling fans that draw cool air in through one or more side panels, through a heat exchanger, and vent warmer air to the cabin through the top panel. The compressors require minimum installation clearances to ensure an effective cooling airflow. There is some anecdotal evidence that certain air-cooled cryocooler compressors have experienced performance issues related to inadequate cooling during operations at higher elevations, such as the Gemini-N observatory at Mauna Kea in Hawaii. However, several cryocooler system vendors have cited a proven track record of their systems' performance while operating at the 8,000 to 10,000 foot pressure altitudes typical of SOFIA during stratospheric flights up to the ceiling of 45,000 feet altitude. That said, the importance of respecting the specified minimum installation clearances and maximum ambient temperature conditions has been highlighted as being particularly important at higher elevations.

The heat rejection of air-cooled CCC compressors to the ambient environment is significant, essentially identical to the input power. In other words, a compressor that draws 7.5 kW (steady state) and 8.3 kW (maximum) of input power will also reject the same number of Watts in thermal power during operation. So, as a first-order approximation (neglecting the effects of the Power Factor), an air-cooled CCC system with a 20 kVA power budget will reject ~20 kW of heat into the SOFIA cabin.

This is a significant additional heat load aboard SOFIA, and certainly it will be necessary to ensure that this will not create a localized "hot spot" where this might adversely impact SOFIA Telescope Assembly or MCCS subsystem operations, particularly during extended ground operations (e.g., line ops) during the summer daytime hours. However, to put this in perspective, the 747SP is designed to accommodate nearly 350 humans (331 passengers, 3 cockpit crew plus flight attendants), and given that humans each produce ~100 W of heat, it seems clear that the 747SP environmental control systems are able to handle at least ~35 kW of heat above and beyond that generated by the avionics and other active aircraft systems. Several SOFIA staff members with significant flight experience have also pointed out that on most flights, a "space heater" in the vicinity of the PI Racks and mission crew workstations would be a most welcome addition, as the crew cabin tends to be a bit on the chilly side during the long stratospheric flights.

2.2.2.6 Acoustic Emissions

CCC compressors are noise sources, emitting upwards of 70 ~ 74 dBA at a distance of 1 meter. This is not expected to add significantly to the ambient inflight noise environment aboard SOFIA, when all on board are generally wearing noise-cancelling headsets for voice communications with other crew members. However, during extended ground operations (e.g., during hangar ops or line ops), it may be advisable or even necessary for those in the vicinity of the CCC compressors to wear appropriate Personal Protective Equipment (PPE), i.e., ear plugs or similar.

Cold heads are also a source of acoustic emissions, though typically only ~30 dBA at a distance of 1 meter (for both PT and GM technology cold heads).

2.2.2.7 Effect of Tilt on Cold Heads

Some cold heads are sensitive to orientation. Pulse Tube cold heads, in particular, perform best when in a vertical orientation and exhibit convection losses and associated performance degradation with respect to cooling power and/or base temperature stability when tilted off the vertical axis. Because the cold heads are integral to the SI cryostats, which are mounted to the TA IMF, the cold heads are subject to the full range of TA elevation angles (nominally ±20 degrees from vertical). Gifford-McMahon cold heads tend to be far less sensitive to tilt-related performance effects but have mechanically- or pneumatically-driven displacers and associated moving parts that are integral to the cold head (and therefore the SI cryostat) and tend to exhibit increased vibration levels. Such considerations fall primarily within the purview of the SI developer and may be a factor in the selection of the cold head(s).

2.2.2.8 Effect of Tilt, Acceleration and Turbulence on CCC Compressors

CCC compressors also tend to be sensitive to tilt and other perturbations to the effective gravity vector. This is related to disturbances in the level and flow of the oil, which both lubricates and cools the compressors during operations. Excessive tilt angles can lead to overheating of the compressor, which can result in a shutdown condition.

In addition, large and/or sudden disturbances, such as tilting or extreme turbulence, can overcome the oil separator, possibly leading to oil contamination of the He. The compressors include adsorbers that are intended to capture oil mist, but if these become saturated, and oil breakthrough into the He lines and the cold heads occurs, this would effectively end that observing campaign and necessitate an instrument warm-up and lengthy cold head clean-up procedures (estimated minimum 1 week recovery).

Typically, CCC compressor manufacturers specify a maximum non-operating (i.e., storage) tilt angle, as well as a smaller operating tilt angle. For example, the Sumitomo Heavy Industries (SHI) compressors selected by the upGREAT developer have a specified maximum non-operating tilt angle of ±30 degrees and a maximum operating tilt angle of ±5 degrees. The non-operating tilt angle is not expected to be an issue other than noting that the compressors must remain within the smaller operating tilt angle for a specified period of time (approximately 45 ~ 60 minutes) before the compressor is switched on.

The take-off sequence includes the ground take-off roll, climb-out, acceleration in level flight, and climbing to higher flight level. See Figure 2.2.2-1 for a graphical depiction of the various phases of a SOFIA take-off and climb-out profile.

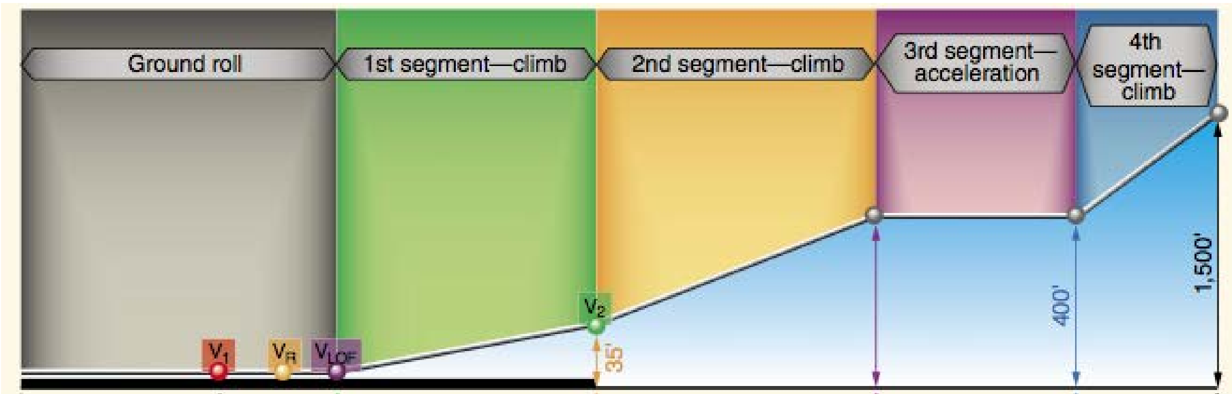
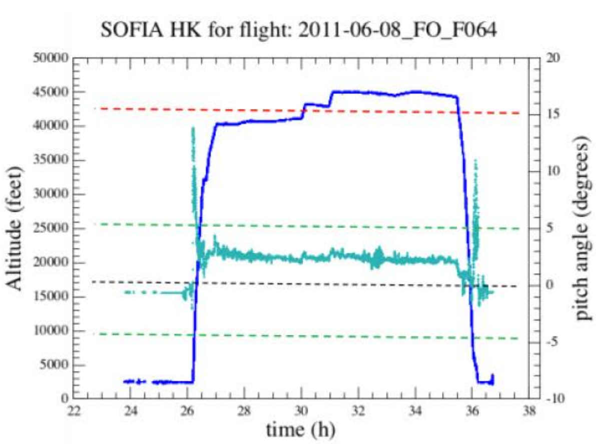


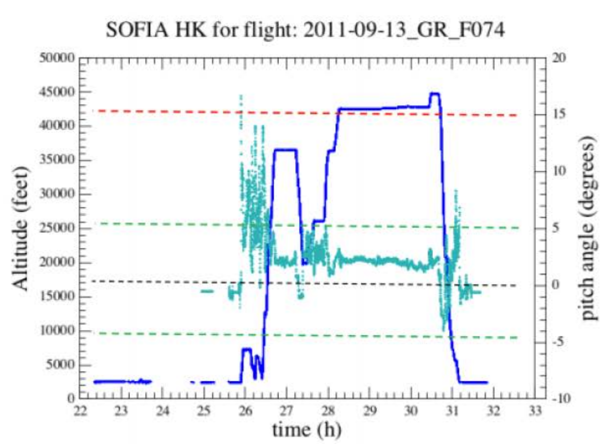
Figure 2.2.2-1: Various phases of a SOFIAtake-off and climb-out profile

A review of aircraft flight data from recent SOFIA flights reflects several distinct tilt and acceleration regimes during the various phases of the flight. Generally, each flight has two periods during which the pitch angle of the aircraft exceeds 5 degrees, once during take-off and ascent, and once during the descent and final approach.

Please see Figures 2.2.2-2a and 2.2.2-2b for plots showing time series housekeeping pitch angle (green trace) and altitude (blue trace) data for two different SOFIA flights during the Early Science mission. The green dashed line represents the compressor operational tilt limit, and the red dashed lines represent the non-operational (storage) tilt limit.



Pitch angles during a typical flight



Pitch angles during a non-typical flight

Figure 2.2.2-2a: Pitch angles and altitudes of SOFIA aircraft during a typical flight; and
Figure 2.2.2-2b: during a non-typical flight.

A typical flight generally includes 2 episodes during which the pitch angle is in the 10 to 14 degree tilt range, one during take-off and ascent, and other during descent and final approach, each of 5 ~ 10 minute duration. However, there have been flights with longer-duration exposure to pitch axis tilt in the 10 to 15 degree range, even exceeding 15 degrees during very brief "spikes".

The tilt in the roll axis is not anticipated to be a concern for CCC compressor operations, due to the standard aviation practice of executing coordinated turns, in which the rudder and ailerons are operated in concert to overcome "adverse yaw", resulting in a gravity vector that typically does not significantly deviate from the aircraft normal axis. See Figure 2.2.2-3 for a graphic illustration of the forces acting on an aircraft during coordinated turns.

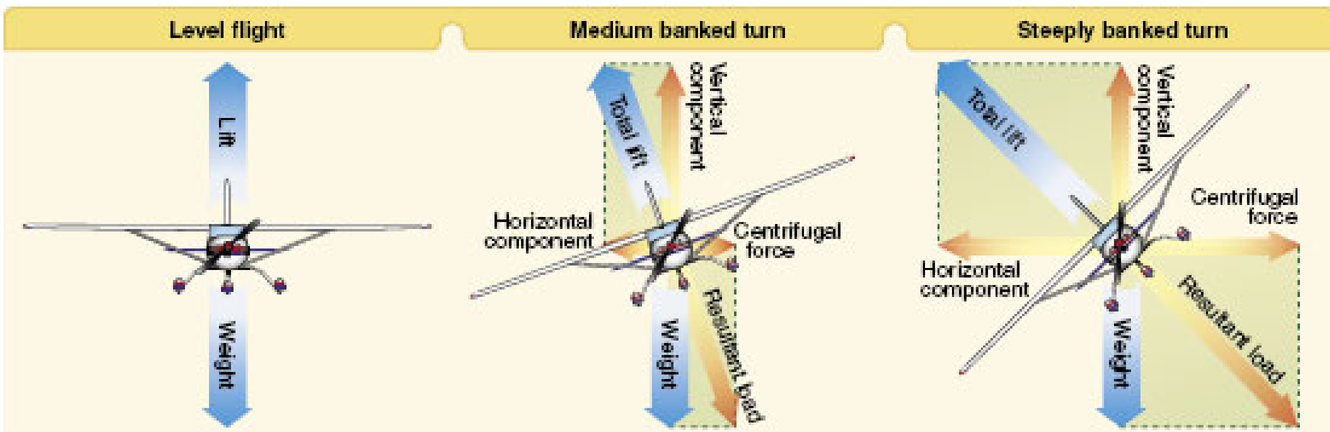


Figure 2.2.2-3: Forces acting on an aircraft during coordinated turns

It is possible that some CCC compressors (particularly those with a horizontal compressor "capsule") may be more tolerant of tilt in certain axes, and if so, it may be feasible to mitigate the risk of contamination by orienting the compressors such that the more forgiving axis is aligned with the aircraft pitch axis.

Though there are anecdotal reports from two of the candidate CCC vendors concerning the successful operation of their compressors in shipboard applications with fairly frequent (albeit transient) excursions up to ±30 degrees, the consequences of an oil contamination event are severe to the point where proactive mitigations should be considered. Mitigations discussed with CCC system vendors, the upGREAT project team, and AFRC-OE include:

1. A compressor shutdown circuit with logic triggered by TBD high acceleration events (inclinometer and/or accelerometers), as well as a variety of other temperature and pressure measurements, as discussed within section 2.2.2.4
2. Use of an additional (externally-mounted) oil mist adsorber at the compressor output
3. Periodic weighing of these adsorbers (i.e., on the ground between flight series or even between flights) to determine oil saturation status and trend, or possibly even the use of an oil mist sensor that could be placed upstream of adsorber canister(s) to provide a real-time indication of oil mist loading

4. Use of molecular sieve filters between external adsorbers and cold heads
5. Use of vibration isolators for the compressor mounts to isolate the compressors from higher frequency components (> ~10 - 20 Hz) of disturbances resulting from atmospheric turbulence, take-off and landing events, etc.
6. A compressor mount that is gimbaled (in the pitch axis) such that aircraft accelerations will bias the tilt appropriately (a roll axis gimbal will not be necessary, given the resultant normal load during coordinated turns); any dynamic or gimbal mount will of course require adequate damping, to avoid oscillations
7. Inclinometer and/or accelerometer sensor(s) and logic that will interrupt compressor operations if tilt and/or turbulence become too severe (will require manual restart due to ON / OFF cycle frequency limits)

CCC compressors often have operational constraints surrounding ON / OFF cycling. As an example, a Sumitomo air-cooled compressor should not be turned ON within 3 minutes of being turned OFF, and no more than 6 ON / OFF sequences within a 1 hour period. For this reason, the shutdown circuitry triggered by tilt and/or acceleration events should require a manual override to restart a compressor following an event-triggered shutdown. Several first-generation SOFIA SIs (including GREAT) already employ similar logic for power distribution to SI subsystems that are sensitive to ON / OFF power cycling.

It is worth noting that the effective tilt in the pitch axis represents a superposition of the actual pitch angle and the concurrent longitudinal acceleration on the gravity vector. During the take-off and climb-out phases, these effects are generally additive, while on descent and final approach, the deceleration will tend to mitigate the effect of the pitch angle.

While consideration of the pitch angle itself suggests that SOFIA typically exceeds the ±5 degree CCC compressors operational tilt envelope only during a few discrete periods of limited duration, it should be noted that the specified maximum operational tilt angle of 5 degrees corresponds to a 1.0 g * sin(5 degrees) = 0.09 g longitudinal or lateral acceleration vector component. This simple analysis suggests that the compressors may be quite sensitive to quasi-steady accelerations of less than 0.1 g.

An analysis of SOFIA inflight housekeeping data for quasi-steady lateral and longitudinal accelerations has been conducted, to support Cryocooler development team assessment of the effective tilt (resultant acceleration vector) as well as the magnitude and predominant frequency content of turbulence. These findings have confirmed that the resultant acceleration vector in the roll axis stays well within the ±5 degree tilt limit, but will also inform the development team re: the specifications for the various mitigation approaches to be incorporated into the design.

The initial Phase I implementation of the Cryocooler System for the upGREAT LFA channel will likely incorporate most (if not all) of the mitigation approaches discussed above, but it is anticipated that development testing and hands-on operational experience in the SOFIA flight environment will support a descoping of these approaches for the follow-on Phase II airborne Cryocooler System.

In any case, the consequences of oil contamination of the He lines and cold heads is adequately severe that mitigations such as the use of an external oil mist adsorber and molecular sieve filters, use of a sight glass to help identify oil “breakthrough” from the internal adsorber, combined with operational controls such as periodic weighing of the external adsorber to determine the oil load / saturation status, seem prudent.

2.3. Support Environment

The logistical support and maintenance of the airborne SOFIA Cryocooler System and its component parts will be covered by the SOFIA Airborne Platform Logistics Plan (APP-DF-PLA-PM23-2000). This includes regular maintenance of compressors as well as any spare compressor hardware, oil mist adsorbers, tools required for regular servicing and maintenance, compressed He lines, Quick Disconnect (QD) fittings, etc.

Ultimately, it is expected that the ground-based CCC He compressors and associated components used within the AFRC Bldg. 703 SI labs will be within the scope of a corresponding SSMO / laboratory logistics and maintenance plan. However, such a document has not yet been developed, and because the initial Phase I implementation of the SOFIA Cryocooler System is upGREAT-specific, and the He compressors and lines are being provided by the upGREAT project team, it is expected that servicing and maintenance of the laboratory CCC systems will be the responsibility of MPIfR.

On aircraft spare parts will be limited to those necessary for inflight troubleshooting. This will involve only operational changes, power cycling, and possibly replacement of fuses or other external parts not requiring the use of tools. Maintenance, repair, and/or replacement of other components will be limited to ground support activities only. While replacement of externally-mounted oil mist adsorbers and/or molecular sieve filters could be considered (with use of suitable DESO QD fittings), purge and recharge procedures of the He loop(s) using pressurized supply bottles has been considered only for ground ops using GSE.

CCC compressors have defined service and maintenance intervals for replacement of the compressor oil mist adsorbers and cleaning of the air cooler filters and heat exchangers. Depending on the specific CCC compressor design, operations may additionally include periodic checks of He static pressure and weighing of the oil mist adsorbers and/or external molecular sieve filters to determine how close they are to oil saturation levels.

Service and maintenance intervals will also be affected by the environmental conditions. For a static, ground-based compressor, replacement of the oil mist adsorbers is typically specified for every 20,000 - 30,000 hours of compressor operations. The tilt, acceleration and turbulence environment of SOFIA may drive more frequent adsorber replacements. Given the lack of data regarding the operations and performance of CCC systems in an airborne environment, and the rather severe consequences of an oil breakthrough event due to an adsorber saturation, it may be prudent to preemptively replace these adsorbers. This could be triggered by milestones such as the start of a new observing cycle and/or be in response to an adsorber canister weight measurement (or trend analysis), well before the published service interval. Development testing leading up to integration and operations are expected to provide some indication of whether and how frequent such system maintenance activities are needed. Other regular maintenance activities are expected to be far less frequent.

It is anticipated that the service and maintenance needs of the laboratory and airborne systems will involve similar procedures, though the sensitivity of the CCC compressors to dynamic effects such as tilt and turbulence may well demand more frequent servicing for the airborne system. This may be somewhat offset by an expected lower duty cycle of the airborne system, as well as design approaches to mitigate the effects of the aircraft environment, such as shock and vibration isolation, gimbal mounting, and use of acceleration and tilt sensors to shut down the compressor when measured conditions are outside a pre-established safe operating envelope. It is our expectation that the use of such design approaches will preclude the need to perform any servicing of the He compressors, external oil mist adsorbers or molecular sieve filters, during a flight series.

System thermal performance may be quite sensitive to contamination of the He in the closed loop. Pulse Tube cold heads, in particular, generally require high purity He gas (99.999% Grade 5 or 6) and tend to be very sensitive to oil mist contamination. Even the unavoidable breaking and remaking of the low air-inclusion DESO QD fittings at the Cryocooler System-to-SI interfaces will systematically introduce trace amounts of air, and potentially other contaminants, into the He loops, so periodic flushing and recharging of the He loop will be required.

Given the ramifications of unacceptable system performance during an inflight observation, it may be considered prudent to proactively flush and recharge the He loops with fresh He after each SI installation. This will require that the SOFIA Cryocooler System development include Ground Support Equipment (GSE), likely including a vacuum pump, a portable He supply bottle, a regulator, gauges, valves and transfer tubing, that can be used both in the laboratory and aboard SOFIA (while on the ground).

Provision, servicing and adjustment of the cold heads will be the responsibility of the MPIfR upGREAT team.

Compressed He lines and other supporting equipment from the Cryocooler System interface near the CWP to the SI will be provided by the SI team and become part of standard SI maintenance (see the SOFIA Facility Science Instrument Maintenance Plan, SCI-US-PLA-PM17-2065, for details).

Procedures will need to be written for SI cool-down, disconnection for cold transport, reconnection and resumption of cooling. Regular inspections will be necessary to ensure the health of the Cryocooler System. This includes, but is not limited to, inspection of compressors, oil mist adsorbers, molecular sieve filters, compressed He flex lines, valves, and QD fittings.

2.4. Use Cases

2.4.1. Initial cool-down in IRR

Once an upGREAT channel cryostat has been delivered to AFRC Bldg. 703 and is being prepared for an upcoming Observing Cycle flight campaign, a variety of SI-specific operating and maintenance procedures may be executed. These generally include some initial operations with the SI warm and in various states of assembly, followed by closeout and pump-out of the cryostat vacuum jacket, a cool-down to cryogenic temperatures, and cold functional testing.

In parallel to these SI precool-down operations, the ground-based CCC systems will be prepared for operations. The specifics of this will be influenced by the design of the CCC systems, but are likely to include such things as any regular maintenance items, checking oil levels in the compressor as well as within the oil mist adsorber canisters and/or molecular sieve filters, cleaning cooling air fans and heat exchanger fits, and flushing and recharging the compressor and He lines with fresh, high-purity He gas (though it may be best to perform such a flush and recharge on the integrated Cryocooler – SI cold head system, once the lines have been mated).

When both the SI cryostat(s) and the laboratory CCC systems are ready for cool-down operations, the Double-Ended Shut-Off (DESO) Quick Disconnect (QD) fittings that interface the compressed He lines to the cold head rotary valve are mated and the CCC compressors are started, initiating the Cryocooler cool-down sequence.

Per SE01-2081, each AFRC Bldg. 703 IRR will be serviced by 2 CCC compressors, each of which is to have a separate 60 A service panel. As mentioned earlier, it seems very likely that during initial upGREAT operations the compressors will be operated within the IRR or PIF where GREAT is located and these power circuits may be limited to 30 - 35 amps each. Nonetheless, it is expected that the two CCC compressors may be operated concurrently in the AFRC Bldg. 703 IRRs, with no need to "stagger-start" them to avoid them both being in their max power condition concurrently (though starting both compressors at the same instant should generally be avoided as "best practice" so that the compressor start-up transients are not concurrent).

During active CCC operations, various SI and CCC system parameters will be monitored, locally and remotely. These are likely to include He line pressures, various compressor and motor temperatures, oil mist adsorber weight, and various SI housekeeping parameters, including 1st and 2nd stage cold plate temperatures.

Remote monitoring of laboratory CCC systems and SIs has network and information security implications that will need to be addressed but are outside the scope of this SOFIA Cryocooler Concept of Operations document.

2.4.2. Shut down and disconnection for transport of SI to SOFIA

Once all SI cold functional testing and optical alignment has been completed in the lab, and the SOFIA observatory and staff are ready to transport, weigh and install the instrument, the SI will be "safed" per SI-specific procedures, and the CCC compressors will be stopped. He line QD connections will be unmated and capped for protection, and the SI will be transported out of the laboratory to the aircraft.

For a variety of technical and operational reasons, the time that the SI is not being serviced by a CCC system and is therefore warming up should be minimized and aggressively managed. This is best for the stability of the detectors and cold electronics and minimizes the cool-down period once CCC operations are resumed aboard the SOFIA observatory, before cold functional checkout, line-ops, or observing flights can proceed.

As a rule, SIs are weighed on their installation carts using a scale located on the hangar floor before they are loaded onto SOFIA (the installation carts are then weighed once the SI has been installed, to obtain a tare weight to allow the SI mass to be calculated). To the extent that this SI weighing operation can be timelined and executed efficiently, it may not be an issue, but it may be beneficial to pursue a procedural change with AFRC-OE in which the official flight mass of the (dry) SI be established with a weighing of the warm SI prior to cool-down.

Figure 2.4.2-1 shows initial thermal test results for the upGREAT LFA cryostat showing temperature transients at the 77 K first stage and 4 K 2nd stage, as well as the cryostat vacuum jacket pressure, associated with an interruption of CCC refrigeration. In this plot, the CCC compressor (and pulse tube rotary valve) is shut down at t = ~0.75 hours, and resumed about 2 hours later at t = ~2.75 hours. Note that ~2 hours after compressor operations were interrupted, the cryostat vacuum has degraded to ~1e-4 mBar, the threshold at which cryostat heat load due to gas conduction becomes significant and the rate of the warm-up increases.

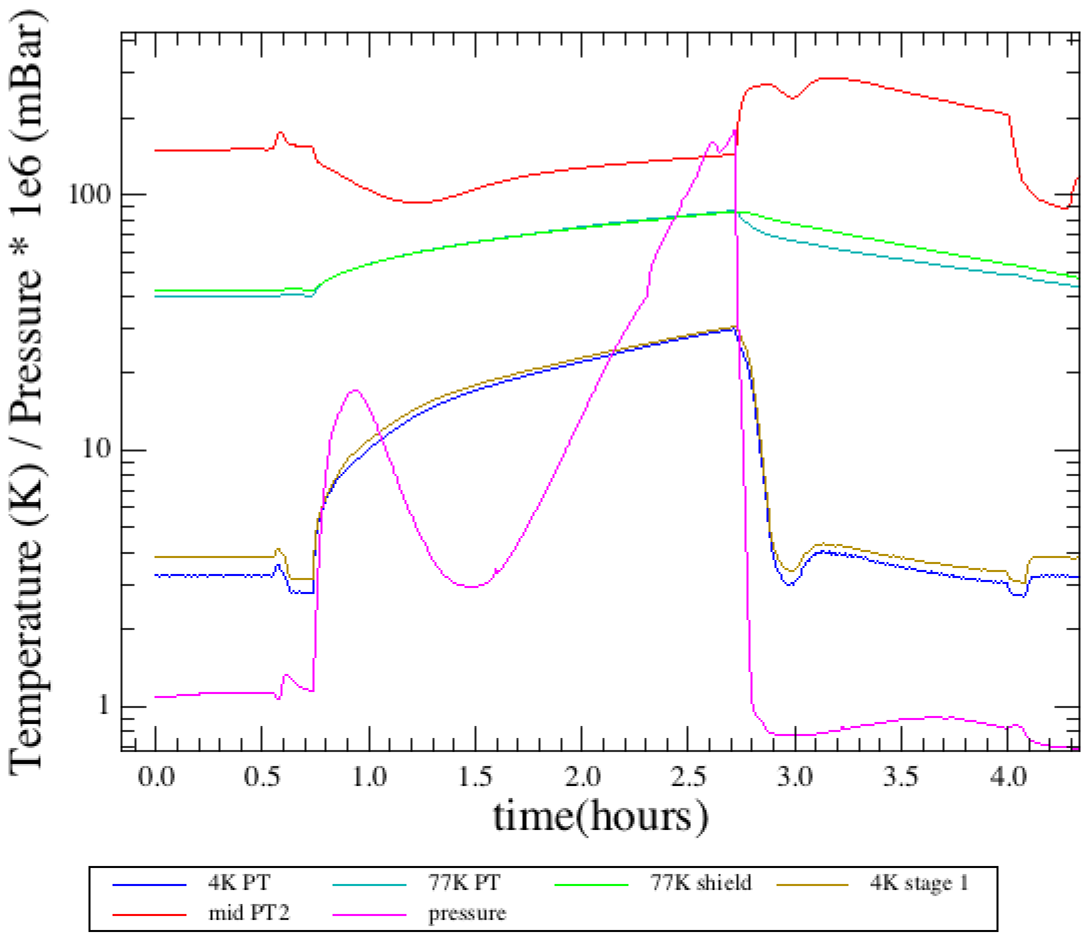


Figure 2.4.2-1: Initial thermal test results for the upGREAT LFA cryostat showing temperature transients at the 77 K first stage and 4 K 2nd stage, and cryostat vacuum jacket pressure, associated with an interruption of CCC refrigeration.

One other issue related to the warm-up of the SI cryostats during this lapse in active cooling is related to the adiabatic expansion of the cold He that is trapped within the cold head volume once the He lines have been unmated. This could potentially lead to an overpressure condition within the cold heads and will need to be addressed in the SI-specific Hazard Reports (HRs) and/or Subsystem Hazard Analyses (SSHAs).

Mitigations should address both a fast-turnaround SI installation procedure, as well as a typically more relaxed SI removal process, in which it may be acceptable to allow the SI to start a post-observation warm-up. This will likely involve the use of a relief or bleed valve to allow the expanding He to escape in a controlled manner.

2.4.3. Interface to SOFIA Cryocooler System, SI Installation, and Resumption of Cooling

Once the SI is aboard SOFIA for integration and installation is underway, and the SOFIA CCC systems have been prepared for pre-flight and declared ready, the observatory He line QDs will be mated to the SI cryostat cold head QDs, the pressurized He lines will be restrained for safety, and the SOFIA airborne CCC compressors will be started. Depending on the performance characteristics and power consumption timelines of the selected compressors and integrated CCC systems, it is possible that the start-up of the two compressors may need to be "stagger started" (perhaps by as much as 45 - 60 minutes), as described in Section 2.2.2, in order to remain within the SOFIA Cryocooler System power budget.

The SOFIA Cryocooler System design and operations should support connecting the airborne CCC systems to the upGREAT cryostat cold head(s) as early as possible within the SI installation flow, perhaps even before the SI is fully mechanically interfaced to the TA IMF. In this case, any remaining SI and cable installation procedural steps would take place in parallel with the SI cool-down, already in progress.

In cases where the two SOFIA airborne CCC compressors must be "stagger started" due to power budget constraints, the SI-specific laboratory, transportation, and installation procedures can and should be optimized to minimize the time without active CCC cooling, with particular consideration for the cryostat / cold head which is most susceptible to warm-up.

2.4.4. Ground Operations

Certain aircraft ground operations will require momentary interruptions of power, such as changeovers from a ground power cart to aircraft APU or engine generator power. Whenever an SI that uses CCC cooling is onboard, even if the SI itself isn't powered, all such aircraft operations must be carefully pre-coordinated with the PI team and MOPS, and if the CCC systems are active any interruptions in CCC operations will need to be minimized and timelined with MOPS staff, so that CCC cooling can be resumed smoothly and quickly following each interruption.

Presently, there are no aircraft tugs capable of providing power to the SOFIA aircraft. Until such time that a powered tug is available, it is unavoidable that CCC operations will need to be shut down during the tow-out / tow-in between AFRC Bldg. 703 hangar and the flight line, where a ground power cart can be connected, or the onboard APU can be started, and powered CCC operations may resume.

Coordination with AFRC-OE staff indicates that such tow-out / tow-in operations are typically no longer than 30 - 45 minutes in duration, and initial upGREAT thermal test results such as those depicted in Figure 2.4.2-1 show that such interruptions in CCC operations will not result in any unacceptable impacts to the day-of-flight operations or observing timelines.

Another challenging aspect of the operational environment aboard SOFIA during ground operations is related to heat rejection and adequate cooling of the He compressor(s). This is particularly true for extended ground-based operations (e.g., line ops) during the hot summer months, and it has been a challenge to keep the temperatures aboard SOFIA adequately low to avoid equipment overtemperature conditions in certain MCCS racks.

The SOFIA aircraft maintenance has pointed out that SOFIA can accept up to three (3) connected diesel-powered air conditioning carts, so it is believed that the additional 10 - 20 kW heat load from cryocooler He compressors can be accommodated. It is worth noting, though, that these diesel air-conditioning carts do need to be refueled after ~8 hours of operations, which may also result in some brief interruptions or reductions in cooling when operating for long durations on the ground.

As with the active CCC operations in the laboratory, it will be important to closely monitor the performance of the airborne CCC systems and the SI when operating aboard SOFIA. The details of this will be coordinated with the MPIfR upGREAT team and documented in SE03-2059, upGREAT Cryocooler System to upGREAT Science Instrument ICD (CRYO_SI_01), but will also invoke network and information security issues that are outside the scope of this Concept of Operations document.

However, it is considered essential that such networking issues be resolved, such that the important SOFIA Cryocooler System and SI housekeeping parameters may be remotely monitored by onsite and offsite PI team and USRA MOPS staff, potentially including carefully controlled remote access to SI computers from the public internet via an appropriately configured firewall.

This is a use case for the SOFIA SkyNet System (formerly EOCS) documented within APP-DF-PLA-PM17-2068, *EOCS Concept of Operations*, but the implementation of network connections between SkyNet and both the MCCS and the internet via ground-based LANs is dependent on SOFIA program direction and information security policy decisions. By the time that upGREAT CCC operations aboard SOFIA commence (expected during CY2015Q1), it is anticipated that a viable solution will be identified to support such SI connectivity from the public internet while the SI remains integrated to the MCCS.

The specific designs and cryogenic requirements of future instrumentation cannot be foreseen at this point; however, one can imagine other uses being desired, including hybrid cryostats that use expendable LN2 in conjunction with the CCC.

For maximum flexibility to allow SOFIA to accommodate the widest range of future SI designs, to the maximum extent possible the Cryocooler System should be designed to envelope the highest cooling performance that is possible within the constraints of the physical and mass accommodations and the power budget allocated to the system.

3. SUMMARY OF IMPACTS

The primary stakeholders of the SOFIA Cryocooler System are the SIs. However, the design details of the Cryocooler System will not have a significant impact on the SI design, to the extent that the cooling needs of the SI remain within the performance envelope of the CCC compressors that are selected.

There are fairly modest impacts on the mass budget of the SI. While the mass of the cold head and associated rotary valve is not insignificant (~25 to 30 kg), in many cases this is offset by the mass of the expendable LN2 and LHe cryogens themselves and generally obviates the mass associated with the nested liquid cryogen reservoirs and radiative heat shields. The mass of the CCC compressors, filters, and compressed He lines are not allocated to the SI, though the mass of the flexible compressed He lines between the SI cryostat(s) and the Cryocooler System interface near the CWP does affect TA balancing and pointing performance and in some cases may need to be accounted for within SI mass and CG calculations and budgets.

As mentioned above, the use of CCC systems has great potential to reduce the MOPS staffing requirements that has been driven by SI cool-down and cryogen top-off procedures.

Procurement and maintenance of the SI cold head(s), as well as the flexible compressed He lines between the SI cryostat(s) and the Cryocooler System interface near the CWP are the responsibility of the SI and/or USRA / SSMO. Procedures will need to be developed specific to the needs of each individual SI.

It is anticipated that the implementation, design and maintenance of the SOFIA Cryocooler System will be the responsibility of AFRC-OE (Operations Engineering) and AFRC-RE (Flight Systems) staff supporting the SOFIA Program, with S&MA support from AFRC-SF (Safety), and installation support from AFRC-OM (Maintenance) and AFRC-OA (Avionics). This includes the detailed design, FMEA, airworthiness reviews, environmental acceptance, and verification of requirements, as well as ongoing regular and repair maintenance.

The largest impacts associated with the use of the SOFIA Cryocooler System, particularly for the airborne segment aboard the SOFIA observatory, are likely those related to the implications of providing power to the onboard CCC systems, and potentially the SI, on a “24 / 7” basis, during an observing cycle flight campaign, at least through the final observation.

Under present (and foreseeable) AFRC Operational Policies, one or two technicians must be present aboard an aircraft at all times when power is being applied to the aircraft or any onboard equipment. Because of this, the requirement to maintain active CCC cooling of an integrated SI between flights during a flight series may well have significant staffing impacts, though it should be noted that adequate staffing will often be present for other, already planned aircraft or observatory maintenance tasks.

In addition, the increased importance of ensuring remote monitoring capability for both the SI and the active onboard CCC systems has implications for network architecture and information security policies that will need to be worked through and put into place in a timely manner to support the upGREAT channel integration and commissioning activities.

APPENDIX A. ACRONYMS

ADR	Adiabatic Demagnetization Refrigerator
AFRC	Armstrong Flight Research Center (formerly DFRC)
ARC	Ames Research Center
AWG	American Wire Gauge
CB	Circuit Breaker
CCC	Closed Cycle Cryocooler
CCR	Configuration Change Request
CLA	Cable Load Alleviator
ConOps	Concept of Operations
COTS	Commercial Off The Shelf
CWP	Counterweight Plate
CWR	Counterweight Rack
DAOF	Dryden Aircraft Operations Facility (now AFRC Building 703)
DAS	Data Acquisition Subsystem (of MCCS)
dBA	Decibels (A-weighted scale)
DESO	Double Ended Shut-Off (QD fitting)
DFRC	Dryden Flight Research Center (now AFRC)
EOCS	External Observatory Connections Subsystem (now SkyNet)
FC	Frequency Converter
FMEA	Failure Modes and Effects Analysis
FOC	Full Operational Capability
GM	Gifford-McMahon (cold head technology)
GREAT	German Receiver for Astronomy at Terahertz Frequencies
GSE	Ground Support Equipment
He	Helium (gas)
HFA	High Frequency Array (upGREAT channel cryostat)
HR	Hazard Report
HVAC	Heating, Ventilation and Air Conditioning
Hz	Hertz (cycles per second)
I/F(s)	Interface(s)
ICD	Interface Control Document
ID	Inner Diameter
IMF	Instrument Mounting Flange
INF	Instrument Flange
IRR	Instrument Readiness Room
K	Degrees Kelvin
kW	kilo Watts
kVA	kilo Volt-Amperes
LFA	Low Frequency Array (upGREAT channel cryostat)
LHe/LHeI	Liquid Helium
LHeII	Superfluid Helium
LN2	Liquid Nitrogen
MAWP	Maximum Allowable Working Pressure (equivalent to MNOP)
MCCS	Mission Controls and Communications System

MDP	Maximum Design Pressure
mK	milli-Kelvin
mm	millimeter
MNOP	Maximum Normal Operating Pressure
MOPS	Mission Operations
MPIfR	Max Planck Institut für Radioastronomie (Bonn, Germany)
NRE	Non-Recurring Engineering (costs)
OD	Outer Diameter
OEM	Original Equipment Manufacturer
OPP	Observatory Power Panel
PDS	Power Distribution Subsystem (of MCCS)
PF	Power Factor
PI	Principal Investigator
PIF	Preflight Integration Facility
PPE	Personal Protective Equipment
PT	Pulse Tube (cold head technology)
QD	Quick Disconnect (fitting)
S&MA	Safety & Mission Assurance
SHI	Sumitomo Heavy Industries
SI	Science Instrument
SRR	System Requirements Review
SSHA	Subsystem Hazard Analysis
SSMO	SOFIA Science & Mission Operations
SOFIA	Stratospheric Observatory for Infrared Astronomy
SNACS	Standard New Astronomy Cryostat for SOFIA
TA	Telescope Assembly
TAAS	Telescope Assembly Alignment Simulator
TBD	To Be Determined
THD	Total Harmonic Distortion
UPS	Uninterruptible Power Supply
VAC	Volts Alternating Current
VDC	Volts Direct Current
V&V	Verification & Validation
VPS	Vacuum Pump System

APPENDIX B. SUMMARY OF TRADE STUDIES SURROUNDING USE OF CCC CRYOCOOLER SYSTEMS FOR THE SOFIA PROGRAM

Trade	Brief Description	Trade Space and Comments	Key Conclusions
1	CCCs vs. expendable Cryogen	• Continued use of expendable cryogen baths have advantages from a temperature stability point-of-view, and CCCs have higher upfront NRE costs and operational complexities, including need for "24 / 7" power to cryocoolers on SOFIA between flights, as well as network connectivity to SIs from remote locations. • However the costs are offset by the high (and rising) cost of LHe, and CCCs eliminate safety concerns associated with rapid boil-off over-pressurization, oxygen displacement, and cryogen handling. • Use of CCCs now common practice at most world-class observatories.	Depending on assumptions made re: number of active SIs, flight rates and flight durations, as well as costs of LHe that are high but plausible, the annual cost of expendable cryogens could be in the range of \$320K / year (max) or \$220K / year (average). The NRE costs of a CCC system compare favorably to these annual projected cryogen costs, with a "break even" point quite early during the 20 year SOFIA mission. In addition, there have already been several cases in which SI cool-down, testing and development timelines have been impacted by the availability of LHe.
2	400 Hz vs. 50 / 60 Hz input power	• No commercially available options for suitable 400 Hz compressors; R&D would involve significant lead time and NRE. • 60 Hz 3-phase power available in DAOF labs, but on SOFIA aircraft, 400 Hz 3-phase power will need to be converted to either 60 Hz or 50 Hz 3-phase power, with associated power conversion inefficiencies. • Possible compressor motor overheating issues due to power quality from inverter (Frequency Converters, UPSs).	R&D NRE and lead-time challenges of developing suitable 400 Hz compressors, the need to ensure interoperability between the ground laboratory and airborne segments of the Cryocooler System, and flexibility to accommodate a range of CCC compressors to meet SI specific needs favor the use of 60 Hz, 3-phase compressors with platform-provided Frequency Converters. Care should be taken to specifying 20 kVA Frequency Converter with a high quality power output waveform (suitable filtering), and adequate testing should be performed to ensure compatibility with selected compressor(s).

Trade	Brief Description	Trade Space and Comments	Key Conclusions
3	Facility- vs. SI-provided CCC	• SIs have different thermal control needs and should be able to select the CCC cold head technology and model that best suits the need. • However, a Facility-engineered and provided system minimizes the NRE and high overhead associated with development, integration and airworthiness certification of multiple systems. • "Hybrid" approach, in which SI developers have flexibility to select from a range of cold heads that are operable by a bounded set of compressors seems feasible, despite complexities associated with pairing of "mismatched" cold heads and compressors and optimization of large thermal performance parameter space.	Initial He compressor selection will be driven by needs of the upGREAT SI (ca. CY2014Q4 ~ CY2015Q1), however to the extent possible, compressor physical accommodations should envelope the widest possible range of air-cooled compressors consistent with the 20 kVA Cryocooler System power budget.
4	Air- vs. Liquid-cooled compressor	• Water-cooled compressors require less power, are quieter, and reject less heat to the surrounding ambient environment (i.e., aircraft cabin, lab). • However, water-cooled compressors require a supply of chilled water, and the heat transferred to the cooling bath must be rejected elsewhere (additional complexity of circulating chiller baths and heat exchangers). •	Though the use of water-cooled compressors do have several advantages, there are several issues surrounding the need for the required supply of chilled water, as well as the complexities associated with the need to reject the heat from the cooling water. These factors, combined with the importance of ensuring interoperability of an SI and cold heads in both the laboratories and aboard the SOFIA observatory point toward the use of air-cooled LHe compressor systems.

Trade	Brief Description	Trade Space and Comments	Key Conclusions
5	GM vs. PT cold head	• GM cold heads more mature technology. • GM cold heads less sensitive to tilt and resulting thermal performance degradation. • GM cold heads less sensitive to He contamination. • PT cold heads have no moving parts (aside from rotary valve which can be mounted remotely for isolation), very low vibration, and require less maintenance. • PT cold heads require He compressors that can provide higher flow rates. • Sumitomo PTs not yet qualified for use with air-cooled compressors.	Because the cold head itself is integral to the SI cryostat, vibrational energy imparted to the cryostat and optics must be minimized. Vibration isolation across high vacuum cryostat interface is difficult. With remote rotary valve option, Pulse Tube cold heads themselves have no moving parts and very low vibration. This combined with the secondary benefit of higher reliability and lower maintenance tips the balance with respect to GM cold heads for this application, despite several advantages of the latter cold head technology.