Phase 1 Cryocooler System Specification

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Phase 1 Cryocooler System Specification

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Revision History

REV	DATE	DESCRIPTION	APPROVAL
0.1	3/24/2014	Initial draft for stakeholder review	
0.2	4/17/2014	Updated draft for Cryocooler SRR reflecting comments from stakeholder review of draft 0.1, and direction from SOFIA Program management to descope the initial implementation of cryocoolers aboard SOFIA to accommodate just the needs of the upGREAT SI (initially only the LFA channel cryostat, with the HFA channel cryostat approximately 1 year later).	
0.3	5/30/2014	Updated draft reflecting discussions at 4/17/2014 Cryocooler SRR, resolution to RFIs / RFAs, and follow-up discussions at 5/12/2014 and 5/22/2014 Face-to-Face TIMs w/ GREAT PI and upGREAT Project Engineer.	
0.4	6/10/2014	Updated DFNS doc. # to SOF-NASA-SPE-SE01-2076 to reflect PMB direction due to recent / ongoing SOFIA Program transition, and updated draft incorporating resolution to additional comments submitted from review of Draft 0.3	
0.5	7/18/2014	Updated draft incorporating trace to SE01-004 parent requirements, and added V&V Method for ParID 3.3.7. Additional updates to reflect resolution to comments submitted by Cryocooler System development PM. Also, reverted to originally assigned DFNS doc. #, as the updates to the DB schema and SOFIA Portal doc. finder tool necessary to support the assignment / searches for new SOF-NASA-... doc. numbers may not be implemented until Fall or Winter 2014.	
-	7/23/2014	Initial baseline release (OCCB) per OCCB-CCR-0160 (JIRA # SOF-2391)	OCCB
A	1/27/2016	Updated to Rev. A with updated title reflecting Phase 1 vs. upGREAT Cryocooler System per OCCB-CCR-0593 (JIRA # SOF-3394) to support Phase 1 Cryocooler System V&V effort. See CCR for detailed FROM: / TO: changes.	OCCB

DocID	Rev	ParID	Text	Notes
SE01-2076	A	1	**Purpose, Subsystem Description and Scope**	
SE01-2076	A	1.1	**Purpose**	
SE01-2076	A		The purpose of this specification is to define the requirements for the Phase 1 airborne Closed Cycle Cryocooler (CCC) System in support of the upGREAT Science Instrument (SI) aboard the Stratospheric Observatory for Infrared Astronomy (SOFIA).	GREAT flights in the Spring 2015 timeframe will include only the upGREAT Low Frequency Array (LFA) channel cryostat (i.e., only a single compressor needed). It is anticipated that the upGREAT (HFA) channel cryostat will require an upgraded Phase 2 Cryocooler System with a second compressor.
SE01-2076	A		This will support development of the airborne cryocooler system that will allow the SOFIA observatory to accommodate the upGREAT Low Frequency Array (LFA) channel cryostat. It is anticipated that the Cryocooler System will be upgraded with a second compressor to additionally support concurrent operations with the upGREAT High Frequency Array (HFA) channel cryostat. For this Phase 2 development, the SOFIA Cryocooler System requirements and design are expected to evolve into a more capable, permanently installed observatory mission system capable of supporting all next generation SOFIA Science Instruments (SIs) that are cooled with CCC systems in lieu of expendable LN2 and LHe cryogens. The Phase 2 Cryocooler System development is outside the scope of this specification, and will be the subject of a follow-on requirements document.	SE01-003, *SOFIA System Spec.* , ParID 3.1.19 provides a top-level requirement for the SOFIA System to support cryocooled SIs, both aboard the SOFIA observatory (via flowdown to SE01-004, *SOFIA Airborne Systems Spec.*) and in the Armstrong Flight Research Center (AFRC) Bldg. 703 (formerly DAOF) SI labs and PIF (via flowdown to SE01-006 and SE01-2008). The corresponding specification for flight cryocooler systems for use in the SI labs at AFRC Bldg. 703 is APP-DA-SPE-SE01-2081, *DAOF Cryocooler & Accommodations Spec* .
SE01-2076	A		This specification is a SOFIA Level 3 System/Subsystem specification, sub-tier to the Level 2 SE01-004, *Airborne System Specification* , as defined in SE01-068, *SOFIA Specification/Product Tree* .	The SOFIA airborne cryocooler system will support SI operations whenever SIs are integrated with the SOFIA observatory.
SE01-2076	A	1.2	**Subsystem Description**	
SE01-2076	A		SOFIA SIs, starting with upGREAT, will use closed-loop He cryocoolers in lieu of expendable liquid cryogen baths to maintain suitably low temperatures for their detectors. Generally, such cryocooler systems include a Helium (He) compressor, a cold head with two (2) stages, interconnecting tubing and/or flex lines for the compressed He, and a power cable from the compressor that drives the rotary valve associated with the cold head.	
SE01-2076	A		There are several different technologies for the cryocooler system cold heads, including Gifford-McMahon (GM), Joule Thompson (JT), and Pulse Tube (PT). These different cold head technologies each have various advantages and disadvantages, however Pulse Tube cold heads are preferred for use with the cryostats of SOFIA SIs due to their absence of moving parts (aside from an electrically powered rotary valve, which can be mounted remotely from the SI cryostat-mounted cold head) and resulting high reliability, low maintenance, and low vibration imparted to the SI and to the SOFIA Telescope Assembly (TA).	
SE01-2076	A		Generally, each cold head requires a dedicated He compressor and interconnecting pressurized He supply and equalization (return) lines, and must be "tuned" to the paired compressor for optimal performance. The cryocooler systems that will be used aboard the SOFIA airborne observatory for the flight cryocooler systems will be matched with equivalent systems for use in the AFRC Bldg. 703 IRRs and PIF. To the maximum extent possible, the Phase 1 cryocooler system that will be used aboard the SOFIA observatory to support the upGREAT SI will replicate the system that has been selected by the MPIfR upGREAT team.	
SE01-2076	A		It is not uncommon for mid- and far-infrared instruments to have two (2) cold heads, either servicing different cryostats, or in some cases "ganged" together to cold plates to increase thermal pumping capacity. In order to accomnmodate instruments such as upGREAT (with 2 modular cryostats) and for maximum flexibility in accommodation of future SIs, it is anticipated that the SOFIA Phase 2 airborne cryocooler system will include two (2) compressors, along with two (2) pairs of supply / return compressed He lines.	Typical acoustic emissions from one (1) air-cooled cryocooler compressor is 70+ dBA @ 1 meter distance. Typical heat rejection from one (1) cryocooler compressor of adequate size / capacity is up to 7.8 kW steady-state / 8.3 kW start-up (duration up to 1 ~ 2 hours).
SE01-2076	A	1.3	**Scope**	
SE01-2076	A		The scope of this specification is the SOFIA Phase 1 airborne Cryocooler System and associated GSE. The ground-based systems for use in the AFRC Bldg. 703 IRRs and PIF, while closely related and covered within the same Concept of Operations (ConOps) document, are not within the scope of this specification, but are instead addressed within APP-DA-SPE-SE01-2081, *DAOF Cryocooler & Accommodations Spec* .	
SE01-2076	A		The scope includes the procurement and integration of one (1) cryocooler He gas compressor needed to service the upGREAT LFA or HFA channel aboard SOFIA. Phase 2 Cryocooler System development, including two (2) He gas compressors and associated He lines as needed to support concurrent operation of the LFA and HFA channels is outside the scope of this specification, and will be the subject of a follow-on requirements document. Therefore, within the context of this specification, Cryocooler System and Phase 1 Cryocooler System are used interchangeably.	The initial Cryocooler System configuration will include one (1) Sumitomo Heavy Industries (SHI) Cryogenics compressor specified by the upGREAT development team.

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SE01-2076	A		Note that while a complete closed loop cryocooler system includes a cold head (and associated rotary valve), the cold heads are - as a rule - to be specified, procured and integrated by the SI developer into the SI cryostat. As such, cold heads and related spares, documentation, etc., are outside the scope of this specification.	
SE01-2076	A		It should be noted, however, that one or more cold heads (not within the scope of this specification) will need to be made available in order to support V&V activities surrounding the functional and performance requirements set forth in Section 3 of this specification.	
SE01-2076	A	2	**Applicable Compliance and Reference Documents**	
SE01-2076	A		The following ICDs, specifications and standards form a part of this specification to the extent specified herein. Configuration controlled documents will be the latest revisions available, unless otherwise stated as specific	
SE01-2076	A		Those documents that are cited as sources of mandatory requirements appear in the Compliance Documents section. These are applicable to cryocooler system design and development activities performed in-house or outsourced by the cryocooler system developer.	
SE01-2076	A		Those documents that are cited as sources of recommended guidelines or for reference only appear in the Guidance / Reference Documents section.	
SE01-2076	A	2.1	**Precedence**	
SE01-2076	A		In the event of a conflict between the text of this document and the referenced documents cited herein, the text of this document takes precedence. Nothing in this document, however, supercedes the contractual requirements unless a specific exemption has been obtained and approved. As appropriate, reference is made to other project documentation for use as guidance in developing the content of this document and as such forms a basis for requirements to the extent specified herein.	
SE01-2076	A	2.2	**Compliance Documents**	
SE01-2076	A	2.2.1	**SOFIA Specifications and other Compliance Documents**	
SE01-2076	A		SOF-DF-SPE-SE01-004, *SOFIA Airborne System Requirements*	
SE01-2076	A		SOF-DF-SPE-SE01-068, *SOFIA Specification/Product Tree*	
SE01-2076	A		APP-DF-PLA-PM23-2000, *SOFIA Airborne Platform Logistics Plan*	
SE01-2076	A		USRA-DAL-1126-00, *Structural Design Criteria for the Stratospheric Observatory for Infrared Astronomy (SOFIA) Program*	
SE01-2076	A		SOF-AR-SPE-SE01-2028, *SOFIA Science Instrument System Specification*	ParIDs 3.5.2.2 through 3.5.2.8 are cited within ParID 3.5.11 of this specification to ensure that any unique GSE installation carts required for installation / removal of cryocooler system components, such as the compressor(s) and/or compressor mounts, will meet these necessary structural and stability requirements.
SE01-2076	A	2.2.2	**Interface Control Documents (ICDs)**	
SE01-2076	A		SOF-DA-ICD-SE03-036 (TA_SI_01), *Cable Load Alleviator Device / Science Instrument Cable Interface*	
SE01-2076	A		SOF-DF-ICD-SE03-048 (TA_MCCS_P), *Telescope Assembly to Mission Controls and Communications System (MCCS) Physical Interface*	
SE01-2076	A		SOF-AR-ICD-SE03-2029 (MCCS_SI_05), *Principal Investigator Patch Panel to Principal Investigator Equipment Rack(s) ICD*	
SE01-2076	A		APP-DF-ICD-SE03-2038, *Global Power Budget ICD*	
SE01-2076	A		APP-DA-ICD-SE03-2059 (CRYO_SI_01), *Cryocooler System to Science Instrument ICD*	
SE01-2076	A		APP-DF-ICD-SE03-2060 (CRYO_AS_01), *Cryocooler System to Aircraft System ICD*	
SE01-2076	A		SOF-DF-ICD-SE03-2015 (SI_AS_01), *Principal Investigator Equipment to PI Rack to Aircraft System*	
SE01-2076	A		SOF-AR-ICD-SE03-205 (SIC_AS_01), *Science Instrument Cart to Aircraft System Interface*	Language and figures within this ICD cite other applicable requirements within SE03-002 (GLOBAL_09) and SE03-004 (GLOBAL_07) for installation envelope and SOFIA floor panel loading constraints. Additionally, Figure 1 in this ICD depicts the SI Cart Path which must remain unobstructed by cryocooler system installation, to ensure that the cryocooler system will not impede the installation of the SI (i.e., upGREAT).
SE01-2076	A		SOF-DF-ICD-SE03-017 (TA_AS_10), *Aircraft Cabin/TA Envelope Interface*	Defines the envelope of the TA within the aircraft cabin.
SE01-2076	A		SOF-DA-ICD-SE03-002 (GLOBAL_09), *Science Instrument Envelope Interface*	Defines the envelope of the SI within the aircraft cabin.

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SE01-2076	A	2.2.3	**Standards**	
SE01-2076	A		DCP-O-018, *Environmental Acceptance Testing, Electronic and Electromechanical Testing*	
SE01-2076	A		RTCA/DO-160, *Environmental Conditions and Test Procedures for Airborne Equipment*	SE01-004 cites RTCA/DO-160D for vibration environmental acceptance test requirements.
SE01-2076	A		MIL-STD-464A, *Electromagnetic Environmental Effects Requirements for Systems, Para. 5.6*	
SE01-2076	A		DCP-S-065, *Pressure Vessels & Pressurized System Safety*	
SE01-2076	A		DCP-S-002, *Hazard Management Procedure*	SE01-004 cites DCP-S-002 to levy the hazard analysis process on airborne systems.
SE01-2076	A		NPD 8710.5, *NASA Policy Directive for Pressure Vessels and Pressurized Systems (PVS)*	
SE01-2076	A		FAA Advisory Circular (AC) 43.13-1B, Chapter 11, *Aircraft Electrical Systems*	
SE01-2076	A		CFR Title 14, *Aeronautics and Space* , Part 25 § 25.1438 (b), *Pneumatic Systems*	Applicable to qualification and acceptance of atmospheric flight Pressure Vessels and Pressurized Systems (PVS) per NASA Policy Directive NPD 8710.5D. ANSI/AIAA S-080-1998, had been applicable to "Atmospheric Flight PVS" (i.e., airborne) applications per NPD 8710.5C, and remains fully applicable to "Spaceflight PVS" per NPD 8710.5D. This standard specifically addresses requirements for PVS applications such as sealed containers and cryostats / dewars that are far more representative to our application than the "pneumatic systems" discussed in 14 CFR Ch. I §25.1438 (b).
SE01-2076	A		NASA-STD-5005, *Standard for the Design and Fabrication of Ground Support Equipment*	
SE01-2076	A		NASA-STD-8719.17, *NASA Requirements for Ground-Based Pressure Vessels and Pressurized Systems (PVS)*	
SE01-2076	A		NPR 6000.1, *NASA Requirements for Packaging, Handling, and Transportation [March 2005/Rev. G]*	
SE01-2076	A	2.3	**Guidance / Reference Documents**	
SE01-2076	A	2.3.1	**SOFIA Specifications and other Reference Documents**	
SE01-2076	A		APP-DA-PLA-PM17-2076, *upGREAT Cryocooler Concept of Operations*	While this specification (SE01-2076) drives the Verification activities for the Cryocooler System, the PM17-2076 ConOps document will drive the associated Cryocooler System Validation efforts.
SE01-2076	A		APP-DA-PLA-PM17-2078, *"24/7" Power and Network Connectivity between Flights Concept of Operations*	This ConOps addresses the need for provision of power and network connectivity between flights during an observing campaign / flight series, including associated staffing and equipment requirements.
SE01-2076	A		APP-DF-DWG-SE02-2924, *Layout of Personnel Accommodations (LOPA) - Main Deck*	The LOPA drawing depicts the location of the SOFIA main deck reinforced floor areas, and is cited within the rationale / notes field of ParID 3.3.10.
SE01-2076	A		PM11-001, *NASA Public Use Airworthiness Certification Plan*	
SE01-2076	A		SCI-AR-SPE-SE01-2081, *DAOF Cryocoolers and Accommodations Specification*	Counterpart specification for Cryocooler ground segment accommodations for CCC-cooled SIs in AFRC Bldg. 703 (formerly DAOF) IRRs and PIF laboratories.
SE01-2076	A		SOF-DF-PD-PD-2009, *SOFIA Lexicon*	Global definition of Acronyms, Abbreviations and Nomenclature for the SOFIA Program.
SE01-2076	A		UGA-2200-006, *upGREAT Closed-Cycle Coolers Specification*	
SE01-2076	A		GH-2221-001, *upGREAT Cryostat System Safety Assessment*	
SE01-2076	A	2.3.2	**Interface Control Documents (ICDs)**	
SE01-2076	A		SOF-AR-ICD-SE03-205 (SIC_AS_01), *Science Instrument Cart to Aircraft System ICD*	This ICD is applicable to SI carts, but includes relevant information re: layout of reinforced floor on SOFIA, equipment cart mass and load constraints, etc.
SE01-2076	A		SCI-AR-ICD-SE03-2017 (SIC_SSMO_01), *Science Instrument Cart to SSMO Facility*	This ICD is applicable to SI carts, but includes relevant information re: layout of AFRC Bldg. 703 (formerly DAOF) laboratory accommodations, including IRRs and PIF.
SE01-2076	A	2.3.3	**Standards**	
SE01-2076	A		MIL-STD-1472D, *Human Engineering Design Criteria [Feb. 1994/Rev. D, Notice 3]*	
SE01-2076	A	2.3.4	**Other**	
SE01-2076	A		CD32ZZ-067, *Technical Instruction, CSA-71A Compressor Unit, Sumitomo Heavy Industries (SHI)*	Rev. R (Sept. 24, 2013) is the most recent known revision.

DocID	Rev	ParID	Requirement Text	Rationale / Notes	V & V Method	SE01-004 Parents
SE01-2076	A	3	**Requirements**			
SE01-2076	A	3.1	**Functional**			
SE01-2076	A	3.1.1	The SOFIA Phase 1 cryocooler system shall support operation of SIs that are cooled to cryogenic temperatures using a Closed Cycle Cryocooler (CCC) cold head aboard the SOFIA observatory.	upGREAT multi-pixel detector array modular cryostats for the GREAT SOFIA SI each require a dedicated cryocooler.	D	3.1.86
SE01-2076	A	3.1.2	The SOFIA Phase 1 cryocooler system shall use an air-cooled He compressor.	This is to reduce the complexity and cost associated with the need for water chillers, recirculating baths, and water / air heat exchangers for water-cooled compressors, and to ensure compatibility and interoperability with the air-cooled compressors that will be used to service the cryocooler cold heads of the SIs in the AFRC Bldg. 703 IRRs / PIF.	I	3.1.29
SE01-2076	A	3.1.3	The SOFIA Phase 1 cryocooler system shall support operation of one (1) cold head.	Pulse Tube cold head technology is typically selected by the SI developer due to the absence of moving parts within the cold head itself (the rotary valve can be mounted remotely, and connected to the Pulse Tube cold head only via a He flex line), and resulting low vibration levels imparted to the cryostat. upGREAT has two (2) distinct channels, LFA and HFA, each of which requires its own cold head. upGREAT has selected the transMIT PTD-406C Pulse Tube cold heads.	D	3.1.86
SE01-2076	A	3.1.3.1	The compressor model to be procured, accommodated and installed for the initial Phase 1 cryocooler system implementation (i.e., to support upGREAT) shall be a Sumitomo / SHI Cryogenics model CSA-71A.	This is considered necessary to ensure compatibility with cold heads and thermal design of the upGREAT SI. Procurement to determine whether a sole-source justification is needed. Sumitomo (SHI) Cryogenics of America, Inc. 1833 Vultee Street Allentown, PA 18103 1.610.791.6700 TEL 1.610.791.0440 FAX sales@shicryogenics.com 1700 Wyatt Drive, Suite 8 Santa Clara, CA 95054 1.408.736.4406 TEL 1.408.736.7325 FAX	I	3.1.29
SE01-2076	A	3.1.4	The cryocooler compressor shall drive a mated cold head via a pair of "supply" and "return" compressed Helium (He) gas lines to be routed through the Telescope Assembly (TA) Cable Load Alleviator (CLA).	Cold heads (along with their associated rotary valves, where applicable), will be provided by SI developers, and generally integrated into SI cryostats. Cold heads are interconnected to the compressor via two (2) compressed Helium (He) gas lines, and often a cold head power cable. Pairing of cold heads and compressors requires "tuning" and optimization of various parameters to achieve the desired thermal performance. Most of this tuning is achieved via adjustable orifices and rotary valve frequency at the cold head, though compressor static charging pressure may also be adjusted within limits to tune the performance. In the case of upGREAT, the cold head rotary valve will be controlled and powered by an upGREAT-provided power supply, independently of the compressor cold head power supply, in order to achieve the desired thermal performance.	D	3.1.86
SE01-2076	A	3.1.5	The cryocooler system shall provide a discrete signal indicating that the compressor is operating, to the SI.	The operation of the SI cold head rotary valve needs to be synchronized with the compressor operations, so that the rotary valve does not operate when the compressor is not operating (except in very specific maintenance or He purge and backfill procedures). For upGREAT, the rotary valve is not driven by the SHI compressor's cold head power interface, but rather by a Toshiba "TOSVERT" VFS11S-2004PL-WP variable frequency drive inverter (this particular unit requires 200 VAC, 50 or 60 Hz, 1-phase power, but other makes and models are readily available).	D	3.1.29

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SE01-2076	A	3.1.6	The SOFIA cryocooler system shall collect and utilize the remote drive, alarm / diagnostic and status interfaces provided by the SHI compressor (i.e., discrete input and output signals).	This supports real-time remote control and monitoring of the cryocooler compressor, and allows staff to be dispatched if nominal operations cannot be confirmed remotely. These discrete signals and alarms will be used as inputs to the cryocooler system controller, and also made available to the SI and/or MCCS Instrumentation / DAS subsystems, in accordance with the ICDs cited in Section 3.11 of this specification. The SHI CSA-71A external control / alarm D-Sub 15 contact female connector provides the following discrete signal interfaces: A. Pressure Alarm Signal discrete (Normal = closed / Fault = open > 1 MOhm) B. Temperature Alarm Signal discrete (Normal = closed / Fault = open > 1 MOhm) C. Room (ambient) Temperature Alarm Signal discrete (Normal = closed / Fault = open > 1 MOhm) D. Drive Indication discrete (24 VDC output 0.15 A max. when compressor is operating) E. Control Voltage (24 VDC output 0.15 A max. when main power SW is ON) F. Remote Reset (momentary 24 VDC input for 1 second, provided by controller) G. Remote Drive (Operate = closed / Stop = open)	D	3.5.29
SE01-2076	A	3.1.7	The cryocooler system shall provide separate AC and DC Circuit Breakers (CBs) for the compressor power circuit.	APP-DA-PLA-PM17-2076, upGREAT Cryocooler Concept of Operations, Section 2.2.2.2, Power Interface. These cryocooler system CBs are additional to the single SOFIA Observatory Power Panel (OPP) CB that protects the 20 kVA 400 Hz power interface to the PDS Frequency Converter that provides 60 Hz power to the Cryocooler System. These protect the downstream branch circuits powering each individual compressor and associated equipment, and will support troubleshooting and isolation.	D	3.7.12
SE01-2076	A	3.1.8	The cryocooler system shall provide a compressor power control switch for the compressor.	The Circuit Breakers (CBs) required by ParID 3.1.7 are not to be used to satisfy this requirement unless CBs that are specifically intended for routine power switching applications are specified.	D	3.7.12
SE01-2076	A	3.1.9	The cryocooler system shall provide a DC power control switch for the compressor control power.	The Circuit Breakers (CBs) required by ParID 3.1.7 are not to be used to satisfy this requirement unless CBs that are specifically intended for routine power switching applications are specified.	D	3.7.12
SE01-2076	A	3.1.10	The cryocooler system shall provide an adsorber canister and a molecular sieve filter in the supply (high pressure) line and mounted external to the compressor.	Cryocooler compressors include an internal adsorber canister which captures and removes oil mist from the compressed Helium that is delivered to the supply line and the cold head. In typical (ground-based) applications, these are service items that are replaced at an interval of 20,000 to 30,000 hours of operation, depending on the make and model of the compressor. But because the SOFIA application is dynamic, involving accelerations, turbulence, vibration, and tilt outside the nominal ±5 degree range, the addition of an external adsorber and molecular sieve filter between the compressor and the cold head is a prudent risk mitigation measure. The SHI P/N for the OEM oil mist adsorber for the CSA-71A compressor is RE71TN0460FQ. The externally mounted adsorber canister and molecular sieve filter will be placed in series with the existing OEM internal adsorber canister, as close as practical to the supply (high pressure) port of the compressor. Development vibration and tilt testing will help characterize the extent to which oil will migrate into the adsorber canisters. As goals: A. The external adsorber canister should be mounted such that in situ weighing of the adsorber may be performed between flights using GSE (i.e., on the ground) without requiring either of the QD fittings to be disconnected; B. A means of providing a qualitative assessment of oil or oil mist migration from the compressor into the external adsorber (e.g., an oil mist sensor or sight glass) should be implemented, to provide a real-time and/or between flight indication of conditions that may lead to oil fouling, and to obviate the need for regular weighing of adsorber canisters.	I	3.7.12
SE01-2076	A	3.1.11	The cryocooler system shall include provisions for the use of a GSE manifold with self-sealing Quick Disconnect (QD) coupling(s) for Helium charging / refill operations.	Typically, cryocooler compressors include such a Helium charge / vent port on the front of the compressor, however the MPIfR upGREAT team has developed a GSE manifold that supports a variety of vacuum pump-out, He backfill and purge operations for the compressor, the He lines, and the upGREAT Pulse Tube cold head and associated rotary valve. This port would only be used during ground operations using GSE vacuum pumps and He supply bottles and regulators.	I	3.7.12

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SE01-2076	A	3.1.12	The cryocooler system shall support deployment and operate out of approved remote sites around the world for a minimum of 14 days and a goal of up to 60 days.	Requirement for portability greatly increases the amount science data the SOFIA can collect over its lifetime. Coverage of both the northern and southern hemispheres increases SOFIA's science return. This requirement also leads to site surveys in order to verify the system can be properly operated at the deployed site. This requirement envelopes the PCA requirement that states that the Airborne Observatory will be capable of global operations. The goal of 60 days is driven by infrastructure at the deployment site.	A	3.1.10
SE01-2076	A	3.1.13	The cryocooler system shall include sensors and instrumentation as needed to measure the following operating parameters for the compressor, at a minimum: A. Pressure of He supply line B. Pressure of He return line C. Temperature of Compressor / Motor (capsule skin) D. Temperature of Compressor He gas cooler outlet E. Temperature of Compressor supply outlet line F. Temperature of Compressor housing ambient (internal) G. Inclinometer(s) for determining tilt of compressor relative to effective resultant gravity vector H. Accelerometer(s) for determining turbulence levels	Instrumentation of cryocooler compressor operating parameters will support real-time monitoring and archival of Cryocooler System Health & Status (H&S) Housekeeping (HK) via interface to the GREAT SI. Depending on how the SOFIA Program opts to address the quasi-continous (24 / 7) power requirements and IT security surrounding SkyNet (EOCS) firewall and access for connectivity between the Observatory and non-Observatory systems, these HK parameters may be monitored locally or remotely. In addition, analysis of archived HK parameters will support trend analyses to identify incipient failures and system maintenance needs (e.g., frequency converter faults, low He charge pressure or He line slow leaks).	I, D	3.1.20
SE01-2076	A	3.1.14	The cryocooler system sensors and instrumentation shall be powered by DC excitation voltages between ±10 VDC and ±28 VDC.	This ensures compatibility with the excitation power available from the Instrumentation Excitation rack (potentially using a voltage divider or regulator), though it isn't yet certain that this will be the source of this power.	I	3.1.28

DocID	Rev	ParID	Requirement Text	Rationale / Notes	V & V Method	SE01-004 Parents
SE01-2076	A	3.1.15	The cryocooler system shall include a He compressor control system to control and constrain the compressor operations to within specified operating parameters. The functionality of this control system is defined within ParIDs 3.1.15.1 through 3.1.15.9, below:	For this dynamic application, we need to consider the combined effects of both the actual tilt of the compressor mount (i.e., due to aircraft pitch and roll angles), as well as centripetal and linear accelerations. The cryocooler system will include an inclinometer or accelerometer based system to interrupt power to the He compressors whenever the operating conditions are equivalent to a static tilt of the compressors exceeding the specified tilt range of ±5 degrees (operating). An analysis of aircraft attitude and acceleration during typical and atypical flight profiles will determine whether and to what extent we will need to implement gimbal mounts for the compressors in addition to the inclinometer, acceleromter and/or turbulence sensors and cut-off switches.	T	3.5.29
SE01-2076	A	3.1.15.1	The cryocooler system He compressor control system shall include an autonomous (closed-loop) compressor-safing shut-down function which senses conditions that are detrimental to the compressors and/or could lead to oil contamination of the He lines and mated cold head, and respond by shutting down the He compressor.	Operating the He compressor outside of the specified tilt range could lead to overheating and damage to the compressor and/or oil contamination of the He lines and mated cold head, and would likely delay and possibly end the observing campaign pending compressor servicing and decontamination of the lines and cold head. The autonomous shut-down of the He compressor will be triggered by any of the following conditions: A. Compressor off-normal pitch axis tilt > ± 5 degrees relative to the effective resultant gravity vector B. Extended heavy turbulence [threshold definition and duration TBD] These cryocooler compressor control system functions augment the compressor's intrinsic shut-down functionality. Any conditions that trigger such an autonomous shut-down of the He compressor will require manual intervention to restart the compressor.	T	3.5.29
SE01-2076	A	3.1.15.2	The cryocooler system He compressor control system shall provide all available He compressor housekeeping and safety discrete signals and alarms, as well as instrumentation transducer outputs, to the SI.	These discrete signals and alarms will be made available to the SI in accordance with the ICDs cited in Section 3.11 of this specification, to support real-time monitoring and datalogging / archival. These include all of the SHI CSA-71A compressor intrinsic status discretes and alarms [ref.: ParID 3.1.9] as well as the added instrumentation / transducers [ref.: ParID 3.1.13], and control system status and alarm discretes based on calculated / derived operating parameters.	D	3.1.20
SE01-2076	A	3.1.15.3	The cryocooler system He compressor control system shall prevent a restoration of power to the compressor until the condition(s) that triggered the shut-down is (are) no longer present AND an operator manually intervenes to reset the control system.	Per agreement with MPIfR GREAT PI team at upGREAT Cryocooler TIMs on 12 and 22 May 2014.	D	3.5.29
SE01-2076	A	3.1.15.4	The cryocooler system He compressor control system shall include color-coded and labeled indicators that provide local visual annunciation of all alarms and safety interlock shut-off conditions to notify the operator or safety technician of the status of the compressor.	During in flight operation or extended periods between flights, it is important that the system clearly annunciate the status of the compressor, so that any fault conditions can be quickly identified and appropriate corrective actions may be planned and executed without any unnecessary delays. Between flights, the system may be only periodically monitored by a technician who is not an expert in cryocooler technologies.	D	3.5.29
SE01-2076	A	3.1.15.5	The cryocooler system He compressor control system shall include a manually silenceable audible annunciation of all alarms and safety interlock shut-off conditions.	The cryocooler system may be only periodically monitored by a technician who is not an expert in cryocooler technologies. An audible alarm will quickly get the attention of technicians (who may be working other tasks in other areas of the aircraft) so that they may contact members of the upGREAT SI team for troubleshooting. The alarm silencing function will allow the alarm to be dismissed while others are summoned and during	D	3.5.29
SE01-2076	A	3.1.15.6	The cryocooler system He compressor control system shall provide local display of selectable compressor operating temperature and pressure parameters from instrumentation / transducers.	A pressure transducer readout to display any of the pressure measurements required per ParID 3.1.13 A. ~ B (kPa or psi). A temperature sensor readout to display any of the temperatures required per ParID 3.1.13 C. ~ F. (degrees C).	D	3.3.69
SE01-2076	A	3.1.15.7	The cryocooler system He compressor control system shall provide a manual reset function, for routine resetting of the cryocooler compressor control system and restarting of the compressor after an autonomous shut-down precipitated by the control system and/or the compressor's intrinsic safety interlocks.	This function will use the SHI compressor Remote Reset discrete signal (momentary 24 VDC input for 1 second) to reset the compressor, and clear the fault indicator lamps.	D	3.5.29
SE01-2076	A	3.1.15.8	The cryocooler system He compressor control system shall provide a lamp test function for any incandescent indicator lamps.	A lamp test function provides a quick determination that any incandescent indicator lamp(s) being tested are functional (i.e., would illuminate if and when appropriate). This functionality may be provided via individual "Push To Test" indicator lamps, or via a single momentary "Lamp Test" button that illuminates all indicators. This requirement is Not Applicable (N/A) to LED indicator lamps or software-controlled GUI indicators.	D	3.9.1

DocID	Rev	ParID	Requirement Text	Rationale / Notes	V & V Method	SE01-004 Parents
SE01-2076	A	3.1.15.9	The cryocooler system He compressor control system shall include a protected manual override function that will allow a trained operator to manually restore power to the compressor.	An override function can be helpful in troubleshooting / testing mode, and can potentially avert an RTB scenario in cases where it is clear that the autonomous compressor control functionality is not operating properly. This override function will not bypass any of the OEM interlocks that are intrinsic to the He compressor. This override function, protected via a guard to prevent unintentional activation, bypasses the compressor shut-down logic of the He compressor control system, and is not intended to be used for routine compressor restarts or controller resets following an automomous shut-down precipitated by the control system and/or the compressor's intrinsic safety interlocks [ref.: ParID 3.1.15.7 for routine restart / reset functionality].	D	3.5.28
SE01-2076	A	3.2	**Performance**			
SE01-2076	A	3.2.1	The cryocooler system shall support quasi-continuous powered operations aboard SOFIA.	"Quasi-continuous powered operations" acknowedges that there will be unavoidable interruptions, anticipated to be no longer than 60 minutes in duration, with at least 30 minutes of powered operations between them to allow the SI systems to recover to operating temperatures. Interruptions include planned or unplanned compressor shut-downs due to observatory power lapses during aircraft towing operations and/or power transfers from ground to SOFIA APU / generator power, and shut-downs due to measured or anticipated high linear acceleration, vibration, turbulence and/or pitch angle events. This involves the provision of power on a nearly 24/7 basis during observing campaigns / flight series when an SI that uses the SOFIA cryocooler system is integrated into the SOFIA observatory, and is the subject of APP-DA-PLA-PM17-2078, *"24/7" Power and Network Connectivity between Flights Concept of Operations* . Interruptions to cryocooler system power of this duration would result in a modest temperature rise, and the cool-down "recovery" time following a resumption of cryocooler operations could be accommodated during Day of Flight / Pre-Flight timelines. Reference APP-DA-PLA-PM17-2076, *SOFIA Cryocooler Concept of Operations* , Figure 2.4.2-2 which presents the results of the thermal testing discussed above, and shows that approximately 2 hours after an interruption to cryocooler operation, the cryostat vacuum has degraded to ~1e-4 mBar, the threshold at which cryostat heat load due to gas conduction becomes significant and the warm-up rate increases.	A, D	3.1.86
SE01-2076	A	3.2.2	The cryocooler system, as implemented, will meet the required thermal performance of the upGREAT LFA channel with sufficient performance margins.	The first SI that will make use of the cryocooler system will be the upGREAT LFA channel of the GREAT SI. The initial design and implementation of the SOFIA cryocooler system will focus on a point design that will replicate the systems selected and tested by the MPIfR upGREAT team. While there are some unavoidable differences between the upGREAT lab setup and the airborne system that can be implemented aboard SOFIA, there appears to be adequate thermal performance margin to allow us to take this "shared risk" approach.	N/A	3.1.86
SE01-2076	A	3.2.3	The electronic pressure transducers for each compressor supply and return line shall have an accuracy of ≤1% of the current reading, and precision (resolution) and repeatability within 1% of full scale pressure.	Accurate, precise and repeatable pressure measurements are necessary for determining static He charge and operating pressures, and for diagnostic purposes.	I	3.3.69
SE01-2076	A	3.3	**Physical**			
SE01-2076	A	3.3.1	The cryocooler compressor shall be accommodated via a pallet mounted to seat track and/or other suitable hardpoints.	Use of a pallet mount and existing seat track and/or other suitable hardpoints will obviate the need for significant modifications of the aircraft structure.	I	3.1.46
SE01-2076	A	3.3.2	The maximum total length of each of the supply and return compressed He lines, including the flexible portion of the lines that pass through the Cable Load Alleviator (CLA) wrap, shall be no greater than 40 meters in length.	Thermal performance of Closed Cycle Cryocooler (CCC) systems is known to be sensitive to compressed He line lengths. Typically, 4 K CCC systems use 19 mm (~3/4 inch) ID lines that are 10 meter to 20 meters in length. The upGREAT team and transMIT have performed testing to demonstrate acceptable performance with 25.1 mm (~1 inch) ID lines up to 40 meters in length. It is acknowledged that this limitation on compressed He line lengths significantly constrains the location for accommodation of the CCC He compressors, and would preclude placement in areas of the main deck that would be advantageous from several points-of-view, including overall weight and balance of the SOFIA aircraft. An R&D program with extensive testing would likely be needed to evaluate thermal performance with longer line runs.	A, I	3.1.86
SE01-2076	A	3.3.3	The cryocooler system shall accommodate the mass, footprint, volume and installation minimum clearance envelope of the He compressor specified in ParID 3.1.3.1.	The compressor accommodations layout must respect all manufacturer's installation instructions and constraints (including minimum clearances for cooling airflow and access to controls, electrical and gas connections).	A, I	3.1.14

DocID	Rev	ParID	Requirement Text	Rationale / Notes	V & V Method	SE01-004 Parents
SE01-2076	A	3.3.4	The cryocooler system shall implement Electrical bonding measures in accordance with NAVAIR 01-1A-505-1 Work Package 17 procedures and processes.	Electrical bonding measures ensure required system performance and to protect personnel. Bonding provisions will be compatible with other requirements imposed on the system for corrosion control. For further guidance see MIL-STD-464A.	I, T	3.3.37
SE01-2076	A	3.3.5	The cryocooler system shall provide a signal line to synchronize the SI cold head / inverter with the compressor.	It is necessary that the operations of the Pulse Tube rotary valve be "synchronized" with the compressor operations, such that the rotary valve will only operate when the compressor is operating, except during specific maintenance procedures. This requires that the compressor Drive Indication discrete signal be routed to the SI. Electrical power and signal wires between the cryocooler compressors and the SI cold head interface, including the reach through the CLA, may be a combination of existing / available SOFIA Instrumentation subsystem cabling and/or newly installed cables and interface connectors. The spec. and routing of these cables through the CLA, as well as the P/N and contact arrangements of the interface connectors, will be documented in SE03-2059 (CRYO_SI_01), and SE03-036 (TA_SI_01). SI developers will have the option of powering the cold head via the compressor, or via an SI-provided power source, such as a variable frequency drive inverter. SI-provided power sources may be located in a PI rack (which would be routed through the CLA) or in the CWR or on the SI asssembly itself (bypassing the CLA, in which case the SI developer will be responsible for providing, routing and restraining the necessary power cable).	I	3.1.29
SE01-2076	A	3.3.6	The cryocooler system shall include a pair of supply and return compressed He lines, routed from the He compressor, and through the Telescope Assembly (TA) Cable Load Alleviator (CLA) to the SI cold head interface demark.	The spec. and routing of these hoses through the CLA will be documented in SE03-036 (TA_SI_01). The routing and restraint of these hoses between the compressor and the QD interface to the CLA runs will be documented in SE03-2060 (CRYO_AS_01). The location and QD specification for the SI cold head interface demark will be defined in SE03-2059 (CRYO_SI_01). He gas lines will be a combination of helically or annularly corrugated stainless steel flex lines with a protective braided stainless steel overwrap, and rigid copper or stainless steel tubing with an equivalent effective ID (and cross-sectional area), selected to best match the application for each portion of the run. The number of interconnections should be minimized, and the size of the connections should be commensurate with the tubing diameters, to avoid unnecessary flow impedance and pressure drops.	I	3.1.29
SE01-2076	A	3.3.7	The flexible portion of the cryocooler compressor supply and return compressed He lines shall be annularly or helically corrugated stainless steel flexible tube with a braided stainless steel overwrap, a nominal ID of 1 inch (25.4 mm)*, an OD no greater than 1.36 inch (34.5 mm), and a minimum bending radius no greater than 10 inches (254 mm). * With the exception of the pair of supply / return flex lines that comprise the service loop for a gimbal-mounted compressor, which may have a smaller ID of 3/4 inch (19 mm) nominal ID.	Flex lines w/ a nominal ID of 3/4 inch (19 mm) are commonly specified for 4.2 K cryocooler systems. However, tests of cooling capacity for flex line lengths of up to 40 meters have shown significantly better performance using flex lines with a larger 25.1 mm ID. For this reason, compressed He lines will be the larger 1 inch nominal ID). To minimize the tilt correction error or bias imparted to the gimbal-mounted compressors due to the stiffness of the pressurized flex lines, the relatively short run of supply / return lines between the compressor(s) and the overhead-mounted QD interface to the adsorber and transducer manifold will be nominal 3/4 inch ID. End fittings for compatibility with compressors specified in ParID 3.1.3.1, the extermal adsorber canister (and for the SI interface hoses, the cold head / rotary valve) are #8 (1/2 inch) female Aeroquip seal-sealing quick disconnect fittings, base P/N: 5400-S5-8UL with o-ring seal elastomer Nitrile Butadiene Rubber (NBR), commonly known as Buna-N. End fittings for use in all other intermediate bulkheads or junctions will be larger #12 (3/4 inch) QD coupling pairs (male coupling half to be bulkhead mounted). Recommended flex line that meets or exceeds all of these specifications: HYDRA RS321L12 or RS331L12 (L12 and S12 are believed to be equivalent codes for braided stainless steel overwrap) HYDRA distribution: Witzenmann GmbH Östliche Karl-Friedrich-Straße 134 D-75175 Pforzheim ++49 (0) 7231-581-0 TEL ++49 (0) 7231-581-820 FAX wi@witzenmann.com	I	3.1.29

DocID	Rev	ParID	Requirement Text	Rationale / Notes	V & V Method	SE01-004 Parents
SE01-2076	A	3.3.8	Cryocooler system He gas flex lines shall have a Maximum Allowable Working Pressure (MAWP) no lower than 2.93 MPa (425 psi) and be certified by the manufacturer to a design Qualification ("burst") pressure no lower than 11.72 MPa (1700 psi), and an Acceptance ("proof") test pressure no lower than 5.86 MPa (850 psi).	Per DCP-S-065A ParID 11.2.B, a flexible pressure hose must be specified by the manufacturer with a design Qualification or "burst" pressure of at least four (4) times the system Maximum Allowable Working Pressure (MAWP). Though not specified within DCP-S-065, per discussions on 6/24/2014 with the AFRC PSM, SOFIA CSO and the Cryocooler System PM, it was agreed that each length of hose must be tested to an Acceptance or "proof" pressure of at least two (2) times the system MAWP. Per MPIfR / upGREAT Project Engineer, the transMIT PTD406-C cold heads have been tuned and optimized for use with SHI compressor static He charge pressure of 17.0 ~ 17.5 bar (1.7 ~ 1.75 MPa, or 247 ~ 254 psi). The SHI CSA-71A compressor includes a relief valve that is set to crack at 2.61 ~ 2.75 MPa (378.5 ~ 398.9 psi). Each of the flexible lines are to be additionally protected by relief valves ASME certified to open by 400 psi. It is desirable to include some margin such that a future cryocooler system configuration that requires higher static / operating pressures, and potentially different compressors, can be accommodated with the He flex lines that are installed in the CLA. Therefore, we are specifying a Qualification or "Burst" pressure of 1700 psi, and an Acceptance or "Proof" pressure of 850 psi.	I	3.5.3
SE01-2076	A	3.3.9	The flex line routing and management scheme from the cryocooler compressors to the SI interface shall respect the flex line manufacturer's specified minimum bend radius.	This ensures that the minimum bending radius of the compressed He flex lines will be respected, and facilitates the installation, removal and replacement of flex lines through the conduit, cable trays and/or plenums between the compressor sheds and the IRRs / PIF. The minimum bend radius specified by Witzenmann GmbH for the HYDRA DN25 flexlines is 150 mm (6 inches) for frequent bending. The minimum bend radius specified by SHI for their standard 3/4 inch flexlines is 9 inches.	I	3.1.29
SE01-2076	A	3.3.10	The installed cryocooler system shall remain clear of the SI installation cart path (i.e., SI cart translation path) as defined in SE03-205 (SIC_AS_01), *Science Instrument Cart to Aircraft System Interface* , Figure 1, *SI Cart Path* .	This ensures that the cryocooler system installation will respect the SI cart translation path and not impede SI installation operations, such that the cryocooler system may be installed and ready for operations prior to installation of a cryocooled SI such as upGREAT. The installed cryocooler system may occupy a portion of the SOFIA main deck reinforced floor, as defined on APP-DF-DWG-SE02-2924, *Layout of Personnel Accommodations (LOPA) - Main Deck* , but must remain clear of the SI Cart Path.	A, D	3.1.14
SE01-2076	A	3.3.11	The installed cryocooler He compressor shall remain clear of the TA aircraft cabin envelope as defined in SE03-017 (TA_AS_10), *Aircraft Cabin / TA Envelope ICD* .	This ensures that the cryocooler system installation will respect and not impede the motion of the portions of the TA within the SOFIA cabin over the full range of motion of the TA.	A	3.1.14
SE01-2076	A	3.3.12	The installed cryocooler He compressor shall remain clear of the SI dynamic and static/servicing envelopes as defined in SE03-002 (GLOBAL_09), *Science Instrument Envelope ICD.*	This ensures that the cryocooler system installation will respect and not impede the SI over the full range of motion of the integrated SI / TA.	A	3.3.33
SE01-2076	A	3.3.13	The cryocooler system shall include tooling, jacking and/or hoisting facilities for the use of cabin lifting devices, as needed, to enable the installation and removal of components and subassemblies, without exceeding the He compressor manufacturer's specified non-operating tilt limit of ±30 degrees from vertical.	They cryocooler system development must provide all necessary tooling and facilities necessary for installation, removal and maintenance of larger components and subassemblies.	I, D	3.2.8
SE01-2076	A	3.4	**Environmental**			
SE01-2076	A	3.4.1	The cryocooler system electrical equipment conducted and radiated Electromagnetic Interference (EMI) shall be in compliance with acceptable Electromagnetic Compatibility (EMC) for the aircraft and the observatory per MIL-STD-464A Para. 5.6.	The system must not interfere with Science mission equipment or the operation of the Platform aircraft. Safety and mission success can be adversely affected by EMI.	D	3.4.1
SE01-2076	A	3.4.2	The cryocooler system will reject up to 10 kW of heat to SOFIA main cabin air.	Air-cooled cryocooler He compressors reject essentially the same amount of electrical power that they consume to the ambient environment via forced convection. This is not a verifiable requirement for the cryocooler system, but rather a statement of fact intended to notify the platform engineers that this is an additional heat load that the aircraft and ground air conditioning systems will need to handle.	N/A	3.4.7

DocID	Rev	ParID	Requirement Text	Rationale / Notes	V & V Method	SE01-004 Parents
SE01-2076	A	3.4.3	The cryocooler system shall operate after exposure to the non-operating temperature conditions in accordance with DCP-O-018B Section 8.3.	Per SE01-004 ParIDs 3.4.17 and 3.4.19, DCP-O-018 defines the operating and non-operating temperature environmental conditions that Airborne Systems are expected to endure during the 20 year life of the program. May need to waive some specific environmental range requirements if cost is excessive and lesser ranges will be adequate. Ground Support Equipment (GSE) is excluded from this requirement. Typical storage (non-operating) environmental requirements (SHI FA-40L) are ambient temperature of -20 °C to 65 °C (-4 °F to 150 °F), and Relative Humidity of 10% to 90% (non-condensing).	T, A	3.4.19
SE01-2076	A	3.4.4	The cryocooler system shall operate within the temperature conditions in accordance with DCP-O-018B Section 8.3.	Per SE01-004 ParIDs 3.4.17 and 3.4.19, DCP-O-018 defines the operating and non-operating temperature environmental conditions that Airborne Systems are expected to endure during the 20 year life of the program. May need to waive some specific environmental range requirements if cost is excessive and lesser ranges will be adequate. Ground Support Equipment (GSE) is excluded from this requirement. The SHI CSA-71A compressor includes 3 thermostats that will assert over-temperature discrete alarms and/or shut down the compressor when certain setpoints are exceeded. This is part of the normal and safe operation of the compressor and an over-temperature shut down is not considered a test failure. Typical operating environmental requirements are based on the specific make and compressor model used. SHI CSA-71A ambient temperature range is 5 °C to 28 °C (41 °F to 82 °F) to achieve rated capacity, and maximum Relative Humidity of 25% to 85%. The system can operate at up to 35 °C (95 °F) with a 5% reduction in rated cooling capacity.	T, A	3.4.17
SE01-2076	A	3.4.5	The cryocooler system equipment and installations shall operate in the vibration environment in accordance with DCP-O-018B Figure 8-1 and Table 8-2, Curve PA, applying the maximum random vibration testing reduction factor for mass loading defined in Figure 8-2.	DCP-O-018B Figure 8-1 and Table 8-2, Curve PA defines the vibration loads in the main cabin that the Airborne System is expected to endure during the 20 year life of the program. This requirement excludes Ground Support Equipment. It is recommended that the cryocooler compressor assembly and associated components be tested in their flight configuration on its shock-mounted, vibration isolated pallet mount.	T, A	3.4.15
SE01-2076	A	3.4.6	The cryocooler equipment shall remain functional after exposure to the pressure environments (altitude, decompression) as specified in DCP-O-018B Section 8.3 for Category V (Pressurized Compartment, temp-controlled compartment, with barometric shut-off switch set point of 19,000 ft.).	Per AFRC-OE, the test sequence defined below is considered applicable to airborne systems permanently installed in the SOFIA pressurized main cabin and powered downstream of the decompression relay: 1) At site altitude, power off device and reduce temperature until unit stabilizes at 0˚ F 2) Apply power to device and increase altitude 1000 ft/min to 20,000 feet MSL 3) Hold for 10 minutes 4) Return to site altitude 5) Heat until unit is stabilized at 160˚ F 6) Hold for 1 hour 7) Increase altitude 1000 ft/min to 20,000 feet MSL 8) Hold for 10 minutes 9) Return to site altitude and ambient temperature 10) Perform functional check of device and note any deficiencies	T, A	3.4.7
SE01-2076	A	3.5	**Safety**			
SE01-2076	A	3.5.1	The cryocooler system shall comply with the applicable NASA Public Use Airworthiness Certification processes using 14 CFR 25, MILSTDs, and/or NASA standards.	A SOFIA Program decision was made to follow a NASA self certification process, utilizing FAA standards where applicable. This decision was made due to the one-of-a-kind nature of the Airborne Observatory. Also, it is believed that self certifying would be more appropriate than using the FAA certifying process. A certificate of airworthiness is required to fly within US and international airspace.	I	3.5.3
SE01-2076	A	3.5.2	The cryocooler system shall appropriately guard personnel from surface temperatures which could cause burns and injury except for surface temperatures induced by climatic environments.	Where cryocooler system equipment operating surface temperatures may cause burns or injury to personnel, proper protection will be provided.	I, A	3.5.30
SE01-2076	A	3.5.3	Multiple connectors in the same area shall be unique in size, keyed separately and or uniquely labeled at the connector and on the mating surface.	This is good human engineering practice from T.O. 01-1A-14 and MIL-STD-1472F Chg. 1.	I	3.9.1
SE01-2076	A	3.5.4	The cryocooler system shall be subject to a hazard Analysis per DCP-S-002, *Hazard Management Procedure* .	This requirement promotes safe operation and protects personnel and equipment.	I	3.5.30

DocID	Rev	ParID	Requirement Text	Rationale / Notes	V & V Method	SE01-004 Parents
SE01-2076	A	3.5.5	The cryocooler system pressurized systems, components and lines shall comply with the applicable requirements of DCP-S-065, *Pressure Vessels & Pressurized System (PVS) Safety* .	From a design standpoint, particular attention should be paid to Section 11, *PVS Components* , including 11.1, *Pressure Relief Devices* , 11.2, *Flexible Pressure Hose* , and 11.3, *Valves & Fittings* .	I	3.5.3
SE01-2076	A	3.5.6	Cryocooler system PVS GSE shall comply with the applicable requirements of NASA-STD-8719.17, *NASA Requirements for Ground-Based Pressure Vessels and Pressurized Systems (PVS)* .	This is the NASA Standard applicable to GSE PVS, with considerable "overlap" between these and the counterpart flight system PVS DCP-S-065 requirements.	I	3.5.3
SE01-2076	A	3.5.7	The cryocooler system electrical connectors shall incorporate locking features or provisions for safety wire.	This is good engineering practice from T.O. 01-1A-14. This requirement excludes Ground Support Equipment (GSE), as well as fluidic connectors.	I	3.5.30
SE01-2076	A	3.5.8	The cryocooler system components and installation shall maintain positive Margins of Safety (MS) when exposed to the aircraft ultimate and emergency landing load conditions in accordance with USRA-DAL-1126-00.	A SOFIA Program decision was made to follow a NASA self certification process. This decision was made due to the one-of-a-kind nature of the Airborne Observatory. Also, it is believed that self certifying would be more appropriate than using the FAA certifying process. A certificate of airworthiness is required to fly within US and international airspace. This requirement excludes Ground Support Equipment.	A	3.4.16
SE01-2076	A	3.5.9	The cryocooler system and installation shall incorporate design measures to mitigate slip, trip, pinch, and fall hazards to the same level as existing aircraft main cabin components (maintain risk level below "accepted risk" category).	Though the DCP-S-002 Hazard Management Procedure is applicable to all SOFIA developments, experience has shown that an up-front, verifiable design requirement is helpful to ensure that such hazards do not get overlooked until very late in the development and integration flow, when adequate mitigations become difficult and expensive to implement.	I, A	3.5.30
SE01-2076	A	3.5.10	Cryocooler system electrical circuitry, wiring and components shall be designed, derated, sized, overcurrent protected and fabricated in accordance with FAA Advisory Circular (AC) 43.13-1B, Chapter 11, *Aircraft Electrical Systems* .	De-rating electronic components ensures design limits will not be exceeded. Also see USRA-DAL-1029, section 2 for further guidance. This is applicable to NASA designed equipment and not to COTS.	I, A	3.5.3
SE01-2076	A	3.5.11	Cryocooler system GSE designed for use on SOFIA or at any NASA facility shall comply with the structural and stability requirements of SE01-2028, *SOFIA Science Instrument System Specification* , ParIDs 3.5.2.2 through 3.5.2.8, as applicable.	The cited requirements from SE01-2028 were intended for GSE SI installation carts and stands, but are also considered applicable to any unique GSE installation carts required for installation / removal of cryocooler system components, such as the compressor(s) and/or compressor mounts.	I, A, T	3.5.3

DocID	Rev	ParID	Requirement Text	Rationale / Notes	V & V Method	SE01-004 Parents
SE01-2076	A	3.6	**Reliability**			
SE01-2076	A	3.7	**Maintainability**			
SE01-2076	A	3.7.1	Cryocooler system components (e.g., He compressor, control systems) shall be mounted such that these can be repaired or swapped with a spare unit with a Mean Time To Repair (MTTR) of 4.8 hours or less.	Cryocooler He compressors and other major components should be reparable or replaceable between flights, so that a malfunction of these long lead-time items cannot jeopardize an entire observing campaign. This requirement does not apply to compressed He lines that are routed through the Cable Load Alleviator (CLA), under floor panels, or are otherwise inaccessible.	A, D	3.7.1
SE01-2076	A	3.7.2	The cryocooler system shall include a suitably ruggedized spare of the He compressor model for replacement.	Cryocooler He compressors should be replacable between flights, so that a malfunction of these long lead-time items cannot jeopardize an entire observing campaign. Note, there is no intent that this requirement would support swapping of compressors as an In-Flight Maintenance (IFM) procedure.	I	3.7.6
SE01-2076	A	3.7.3	The cryocooler system shall allow for the maintenance required for continuous airworthiness.	This requirement ensures that at the lower levels the necessary durability and longevity are designed into the hardware. The anticipated annual science return of SOFIA necessitates 20-years of operations to justify the overall costs for development and operation of the facility.	I	3.7.12
SE01-2076	A	3.7.4	Cryocooler system specific inputs to the SOFIA Airborne Platform Logistics Plan (PM23-2000) shall be developed.	This requirement ensures that at the lower levels the necessary durability and longevity are designed into the hardware. The anticipated annual science return of SOFIA necessitates 20-years of operations to justify the overall costs for development and operation of the facility.	A	3.7.6
SE01-2076	A	3.7.5	Replaceable cryocooler system components (adsorber canisters, fuses when so equipped, etc.) shall allow replacement without requiring compressed He loop pump-out and backfill, soldering or welding operations.	The cryocooler system is critical to operations for SIs that use this mission system. Return To Base (RTB) for routine repairs must be avoided wherever practical, and relatively straightforward modifications that reduce Mean Time To Repair (MTTR) by obviating the need to remove and open the compressor housing should be implemented.	D	3.7.12
SE01-2076	A	3.8	**Logistics**			
SE01-2076	A	3.8.1	The cryocooler system compressor and control system mounts shall support installation of the cryocooler system aboard SOFIA, and removal from SOFIA, each within an 8 hour work shift.	This is considered necessary and appropriate to ensure that installation and integration of the SI and necessary mission systems can be performed in a reasonable timeframe to support change-outs between observing campaigns.	D	3.2.8
SE01-2076	A	3.8.2	The cryocooler system shall identify any special tools required for maintenance and inspection, in the Airborne Platform Logistics Plan (PM23-2000).	To the extent possible, maintenance and inspection should be performed using only standard tools per the Airborne Platform Logistics Plan (PM23-2000). However, in the event that certain Special tools are needed, these must be identified and procured.	I	3.7.6
SE01-2076	A	3.8.3	The cryocooler system shall be designed to allow packaging and shipment in accordance with NPR 6000.1G.	Transporting the cryocooler system is likely necessary over the course of the Observatory's projected 20 year service life.	I	3.8.1
SE01-2076	A	3.8.4	The cryocooler system shall provide any specialized or non-standard Ground Support Equipment (GSE) necessary for operations and maintenance of the cryocooler system.	GSE may include compressed He flex lines w/ Aeroquip coupling adapters for interface with He compressor charging / refill port, He cylinder dolly and regulator, dedicated vacuum pump (if necessary).	I	3.7.6
SE01-2076	A	3.9	**Human Factors**			
SE01-2076	A	3.9.1	The cryocooler system equipment designs and equipment modifications should comply with Human Engineering (MIL-STD-1472F Chg. 1 dated 12/5/03). (LOPA)	All SOFIA System components will be consistent with good human factors practices. MIL-STD-1472 is cited as a guidance document.	I	3.9.1
SE01-2076	A	3.9.2	The cryocooler system front panel controls, gauges, electrical and fluidic connections shall be accessible and viewable by an operator.	All SOFIA System components will be consistent with good human factors practices.	D	3.9.1
SE01-2076	A	3.9.3	N/A for Phase 1 Cryocooler System.			
SE01-2076	A	3.9.4	Each compressed He line shall be labeled at both ends, as well as any intermediate interconnection, to clearly indicate "SUPPLY" (or RED) or "RETURN" (or GREEN), as	All SOFIA System components will be consistent with good human factors practices.	I	3.9.1
SE01-2076	A	3.9.5	N/A for Phase 1 Cryocooler System.			

DocID	Rev	ParID	Requirement Text	Rationale / Notes	V & V Method	SE01-004 Parents
SE01-2076	A	3.10	**Parts, Materials & Processes (PMP)**			
SE01-2076	A	3.10.1	The cryocooler system design shall select parts, materials, and processes using best commercial aircraft industry practices as determined by Critical Design Review and airworthiness expert(s).	Required to meet NASA public Use Airworthiness certification process (SE01-003/3.5.5) MAPTIS II does not specify requirements. The MAPTIS-II system contains physical, mechanical and environmental properties for metallic and non-metallic materials. The MAPTIS rates materials based on suitability for the application and defines the criteria for the rating. If the material is not found in the A-rated MAPTIS (universal suitability), then the material selected needs to pass the flammability test outlined in NASA-STD-6001. This requirements is applicable to modifications of COTS but not to the unmodified portion of COTS.	I	3.10.4
SE01-2076	A	3.10.2	The cryocooler system design shall include a protective plating or coating to all metal surfaces which are not corrosion resistant, except where electrical grounding is required.	This requirement excludes Ground Support Equipment. This reqmt pertains to components that may not have corrosion protection.	I	3.10.2
SE01-2076	A	3.10.3	The cryocooler system design shall use materials which do not, through out-gassing, cause the deterioration of other materials, or the degradation of performance of onboard equipment, or exposure of equipment, systems, components, or personnel to hazardous or toxic materials.	Required to meet NASA public Use Airworthiness certification process (SE01-003/3.5.5) MAPTIS II does not specify requirements. The MAPTIS-II system contains physical, mechanical and environmental properties for metallic and non-metallic materials. The MAPTIS rates materials based on suitability for the application and defines the criteria for the rating. If the material is not found in the A-rated MAPTIS (universal suitability), then the material selected needs to pass the flammability test outlined in NASA-STD-6001. This requirement excludes Ground Support Equipment.	A, I	3.10.4
SE01-2076	A	3.10.4	Use of wires coated in polyvinylchloride (PVC) insulation or jacketing shall be prohibited.	Overheated or burning PVC releases toxic vinyl chloride vapors. Reconstruction of PVC components in COTS equipment is recommended if replacement parts that do not use PVC are unavailable, where possible. This is primarily applicable to external cables and connectors. For example, while the power cable for a computer may have a unique connector made of PVC for which a non-PVC replacement is unavailable, the PVC-jacketed and/or insulated cabling between the connectors could be removed and re-fabricated with a Teflon coating. Where reconstruction or replacement of parts that do not use PVC is considered impractical or overly burdensome, the SI developer must clearly identify this early in the design and airworthiness certification review process for assessment of risk and possible airworthy mitigations, possibly including use of shrink tube or other protective sleeving.	I	3.10.4
SE01-2076	A	3.10.5	He gas used to charge the cryocooler systems shall have a purity of at least 99.9999% Grade N6.0, with a dew point temperature of less than -60 °C (-76 °F).	Typically, a He gas purity of between 99.995% and 99.999% with a dew point temperature of less than -60 °C (-76 °F) is specified. However, 99.995% purity is insufficient for the PT cold heads to be used by upGREAT, which are very sensitive to contamination. These require 99.999% Helium grade N5.0 (minimum) or 99.9999% Helium grade N6.0 (recommended). The cost of grade N6.0 is about the same as for grade N5.0, so grade N6.0 is preferred. Mating / unmating the He lines from the cold head several times is enough to introduce excessive contamination levels.	I	3.1.86

DocID	Rev	ParID	Requirement Text	Rationale / Notes	V & V Method	SE01-004 Parents
SE01-2076	A	3.11	**Interfaces**			
SE01-2076	A	3.11.1	The cryocooler system shall operate as specified herein within the power allocation defined (for each single compressor) in SE03-2038, Global Power Budget ICD.	This is the Platform PCB-controlled ICD that defines the SOFIA observatory power bus and power allocated to the cryocooler system. PMB-controlled ICD SE03-2029 (MCCS_SI_05) para. 3.2.1.4 includes additional information re: the location of the power drops and AWG sizing of the conductors from the PDS to the cryocooler power interfaces. The initially baselined cryocooler system power allocation from Observatory Bus 4 is 20 kVA of 115 / 200 VAC, 3 phase, 400 Hz. However, during the 17 April 2014 Cryocooler SRR, the SOFIA Program agreed that the Frequency Converter(s) needed to convert the 400 Hz 3 phase power to 60 Hz 3 phase power would be provided by the MCCS PDS and removed from the scope of the Cryocooler System.	I	3.3.20
SE01-2076	A	3.11.2	Cryocooler system GSE carts and stands to be used within the SOFIA aircraft shall comply with the applicable requirements of SOF-AR-ICD-SE03-205 (SIC_AS_01), SI Handling Cart to Aircraft System ICD.	Language and figures within this ICD cite other applicable requirements within SE03-002 (GLOBAL_09) and SE03-004 (GLOBAL_07) for installation envelope and SOFIA floor panel loading constraints. Additionally, Figure 1 in this ICD depicts the SI Cart Path which must remain unobstructed by cryocooler system installation, to ensure that the cryocooler system will not impede the installation or removal of the SI.	A, I, D	3.3.52
SE01-2076	A	3.11.3	The cryocooler system compressed He lines and cold head connections to the SI cold head, as well as housekeeping data / alarm discretes, shall interface to the SI as defined in ICD CRYO_SI_01 (SE03-2059).	This ICD defines the Cryocooler System-to-SI interface at new patch panel U404, in the vicinity of U402. upGREAT cabling between variable frequency inverter and cold head rotary valve is not within the scope of this ICD.	I	3.1.28
SE01-2076	A	3.11.4	The cryocooler system shall interface with with the TA CLA in accordance with ICD TA_SI_01 (SE03-036).	The compressed He lines are identified in TA_SI_01 for the TA side of the CLA.	I	3.1.29
SE01-2076	A	3.11.5	N/A for Phase 1 Cryocooler System.			
SE01-2076	A	3.11.6	The cryocooler system shall interface with the aircraft in accordance with ICD CRYO_AS_01 (SE03-2060).	This ICD defines the Cryocooler System physical interface with the aircraft.	I	3.1.28

APPENDIX A - Figures & Tables

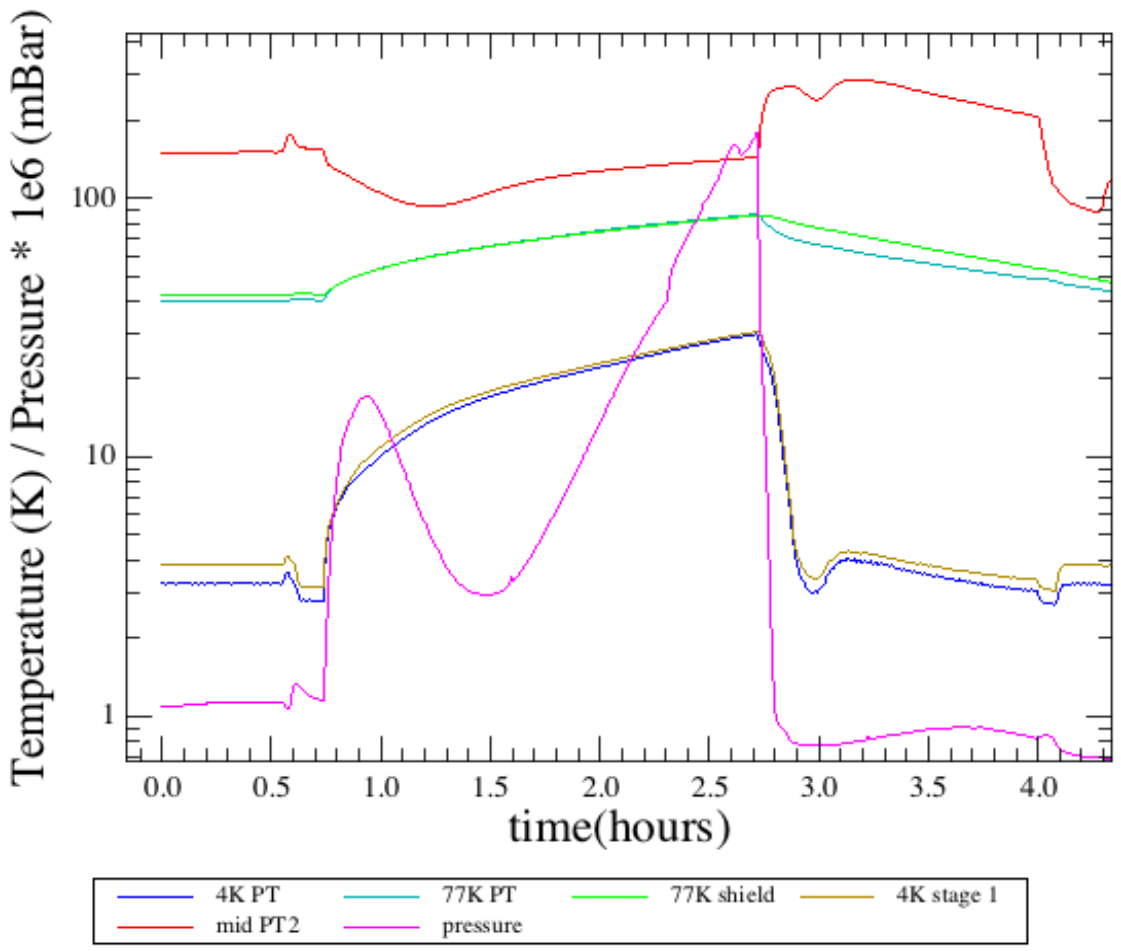
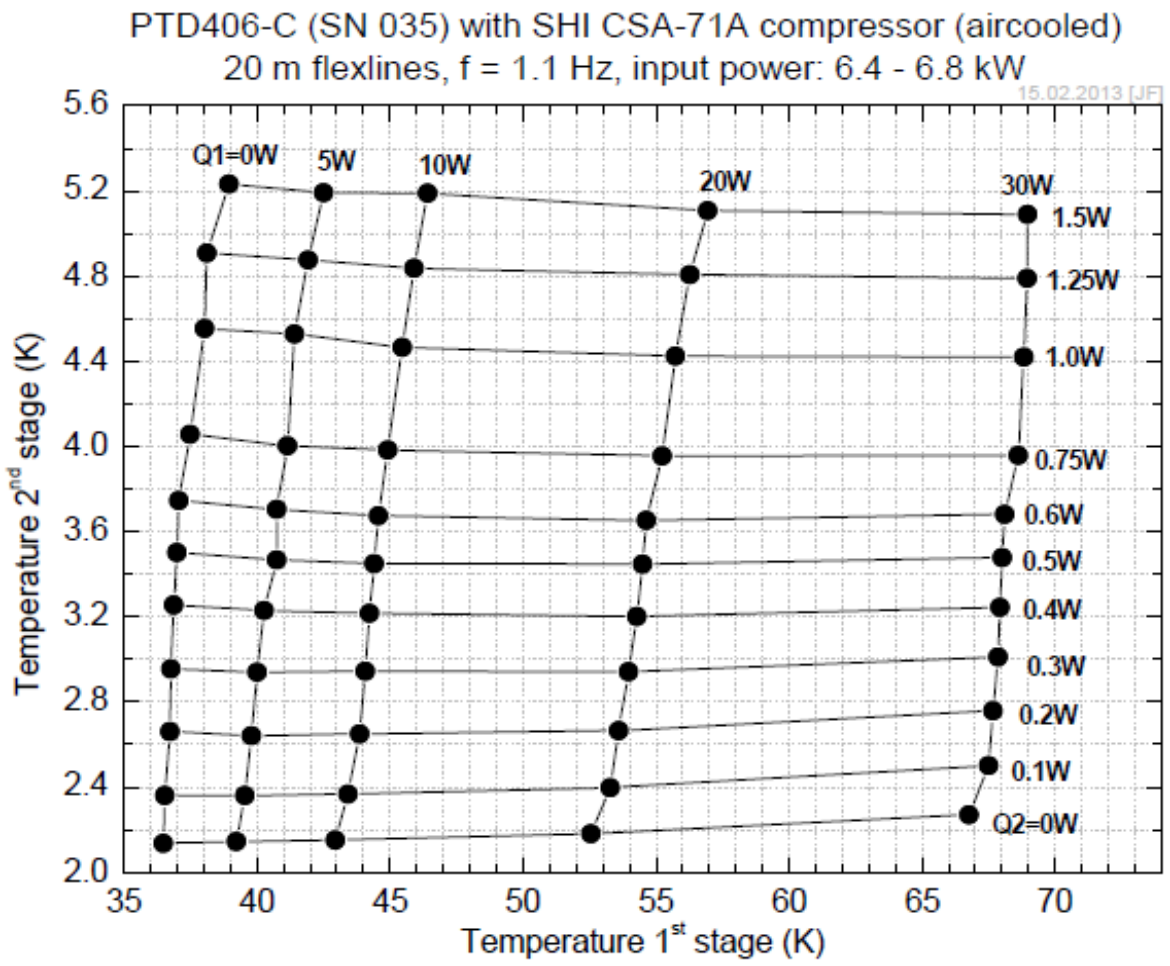


Figure 3.2-1 Warm-up / Cool-down test results from instrumented upGREAT channel cryostat, transMIT PTD406-C Pulse Tube cold head, and SHI air-cooled CSA-71A compressor [reference only]
Note: During this test, compressor operations were shut off @ t = ~0.75 hours, and restored @ t = ~2.75 hours

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 3.2-2 Thermal performance map of transMIT PTD406-C Pulse Tube cold head (w/ remote rotary valve) tuned for operation w/ SHI air-cooled CSA-71A compressor using 50 Hz power [reference only]

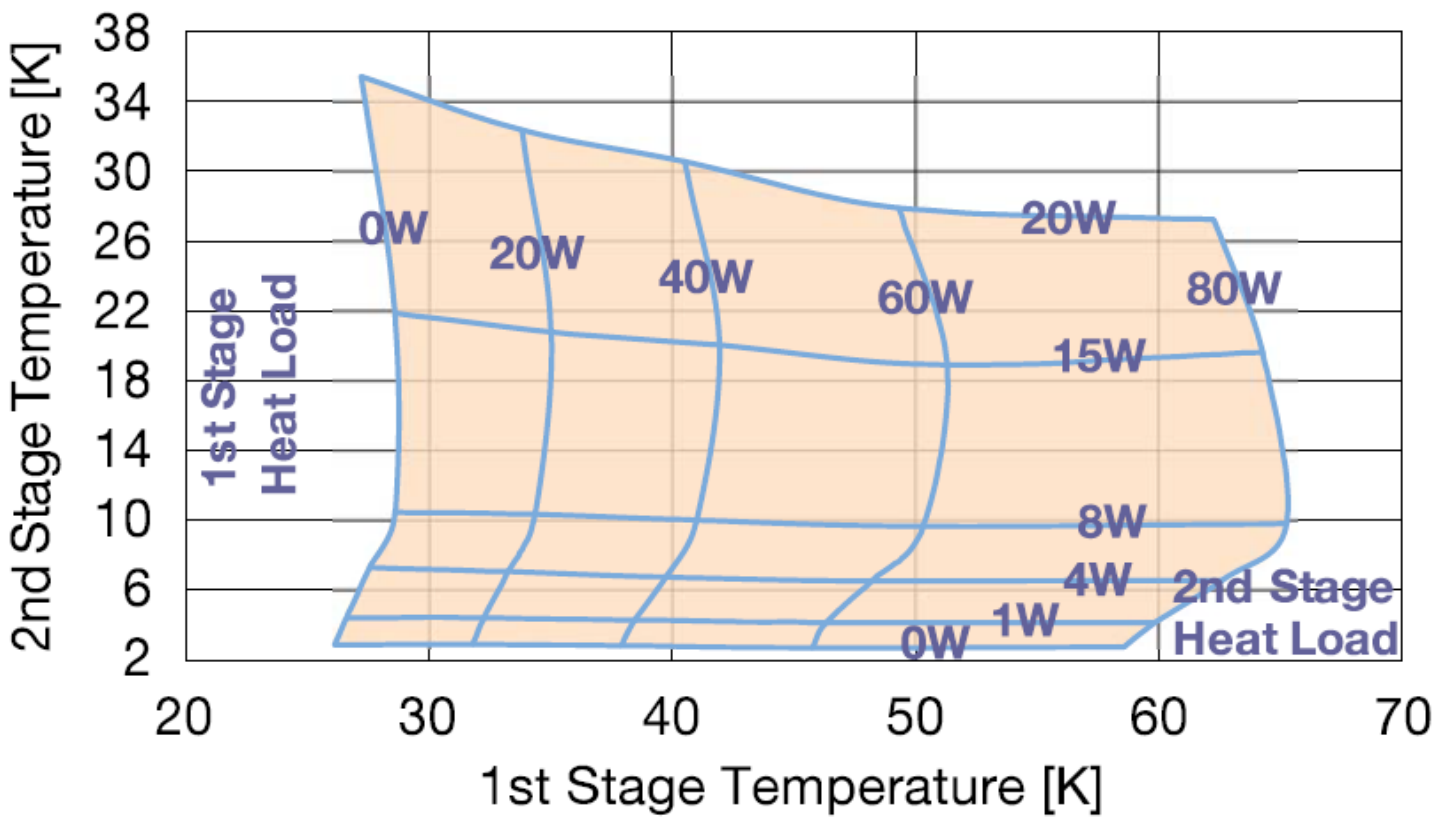
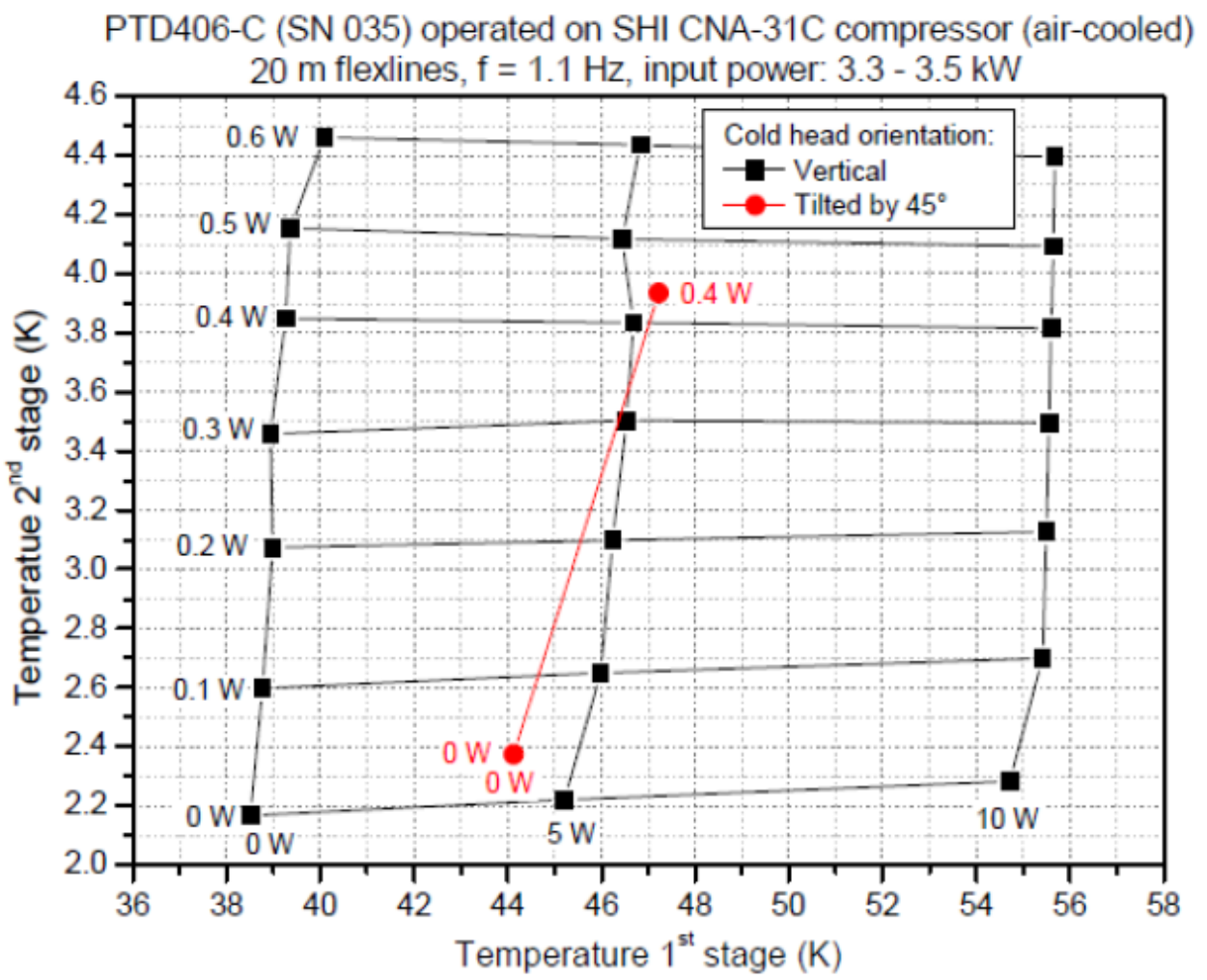


Figure 3.2-3 Thermal performance map of Sumitomo Heavy Industries (SHI) RDK-408D2 Gifford-McMahon (GM) cold head using 60 Hz power [reference only]

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 3.2-4 Thermal performance map of transMIT PTD406-C Pulse Tube cold head (w/ remote rotary valve) tuned for operation w/ SHI air-cooled CNA-31C compressor using 50 Hz power [reference only]

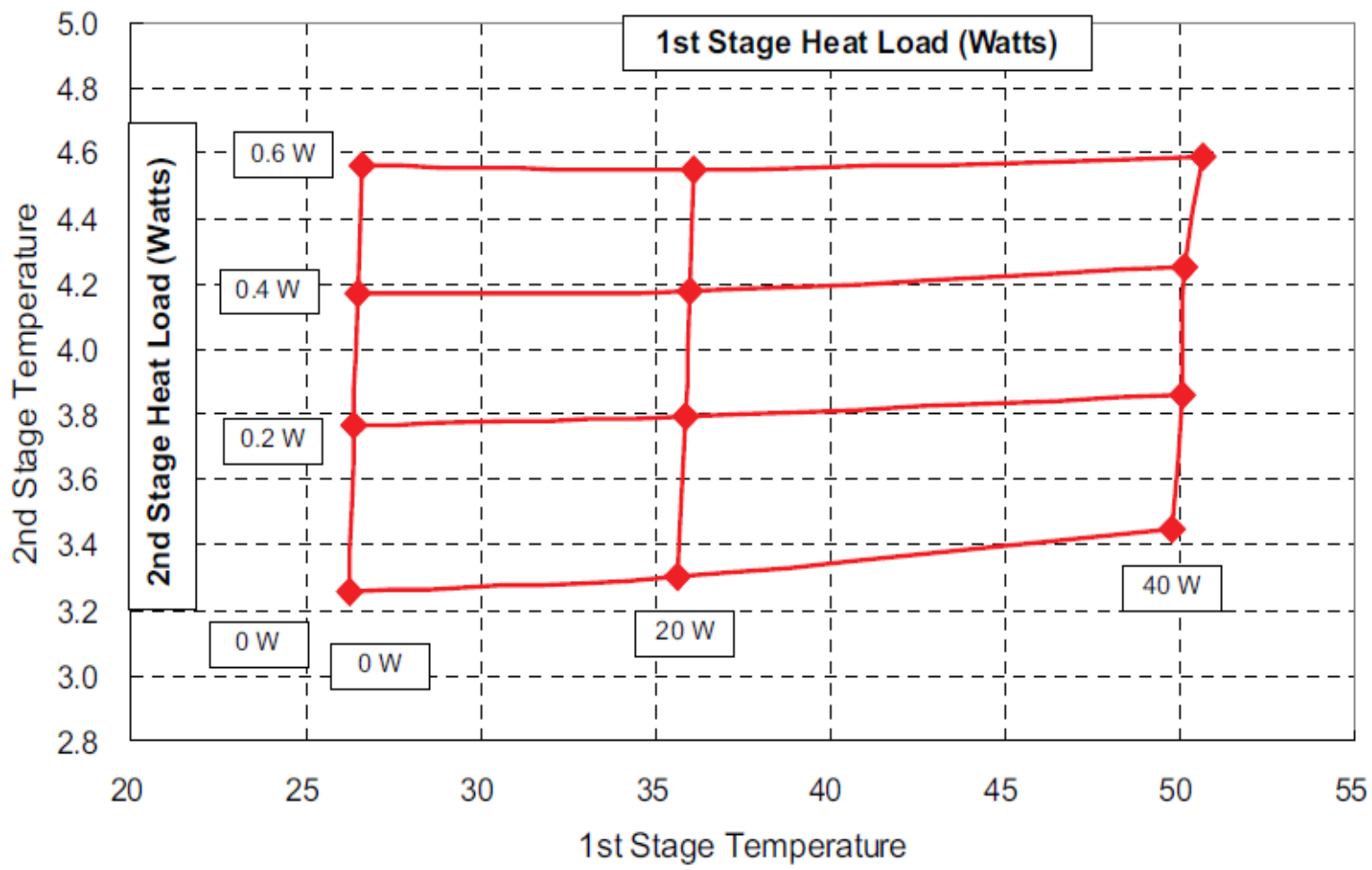


Figure 3.2-5 Thermal performance map of Sumitomo Heavy Industries (SHI) RDK-305D Gifford-McMahon (GM) cold head using 60 Hz power [reference only]

$$P_{(W)} = \sqrt{3} \times PF \times I_{(A)} \times V_{L\text{-}L(V)}$$

Figure 3.11-1 3 phase AC Amps to Watts calculation formula (based on line-to-line RMS voltage)

Note 3.11-1 Cryocooler System Power Budget and SHI He Compressor Load Analysis

Compressors consume several hundred additional Watts of power at start-up, until heat loads from cold head are reduced
Sumitomo shows a start-up power of 5.6 kW for the CNA-31C, with a reduction to 4.8 kW steady-state power
Sumitomo shows a start-up power of 8.3 kW for the CSA-71A, with a reduction to 7.5 kW steady-state power
Typically the reduction from start-up to steady-state takes place ~45 minutes after start-up, dependent of course upon the heat capacity of the cryostat stages

Sumitomo CNA-31C (air cooled) consumes 4.8 kW steady-state and 5.6 kW start-up for perhaps 30 ~ 45 minutes during the initial cool-down from room temperature

Sumitomo CSA-71A (air cooled) consumes 7.5 kW steady-state and 8.3 kW start-up.

Assume a (conservative?) Power Factor of 0.8 (TBD)

Assume that day of flight / pre-flight operational timelines will support a "stagger start" in which the start-up of the 2nd compressor will be after the 1st compressor power consumption has reduced to steady-state:

4.8 kW / 0.8 Power Factor => 6 kVA (CNA-31C @ steady-state)
5.6 kW / 0.8 Power Factor => 7 kVA (CNA-31C @ start-up)
7.5 kW / 0.8 Power Factor => 9.4 kVA (CSA-71A @ steady-state)
8.3 kW / 0.8 Power Factor => 10.4 kVA (CSA-71A @ start-up)

CSA-71A (steady-state) + CNA-31C (start-up) => 9.4 kVA + 7 kVA = 16.4 kVA @ 60 Hz
This corresponds to **20.5 kVA** @ 400 Hz, assuming an **80% power conversion efficiency** (2.5% over 20 kVA power allocation)
If we instead assume an **85% power conversion efficiency** (seems reasonable), this brings us to **19.3 kVA** @ 400 Hz (3.5% under 20 kVA power allocation)

CNA-31C (steady-state) + CSA-71A (start-up) => 6 kVA + 10.4 kVA = 16.4 kVA @ 60 Hz
(no advantage provided by changing which compressor is started first)

APPENDIX B - Open Issues

Open Issue #	SE01-2076 Paragraph	Action Plan	Actionee	Action ECD

TBD To Be Determined
TBR To Be Reviewed
TBS To Be Supplied

APPENDIX C - Definitions, Abbreviations and Acronyms

AFRC	Armstrong Flight Research Center (formerly DFRC)
ARC	Ames Research Center
AWG	American Wire Gauge
BEAP	Building Emergency Action Plan
CCC	Closed Cycle Cryocooler
COTS	Commercial Off The Shelf
DAOF	Dryden Aircraft Operations Facility (now AFRC Building 703)
DAS	Data Acquisition Subsystem
dBA	deciBels (A-weighted)
DFRC	Dryden Flight Research Center (now AFRC)
FC	Frequency Converter
GM	Gifford-McMahon (cold head technology)
GREAT	German REceiver for Astronomy at Terahertz frequencies
GSE	Ground Support Equipment
He	Helium
HFA	High Frequency Array (upGREAT channel cryostat)
HR	Hazard Report
HVAC	Heating, Ventilation & Air Conditioning
Hz	Hertz (cycles per second)
ICD	Interface Control Document
ID	Inner Diameter
IRR	Instrument Readiness Room
IFM	In-Flight Maintenance
JT	Joule Thompson (cold head technology)
kg	kilograms
kPa	kilo Pascals
kW	kilo Watts
kVA	kilo Volt-Amperes
LFA	Low Frequency Array (upGREAT channel cryostat)
LHe	Liquid Helium
MAWP	Maximum Allowable Working Pressure (equivalent to Maximum Normal Operating Pressure or MNOP)
mm	millimeter
MNOP	Maximum Normal Operating Pressure
MOPS	Mission Operations
MPIfR	Max-Planck-Institut für Radioastronomie
MSDS	Material Safety Data Sheet
MTTR	Mean Time To Repair
NASA	National Aeronautics and Space Administration
NEMA	National Electrical Manufacturers Association
OD	Outer Diameter
O&M	Operations & Maintenance
OEM	Original Equipment Manufacturer
PF	Power Factor
PIF	Pre-flight Integration Facility
psi	Pounds per Square Inch
PT	Pulse Tube (cold head technology)
PVS	Pressure Vessels and Pressurized Systems
Q	Heat Flux
Q1	Cold Head 1st Stage Heat Flux
Q2	Cold Head 2nd Stage Heat Flux
RMS	Root Mean Square
RTB	Return To Base
SHI	Sumitomo Heavy Industries, Ltd.
SI	Science Instrument
SNACS	Standard New Astronomy Cryostat for SOFIA
SOFIA	Stratospheric Observatory For Infrared Astronomy
SRR	System Requirements Review
SSMO	SOFIA Science & Mission Operations
TAAS	Telescope Assembly Alignment Simulator
THD	Total Harmonic Distortion
UPS	Uninterruptible Power Supply
VAC	Volts Alternating Current
VDC	Volts Direct Current
V_L	Line Voltage (Phase-to-Phase) in "Y" (or "Wye") connected 3-phase power system
V_P	Phase Voltage (Phase-to-Neutral) in "Y" (or "Wye") connected 3-phase power system