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Simplified Methodology to Estimate the Maximum Liquid Helium (LHe) Cryostat Pressure from a Vacuum Jacket Failure

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October 2015

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September 24, 2015

Report Approval and Revision History

NOTE: This document was approved at the September 24, 2015, NRB. This document was submitted to the NESC Director on September 25, 2015, for configuration control.

Approved:	*Original Signature on File*	9/28/15
	NESC Director	Date

Version	Description of Revision	Office of Primary Responsibility	Effective Date
1.0	Initial Release	W. Lance Richards, NESC Chief Engineer, AFRC	09/24/2015

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Technical Assessment Report

1.0 Notification and Authorization

Mr. Edward J. Ingraham, the Safety and Mission Assurance Lead for the Stratospheric Observatory for Infrared Astronomy (SOFIA) Program at the Ames Research Center, requested that the NASA Engineering and Safety Center (NESC) develop a simplified method of predicting the maximum pressure in a cryogenic liquid helium (LHe) dewar after a sudden loss of vacuum jacket thermal insulation.

Dr. Eugene Ungar, Discipline Deputy for the Life Support/Active Thermal Technical Discipline Team at Johnson Space Center (JSC), was selected as the technical lead for this assessment.

The key stakeholder for this assessment is Mr. Edward J. Ingraham.

2.0 Signature Page

Submitted by:

Team Signature Page on File – 9/30/15

Dr. W. Lance Richards Date

Significant Contributors:

Dr. Eugene K. Ungar Date

Signatories declare the findings, observations, and NESC recommendations compiled in the report are factually based from data extracted from program/project documents, contractor reports, and open literature, and/or generated from independently conducted tests, analyses, and inspections.

3.0 Team List

Name	Discipline	Organization
Core Team		
W. Lance Richards	NESC Lead	AFRC
Eugene K. Ungar	NESC Technical Lead, Discipline Deputy for the Life Support/Active Thermal Technical Discipline Team	JSC
John LaNeave	MTSO Program Analyst	LaRC
Administrative Support		
Linda Burgess	Planning and Control Analyst	LaRC/AMA
Dee Bullock	Technical Writer	LaRC/AMA

3.1 Acknowledgements

The author wishes to thank Mr. Andrew Hong (JSC) for performing the numerical analysis for the present work.

4.0 Executive Summary

The aircraft-based Stratospheric Observatory for Infrared Astronomy (SOFIA) is a platform for multiple infrared astronomical observation experiments. These experiments carry sensors cooled to liquid helium (LHe) temperatures. The LHe supply is contained in large (i.e., 10 liters or more) vacuum-insulated dewars. Should the dewar vacuum insulation fail, the inrushing air will condense and freeze on the dewar wall, resulting in a large heat flux on the dewar's contents. The heat flux results in a rise in pressure and the actuation of the dewar pressure relief system.

A previous NASA Engineering and Safety Center (NESC) assessment [ref. 1] provided recommendations for the wall heat flux that would be expected from a loss of vacuum and detailed an appropriate method to use in calculating the maximum pressure that would occur in a loss of vacuum event. This method involved building a detailed supercritical helium compressible flow thermal/fluid model of the vent stack and exercising the model over the appropriate range of parameters.

The experimenters designing science instruments for SOFIA are not experts in compressible supercritical flows and do not generally have access to the thermal/fluid modeling packages that are required to build detailed models of the vent stacks. Therefore, the SOFIA Program engaged the NESC to develop a simplified methodology to estimate the maximum pressure in a LHe dewar after the loss of vacuum insulation. The method would allow the university-based science instrument development teams to conservatively determine the cryostat's vent neck sizing during preliminary design of new SOFIA Science Instruments.

This report details the development of the simplified method, the method itself, and the limits of its applicability. The simplified methodology provides an estimate of the dewar pressure after a loss of vacuum insulation that can be used for the initial design of the LHe dewar vent stacks. However, since it is not an exact tool, final verification of the dewar pressure vessel design requires a complete, detailed real fluid compressible flow model of the vent stack.

5.0 Problem Description

Accurately predicting the maximum pressure of a LHe dewar after a loss of vacuum insulation requires a detailed real fluid compressible flow model of the vent stack. Owing to the cost and complexity of the applicable codes, developing and executing such a model would typically be beyond the capability of the SOFIA researchers who are planning new experiments. Therefore, a simpler method of predicting the peak pressure is desired for preliminary dewar and vent stack design.

5.1 Simplified Methodology

Predicting the Pressure in a Loss of Vacuum Insulation Condition

The NESC's previous work for the SOFIA Program [ref. 1] recommended using 4 W/cm^2 as the loss of vacuum insulation dewar wall heat flux. The pressure inside the dewar at this condition must be calculated during the design phase to ensure that the dewar is sufficiently strong to withstand a vacuum insulation failure.

The peak pressure during a loss of vacuum insulation event must be calculated through iteration. First, the peak pressure state inside the dewar is assumed and the vent stack mass flow rate is calculated. The wall heating that would create this mass flow rate is then calculated. The dewar pressure is iterated until the result converges to a wall heat flux of 4 W/cm^2.

In the explanation and calculations of the present work, it is implicitly assumed that the dewar pressure is known, since the pressure is required for the iterating calculation that returns the dewar wall heat flux at each step.

The Dewar State during Loss of Vacuum Insulation

The Compressed Gas Association (CGA) Standards [ref. 2] require that the loss of vacuum insulation condition be analyzed at a particular combination of pressure and temperature for a supercritical fluid. At a given pressure, the dewar stack is analyzed at the temperature where

$$\left(1/\sqrt{v}\right)\mathrm{h}_{\mathrm{fg}}^{*} \qquad \text{Eq. (1)}$$

is at a minimum. Here, v is the fluid specific volume and $\mathrm{h}_{\mathrm{fg}}^{*}$ is the pseudo latent heat[1]. The pseudo latent heat includes the effect of the internal energy change in the dewar and allows the energy balance on the dewar to be written simply as

$$\dot{\mathrm{m}} = \frac{\mathrm{Q}}{\mathrm{h}_{\mathrm{fg}}^{*}} \qquad \text{Eq. (2)}$$

[1] The derivation of the pseudo latent heat for a supercritical fluid is contained in Appendix A.

where $\dot{m}$ is the venting mass flow rate and Q is the dewar heat load. The pseudo latent heat for a supercritical fluid is defined as:

$$h_{fg}^{*} = v \left.\frac{dh}{dv}\right|_{p} \quad \text{Eq. (3)}$$

where p is the fluid pressure and h is its enthalpy.

The NESC's previous analytical work [ref. 1] confirmed that evaluating the dewar vent stack at the CGA recommended temperature yielded the lower limit of wall heat flux that was required to obtain the defined pressure. Thus, choosing the CGA-recommended combination of temperature and pressure yields conservative results.

The Origin of the Simplified Methodology

The wall heat flux resulting from a loss of vacuum insulation increases the dewar pressure, which actuates the pressure relief mechanism and results in high-speed flow through the dewar vent stack. At high pressures, the flow can be choked at the vent stack inlet, at the exit, or at an intermediate transition or restriction.

During previous SOFIA analyses, it was observed that there was generally a readily identifiable section of the vent stack that would limit the flow – e.g., a small diameter entrance or an orifice. It was also found that when the supercritical helium was approximated as an ideal gas at the dewar condition, the calculated mass flow rate based on choking at the limiting entrance or transition was less than the mass flow rate calculated using the detailed real fluid model[2]. Using this lower mass flow rate would yield a conservative prediction of the dewar's wall heat flux capability. The simplified method of the current work was developed by building on this observation.

Results of Prior Work

As a follow-on to the work performed for ref. 1, NASA/Johnson Space Center Engineering performed detailed analyses for a number of already designed, built, and accepted dewars that were flown by SOFIA in 2014 and 2015 (refs. 3–8). The supercritical helium compressible flow in the dewar vent stacks was analyzed using SINDA/FLUINT at specified dewar pressures ranging from 228 to 998 kPa (absolute). The vent stack was taken as adiabatic owing to the very short duration of the venting transient. The limiting conditions found in these analyses are summarized in Table 5.1-1.

[2] Because the helium at relief conditions is a near-critical supercritical fluid, an ideal gas representation is not an accurate representation of the venting physics. However, it was found that an ideal gas assumption resulted in a conservative value of the venting mass flow rate and the concomitant wall heat flux.

Table 5.1-1. Results of SINDA/FLUINT Supercritical Analyses

Experiment	Acronym	Reference	entrance	p max (kPa abs)	T (K) model	T CGA (K)	limiting condition
Field-Imaging Far-Infrared Line Spectrometer (FIFI-LS)	FIFI LS LHe	1	re-entrant	502.5	7.08	7.08	choked at inlet and exit
				528.8	7.22	7.22	choked at inlet and exit
Field-Imaging Far-Infrared Line Spectrometer (FIFI-LS) LHeII	FIFI LS Lhe II	1	re-entrant	445.0	6.83	6.83	choked at exit
				471.3	7.01	7.01	choked at exit
Faint Object Infrared Camera for the SOFIA Telescope	FORCAST	2	flush	399.0	6.75	6.56	choked at inlet
				425.3	6.75	6.66	choked at exit of large tube
ground test performed by Savage et al. [ref. 9]		1	re-entrant	998.0	9.00	9.00	choked at exit
				783.0	8.17	8.17	choked at exit
				745.0	8.04	8.04	choked at exit
			flush	998.0	9.00	9.00	choked at exit
				783.0	8.17	8.17	choked at exit
				745.0	8.04	8.04	choked at exit
German REceiver for Astronomy at Terahertz Frequencies	GREAT	3	re-entrant	227.0	5.28	5.24	no choking except at exit orifice
				253.3	5.50	5.50	no choking except at exit orifice
Echelon-Cross- Echelle Spectrograph	EXES without parallel flow path	4	re-entrant	334.1	6.40	6.11	choked at inlet and exit
				360.4	6.48	6.24	choked at inlet and exit
				380.0	6.55	6.40	choked at inlet and exit
				385.0	6.65	6.46	choked at inlet and exit
Echelon-Cross- Echelle Spectrograph	EXES with parallel path	5	re-entrant	334.1	6.40	6.11	choked at inlet and exit of main path and orifice
				360.4	6.48	6.24	choked at inlet and exit of main path and orifice
				380.0	6.55	6.40	choked at inlet and exit of main path and orifice
				385.0	6.65	6.46	choked at inlet and exit of main path and orifice
First Light Infrared TEst CAMera	FLITECAM	6	re-entrant	398.9	6.75	6.52	choked at exits to cabin
				425.2	6.85	6.67	choked at exits to cabin
				598.7	7.48	7.48	choked at exits to cabin
				625.0	7.58	7.58	choked at exits to cabin
High-resolution Airborne Wideband Camera	HAWC+	7	re-entrant	695.2	7.84	7.84	choked at exit
				721.5	7.93	7.93	choked at exit
				876.3	8.51	8.51	choked at inlet and exit

At dewar pressures greater than 500 kPa, the analyses were performed at the CGA-recommended temperature condition. At lower pressures, the lowest temperature where the SINDA/FLUINT model was stable and yielded accurate, thermodynamically consistent results was used. At these pressures, the limit of the model stability was within 0.3 K of the CGA recommendation.

The list of limiting conditions shows that the flow was limited by choking at the stack entrance in fewer than half of the cases. In the majority of the cases, the flow was limited by choking at the exit of the vent stack. Because of this behavior, it is not sufficient to develop a simplified real gas method that only considers choking at the vent stack entrance. The effect of the vent stack length must also be accounted for[3].

Simplified Method

In the simplified methodology, the supercritical helium is analyzed as an ideal gas. Choking is assumed to occur at the entrance of the smallest effective flow area in the stack. Neither assumption is physically correct, but the analysis yields a conservative result over a wide range of applications when compared to a physically correct real fluid analysis.

[3] If the analyzed vent stacks had always choked at the stack entrance, developing a simplified model would have been quite direct. Stack length, intermediate transitions, and other vent design details could have been ignored.

For a supercritical tank with a vent stack of zero length (a limiting case), the ideal gas analysis yields a mass flow rate ~40% lower[4] than does a detailed SINDA/FLUINT model using real gas behavior. If the vent stack length grows, eventually the stack exit will also choke. Still longer vent stacks will choke at the stack exit only. Once this occurs, the venting mass flow rate will decrease with increasing stack length.

The ~40% margin provided by using the ideal gas relations is traded for vent stack length in the simplified methodology. That is, by calculating the mass flow rate based on ideal gas choking at the vent stack entrance, the simplified method yields conservative results for a range of vent stack lengths.

The work in this assessment consisted of comparing the mass flow rate calculated using the ideal gas method with that calculated from a full SINDA/FLUINT model for representative adiabatic vent geometries. The comparative calculations were performed for circular tubes. They were performed for a number of diameters, for a number of entrances and transition types, and over a range of supercritical pressures from slightly above the critical pressure of 227 kPa to a maximum of 1,000 kPa. This allowed the limits of the simplified method to be explored and defined.

The entrances and transitions included in the study are shown in Figure 5.1-1. The figure includes the head losses associated with the entrances and transitions and the associated vena contracta contraction coefficients[5].

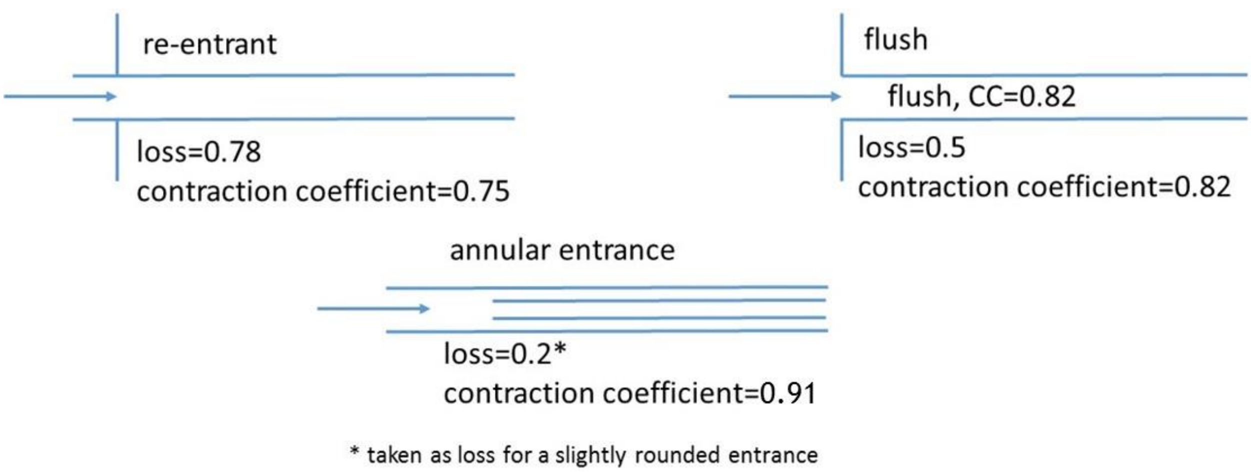

Figure 5.1-1. Loss and Contraction Coefficients for Entrances and Transitions - All Contraction Coefficients Are Based on Incompressible Flow Values

[4] This translates to an allowable wall heat flux 40% lower than for the real fluid case. Therefore, the allowable heat flux is conservatively underpredicted.

[5] These are the vena contracta coefficients for incompressible flow. Although the flow at the dewar stack entrance is compressible, the incompressible flow values are used.

A total of 337 comparative cases were run. Table 5.1-2 lists the pressure, temperature, diameter, tube length, and entrance/transition type for each case. The table includes the CGA recommended temperature for comparison.

Table 5.1-2. Range of SINDA/FLUINT Runs

p (kPa)	T (K)	d (mm)	entrance/transition	l/d	T (K) CGA
228	5.3	10,20,30	re-entrant, smooth, and annular	20 to 200	5.26
250	5.5	10,20,30	re-entrant, smooth, and annular	20 to 200	5.45
300	6.1	10,20,30	re-entrant, smooth, and annular	20 to 200	5.86
400	6.75	10,20,30	re-entrant, smooth, and annular	20 to 200	6.52
500	7.04	10,20,30	re-entrant, smooth, and annular	20 to 200	7.04
600	7.47	10,20,30	re-entrant, smooth, and annular	20 to 200	7.47
700	7.85	10,20,30	re-entrant, smooth, and annular	20 to 200	7.85
800	8.23	10,20,30	re-entrant, smooth, and annular	20 to 200	8.23
900	8.6	10,20,30	re-entrant, smooth, and annular	20 to 200	8.6
1000	8.95	10,20,30	re-entrant, smooth, and annular	20 to 200	8.95

In addition to the SINDA/FLUINT analysis, simplified ideal gas calculations were performed for each case in Table 5.1-2 at the CGA recommended temperature. The supercritical helium was treated as an ideal gas and the flow at the entrance choking limit was found. The calculations were performed as follows:

The ideal gas density and acoustic velocity were calculated at the dewar conditions (pressure and CGA temperature in Table 5.1-2).

The density, ρ, is

$$\rho = \frac{p}{RT} \quad \text{(Eq. 4)}$$

where p is the pressure, R is the ideal gas constant for helium (2077 J/kg K), and T is the absolute temperature.

The acoustic velocity is

$$a = \sqrt{\gamma RT} \quad \text{(Eq. 5)}$$

where γ is the ratio of specific heats (1.67 for helium).

The acoustically limited mass flow rate, $\dot{m}$, was calculated from

$$\dot{m} = \rho\, a\, CC\, FC\, A_{CS} \quad \text{(Eq. 6)}$$

where CC is the contraction coefficient (Figure 5.1-1), A_{CS} is the cross-sectional area at the entrance or transition, and FC is the compressible flow coefficient that accounts for choking at the vena contracta

$$\mathrm{FC} = \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \qquad \text{(Eq. 7)}$$

which is 0.562 for helium.

The mass flow rates calculated by the simple ideal gas method and those calculated from the SINDA/FLUINT model were compared to find the dimensionless length for each case where the two were equivalent. This defines the limit of applicability for the simplified methodology. These limits are listed in Table 5.1-3. For shorter lengths, the ideal gas calculation is conservative – for longer lengths, it is not.

Table 5.1-3. l/d Ratio Points of Equivalence between Detailed SINDA/FLUINT Model and the Simple Methodology

p (kPa)	T (K)	d (mm)	re-entrant l/d limit	flush entrance l/d limit	annular entrance l/d limit
228	5.3	10	159	119	81
228	5.3	20	178	136	91
228	5.3	30	190	139	92
250	5.5	10	>200	177	127
250	5.5	20	>200	194	140
250	5.5	30	>200	>200	148
300	6.1	10	>200	183	132
300	6.1	20	>200	196	145
300	6.1	30	>200	>200	150
400	6.75	10	>200	193	146
400	6.75	20	>200	>200	160
400	6.75	30	>200	>200	164
500	7.04	10	>200	>200	189
500	7.04	20	>200	>200	>200
500	7.04	30	>200	>200	>200
600	7.47	10	>200	>200	185
600	7.47	20	>200	>200	>200
600	7.47	30	>200	>200	>200
700	7.85	10	>200	>200	176
700	7.85	20	>200	>200	191
700	7.85	30	>200	>200	199
800	8.23	10	>200	>200	163
800	8.23	20	>200	>200	177
800	8.23	30	>200	>200	185
900	8.6	10	>200	200	153
900	8.6	20	>200	>200	167
900	8.6	30	>200	>200	174
1000	8.95	10	>200	185	145
1000	8.95	20	>200	>200	160
1000	8.95	30	>200	>200	166

The limits of applicability are plotted in Figure 5.1-2. The figure and Table 5.1-3 show that the annular entrance is the limiting case for all pressures.

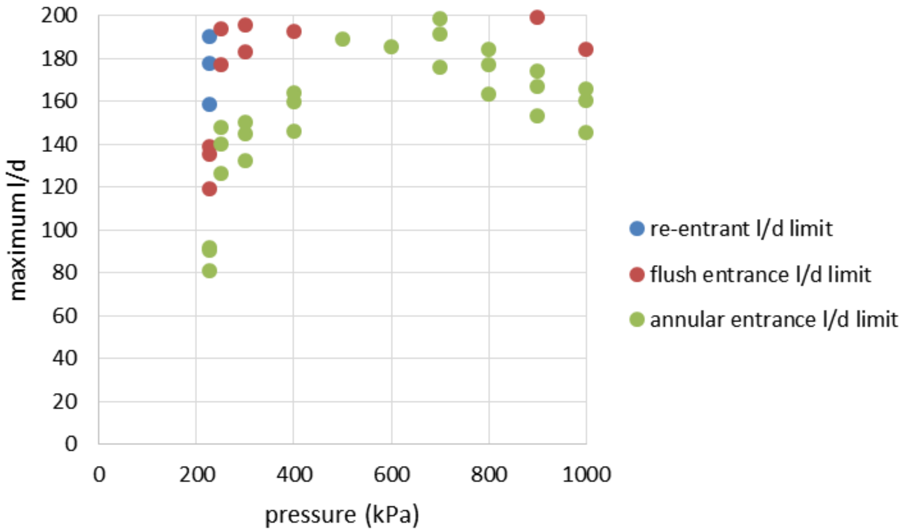

Figure 5.1-2. Diameter Ratio Limits

The lowest values in Figure 5.1-2 define the limits of the simplified methodology. These limits are enveloped by the red area in Figure 5.1-3. For pressures between 228 and 1,000 kPa at diameter ratios below the red area, the simple method yields a conservative prediction of the mass flow rate.

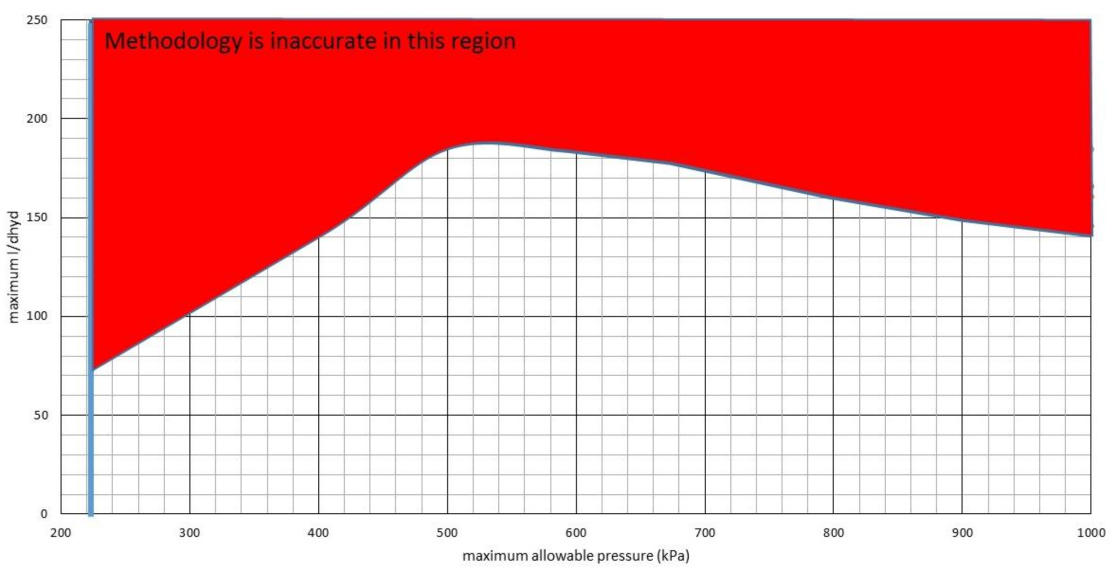

Figure 5.1-3. Limit of Simple Methodology

Comparison with the Detailed Model

The SOFIA dewar vents that were analyzed in refs. 1 and 3–8 contained one section whose entrance had a smaller effective flow area than the remainder of the stack and would thus limit the flow. The effective flow area is the product of the flow area and the contraction coefficient (Figure 5.1-1). The vent stack limiting features for these dewars are listed in Table 5.1-4.

Table 5.1-4. Limiting Section in the SOFIA Dewars

Instrument	Acronym	Limiting section		Entrance to limiting section	Other sections
		Diameter	Length		
Field-Imaging Far-Infrared Line Spectrometer (FIFI-LS)	FIFI-LS	24 mm	438 mm	re-entrant	none
Field-Imaging Far-Infrared Line Spectrometer (FIFI-LS) LHeII	FIFI-LS LHeII	11.8 mm	442 mm	re-entrant	none
Faint Object Infrared Camera for the SOFIA Telescope	FORCAST	18.2 mm	246	flush	downstream larger diameter section with similar length
Echelon-Cross-Echelle Spectrograph	EXES	18.5 mm	495 mm	re-entrant	none
German REceiver for Astronomy at Terahertz Frequencies	GREAT	13 mm	255 mm	re-entrant	downstream larger diameter section with similar length plus parallel restrictive path to relief valve
High-resolution Airborne Wideband Camera	HAWC+	23.6 mm	606 mm	re-entrant	none
First Light Infrared TEst CAMera	FLITECAM	11.7 mm	204 mm	re-entrant	downstream annular section with 94% of the flow area and similar length[6]

The diameter ratio (l/d) for the limiting section of the SOFIA dewars listed in Table 5.1-4 range from 13.5 to 37.5. All are well below the limits shown in Figure 5.1-3. Therefore, the simple method is applicable.

Table 5.1-5 lists the heat fluxes calculated for the SOFIA experiments using the detailed SINDA/FLUINT model and the simplified ideal gas methodology. The simplified method results are conservative for all the cases investigated. The margin on the heat flux ranges from 12 to 45%.

[6] The limiting section is set by the product of flow area and entrance/transition contraction coefficient.

Table 5-1.5. Comparison of Simplified Methodology and SINDA/FLUINT Results

	p max (kPa abs)	q" (W/cm^2) detailed model	q" (W/cm^2) ideal gas	ideal gas margin (%)
FIFI LS He	502.48	3.80	2.73	39
	528.80	4.11	2.95	39
FIFI LS He II	444.98	5.12	3.75	37
	471.30	5.52	4.11	34
FORCAST	398.98	1.96	1.42	38
	425.30	2.14	1.55	39
Savage re-entrant	998.00	3.29	2.82	17
	783.00	3.01	2.35	28
	745.00	2.83	2.18	30
Savage-flush	998.00	3.45	3.09	12
	783.00	3.15	2.57	22
	745.00	2.97	2.39	24
GREAT	226.98	1.58	1.23	28
	253.30	1.88	1.47	28
EXES without parallel flow	334.08	3.27	2.25	45
	360.41	3.54	2.48	43
	380.00	3.82	2.71	41
	385.00	3.92	2.79	40
EXES with parallel path	334.08	3.35	2.30	45
	360.41	3.63	2.54	43
	380.00	3.91	2.78	41
	385.00	3.92	2.86	37
FLIGHTCAM	398.86	1.07	0.83	28
	425.18	1.16	0.92	27
	598.70	1.89	1.56	21
	625.03	2.01	1.66	21
HAWC+	695.18	3.88	2.82	38
	721.50	4.11	2.99	38
	876.31	5.31	4.00	33

The table shows that the simplified ideal gas method yields conservative results for all the SOFIA dewars assessed thus far. By using the simplified ideal gas method within its defined limits, conservative predictions of the allowable wall heat flux on a LHe dewar can be obtained.

To use the simplified methodology to calculate the dewar pressure with 4 W/cm^2 of external heating (the loss of vacuum heat flux), an iterative method is used. The method is detailed in Appendix B.

The simplified method can be used to provide an estimate of the dewar pressure after a loss of vacuum insulation. This result can be used for the initial design of the LHe dewar vent stacks. However, since the simplified method is not an exact tool, final verification of the dewar pressure vessel design requires a complete detailed real fluid compressible flow model of the vent stack.

6.0 Findings, Observations, and NESC Recommendations

6.1 Findings

The following findings were identified:

F-1. A simplified ideal gas method can be used to conservatively predict the dewar pressure under a loss of vacuum insulation if the following conditions are met.

a. The dewar pressure is between 228 and 1,000 kPa.

b. The sections of the stack are short enough that the simplified method is conservative.

c. There is an identifiable limiting entrance or transition.

F-2. The ideal gas method predicts the dewar heat load with margins of 12 to 45% for the SOFIA dewars that have been assessed to date using detailed real fluid SINDA/FLUINT models.

F-3. The simplified method can be used for initial sizing. The dewar maximum pressure for verification must be determined using a detailed compressible real fluid flow analysis.

6.2 Observations

No observations were made in the present work.

6.3 NESC Recommendations

The following NESC recommendations are directed toward the SOFIA Program:

R-1. Use the simplified method to provide an initial estimate of the dewar pressure after a loss of vacuum insulation. ***(F-1, F-2)***

R-2. Use the simplified method only for initial vent stack sizing. A detailed real fluid compressible flow model is required for final design verification. ***(F-3)***

7.0 Lessons Learned

No applicable lessons learned were identified for entry into the NASA Lessons Learned Information System (LLIS) as a result of this assessment.

8.0 Recommendations for NASA Standards and Specifications

No recommendations for NASA standards and specifications were identified as a result of this assessment.

9.0 Definition of Terms

Corrective Actions	Changes to design processes, work instructions, workmanship practices, training, inspections, tests, procedures, specifications, drawings, tools, equipment, facilities, resources, or material that result in preventing, minimizing, or limiting the potential for recurrence of a problem.
Finding	A relevant factual conclusion and/or issue that is within the assessment scope and that the team has rigorously based on data from their independent analyses, tests, inspections, and/or reviews of technical documentation.
Lessons Learned	Knowledge, understanding, or conclusive insight gained by experience that may benefit other current or future NASA programs and projects. The experience may be positive, as in a successful test or mission, or negative, as in a mishap or failure.
Observation	A noteworthy fact, issue, and/or risk, which may not be directly within the assessment scope, but could generate a separate issue or concern if not addressed. Alternatively, an observation can be a positive acknowledgement of a Center/Program/Project/Organization’s operational structure, tools, and/or support provided.
Problem	The subject of the independent technical assessment.
Proximate Cause	The event(s) that occurred, including any condition(s) that existed immediately before the undesired outcome, directly resulted in its occurrence and, if eliminated or modified, would have prevented the undesired outcome.
Recommendation	A proposed measurable stakeholder action directly supported by specific Finding(s) and/or Observation(s) that will correct or mitigate an identified issue or risk.
Root Cause	One of multiple factors (events, conditions, or organizational factors) that contributed to or created the proximate cause and subsequent undesired outcome and, if eliminated or modified, would have prevented the undesired outcome. Typically, multiple root causes contribute to an undesired outcome.
Supporting Narrative	A paragraph, or section, in an NESC final report that provides the detailed explanation of a succinctly worded finding or observation. For example, the logical deduction that led to a finding or observation; descriptions of assumptions, exceptions, clarifications, and boundary conditions. Avoid squeezing all of this information into a finding or observation

10.0 Acronyms List

AFRC	Armstrong Flight Research Center
AMA	Analytical Mechanics Associates
CGA	Compressed Gas Association
cm	Centimeter
EXES	Echelon-Cross- Echelle Spectrograph
FIFI-LS	Field-Imaging Far-Infrared Line Spectrometer
FIFI-LS LHeII	Field-Imaging Far-Infrared Line Spectrometer LHeII (total surface of LHe)
FLITECAM	First Light Infrared TEst CAMera
FORCAST	Faint Object Infrared Camera for the SOFIA Telescope
GREAT	German REceiver for Astronomy at Terahertz Frequencies
HAWC+	High-resolution Airborne Wideband Camera
He	Helium
JSC	Johnson Space Center
K	Kelvin
kPa	Peak Pressure
l/d	Diameter Ratio
LaRC	Langley Research Center
LHe	Liquid Helium
mm	Millimeter
MTSO	Management and Technical Support Office
NASA	National Aeronautics and Space Administration
NESC	NASA Engineering and Safety Center
SOFIA	Stratospheric Observatory for Infrared Astronomy
W/cm^2	Watt Per Square Centimeter

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12.0 Appendices

Appendix A. Derivation of Pseudo-Latent Heat

Appendix B. Simplified Methodology Roadmap

Appendix A. Derivation of Pseudo-Latent Heat

Supercritical Venting Tank with $\frac{dp}{dt} = 0$

Consider the venting tank shown in Figure A-1. The tank contains a homogeneous supercritical fluid at pressure, p. The tank vents through a relief stack. The mass of the fluid in the tank is m, its density is ρ, and its specific internal energy is u. The mass flow rate of the fluid leaving the tank is $\dot{m}$ and its specific enthalpy is h.

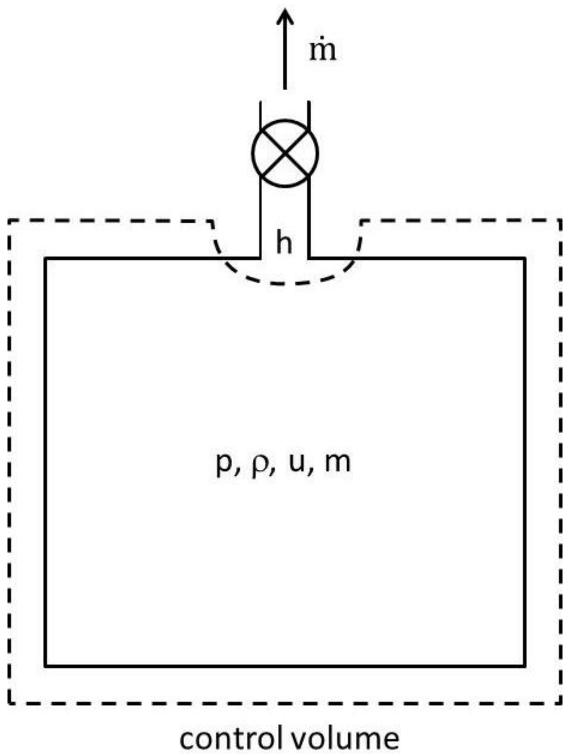

Figure A-1. Control Volume for Venting Supercritical Tank

The control volume for the system is taken as shown in the diagram. Taking part of the control volume border inside the tank creates a negligible error in the representation of the fluid mass, but minimizes the fluid kinetic energy at the exit and allows it to be neglected.

<u>Mass Balance</u> – The mass balance on the control volume is

$$\dot{m} = -\frac{dm}{dt}$$

where t is time.

Energy Balance – The energy balance on the control volume is:

$$Q = \frac{dU}{dt} + \dot{m}h$$

$$U = mu = m(h - pv)$$

The energy balance can be expressed as:

$$Q = \frac{d}{dt}[mh - mpv] - \frac{dm}{dt}h$$

Expanding the energy balance

$$Q = h\frac{dm}{dt} + m\frac{dh}{dt} - mp\frac{dv}{dt} - mv\frac{dp}{dt} - pv\frac{dm}{dt} - h\frac{dm}{dt}$$

Because

$$-mv\frac{dp}{dt} = 0 \text{ since } \frac{dp}{dt} = 0$$

this allows the energy balance to be simplified to:

$$Q = m\frac{dh}{dt} - mp\frac{dv}{dt} - pv\frac{dm}{dt}$$

Specific volume, v, is defined as:

$$v = \frac{V}{m}$$

where V is the tank volume, so

$$\frac{dv}{dt} = -\frac{V}{m^2}\frac{dm}{dt}$$

and

$$\frac{dv}{dt} = -v\frac{1}{m}\frac{dm}{dt}$$

This allows the energy balance to be recast as:

$$Q = m\frac{dh}{dt} + mpv\frac{1}{m}\frac{dm}{dt} - pv\frac{dm}{dt}$$

or

$$Q = m\frac{dh}{dt}$$

$$\frac{\mathrm{dh}}{\mathrm{dt}} = \frac{\mathrm{dh}}{\mathrm{d}v}\frac{\mathrm{d}v}{\mathrm{dt}} = \frac{\mathrm{dh}}{\mathrm{d}v}\left(-\frac{v}{\mathrm{m}}\frac{\mathrm{dm}}{\mathrm{dt}}\right)$$

Recall

$$\dot{\mathrm{m}} = -\frac{\mathrm{dm}}{\mathrm{dt}}$$

so

$$\frac{\mathrm{dh}}{\mathrm{dt}} = \frac{\mathrm{dh}}{\mathrm{d}v}\left(\frac{v}{m}\dot{\mathrm{m}}\right)$$

$$\mathrm{Q} = \mathrm{m}\left(\frac{\mathrm{dh}}{\mathrm{d}v}\frac{v}{\mathrm{m}}\dot{\mathrm{m}}\right)$$

$$\mathrm{Q} = \dot{\mathrm{m}}v\frac{\mathrm{dh}}{\mathrm{d}v}$$

so

$$\dot{\mathrm{m}} = \frac{\mathrm{Q}}{v\frac{\mathrm{dh}}{\mathrm{d}v}}$$

Define the pseudo-latent heat, $\mathrm{h}_{\mathrm{fg}}^{*}$, as:

$$\mathrm{h}_{\mathrm{fg}}^{*} = \frac{\mathrm{Q}}{\dot{\mathrm{m}}}$$

$$\dot{\mathrm{m}} = \frac{\mathrm{Q}}{\mathrm{h}_{\mathrm{fg}}^{*}}$$

The pseudo-latent heat for a supercritical fluid is:

$$\boxed{\mathrm{h}_{\mathrm{fg}}^{*} = v\left.\frac{\mathrm{dh}}{\mathrm{d}v}\right|_{\mathrm{p}}}$$

Appendix B. Simplified Methodology Roadmap

Use of Simplified Methodology

To use the simplified method to predict the maximum pressure in a LHe dewar after loss of vacuum insulation, the following iterative procedure is used:

1. Choose a supercritical pressure to start the iteration.
2. Ensure that the proposed vent stack geometry meets the limits of the simplified method at the chosen pressure.
3. Find the temperature recommended by the CGA for assessment at the chosen pressure.
4. Identify the limiting entrance or transition.
5. Assess the throughput of the vent stack at the pressure of interest using a simplified compressible ideal gas flow technique.
6. Calculate the dewar heat load required to produce the calculated mass flow rate and, by extension, the assumed pressure.
7. Calculate the dewar wall heat flux.
8. Compare the dewar heat flux to the recommended loss of vacuum insulation heat flux, 4 W/cm^2. If another iteration is necessary, adjust the assumed dewar pressure and repeat.

Detailed explanations for the steps follow.

Detailed Roadmap

1. Choose a pressure.

The simplified method can be used for supercritical pressures ranging from 228 to 1,000 kPa. Any pressure in that range can be chosen as the initial pressure.

2. Verify that the vent stack geometry meets the simplified methodology limits.

Use Figure 5.1-3 to verify that <u>all</u> sections of the vent stack are short enough that the simplified method is accurate. For non-circular vent sections, use the hydraulic diameter to calculate the length to diameter ratio.

3. Find the CGA-recommended temperature.

The CGA-recommended temperature can be calculated using the third-order polynomial shown in Figure B-1. This polynomial was developed from numerical differencing of NIST RefProp [ref. 10] helium properties.

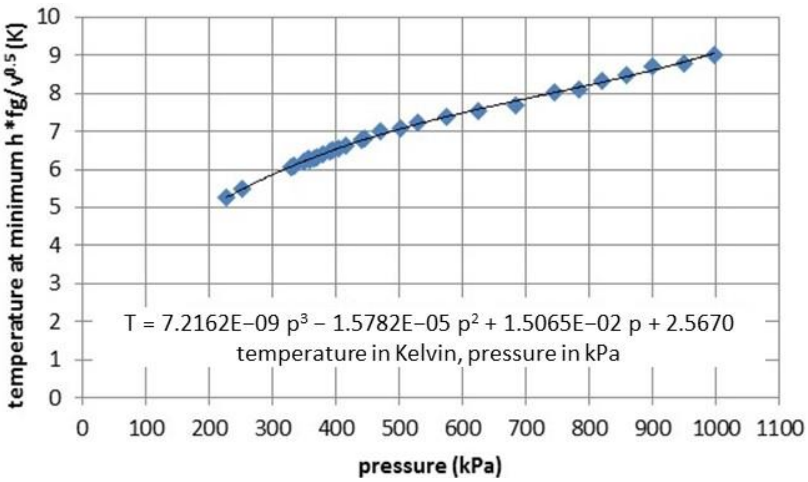

Figure B-1. CGA Assessment Temperature

4. *Identify the limiting entrance or transition.*

Calculate the product of the flow area and the entrance or transition contraction coefficient (Figure 5.1-1) for each section of the vent stack. The limiting entrance or transition is the one with the smallest product of flow area and contraction coefficient.

5. *Calculate the vent stack throughput.*

Use Equations 4–7 to calculate the mass flow rate, $\dot{m}$.

$$\dot{m} = \rho\, a\, CC\, FC\, A_{CS} \quad \text{Eq. (6)}$$

ρ is the helium density calculated using an ideal gas assumption

$$\rho = \frac{p}{RT} \quad \text{Eq. (4)}$$

where p is the pressure, R is the ideal gas constant for helium (2,077 J/kg K), and T is the absolute temperature.

The acoustic velocity, a, is also calculated using an ideal gas assumption

$$a = \sqrt{\gamma RT} \quad \text{Eq. (5)}$$

where γ is the ratio of specific heats (1.67 for helium).

CC is the entrance contraction coefficient (Figure 5.1-1) at the limiting entrance or transition.

FC is the compressible flow coefficient that accounts for choking at the vena contracta

$$FC = \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \quad \text{Eq. (7)}$$

which is 0.562 for helium.

A_{CS} is the cross-sectional area at the limiting entrance or transition.

6. *Calculate the dewar heat load.*

The dewar heat load, Q, is calculated using Equation 2:

$$\dot{m} = \frac{Q}{h^*_{fg}} \qquad \text{Eq. (2)}$$

where h^*_{fg} is the pseudo latent heat. The pseudo latent heat is calculated using the third-order polynomial shown in Figure B-2. This polynomial was developed from numerical differencing of NIST RefProp [ref. 10] helium properties.

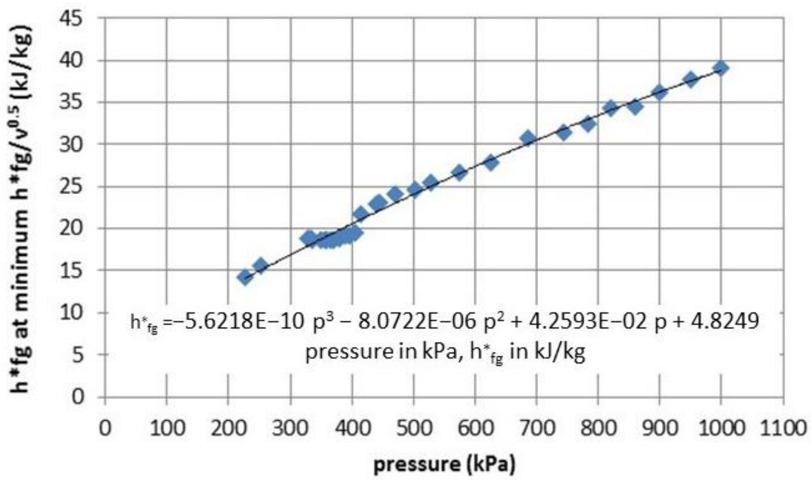

Figure B-2. Pseudo Latent Heat

7. *Calculate the dewar wall heat flux.*

The wall heat flux is the ratio of the dewar heat load and dewar surface area.

8. *Update dewar pressure if required.*

If the calculated heat flux is below 4 W/cm^2, the assumed dewar pressure must be increased. If it is higher than 4 W/cm^2, the assumed dewar pressure must be decreased. Using a linear correction to find the new pressure will lead to rapid convergence

$$p_{new} = p_{old} \frac{q''}{4\ W/cm^2}$$

where p_{new} and p_{old} are the new and previously assumed dewar pressures, respectively.

The procedure is shown in flowchart form in Figure B-3.

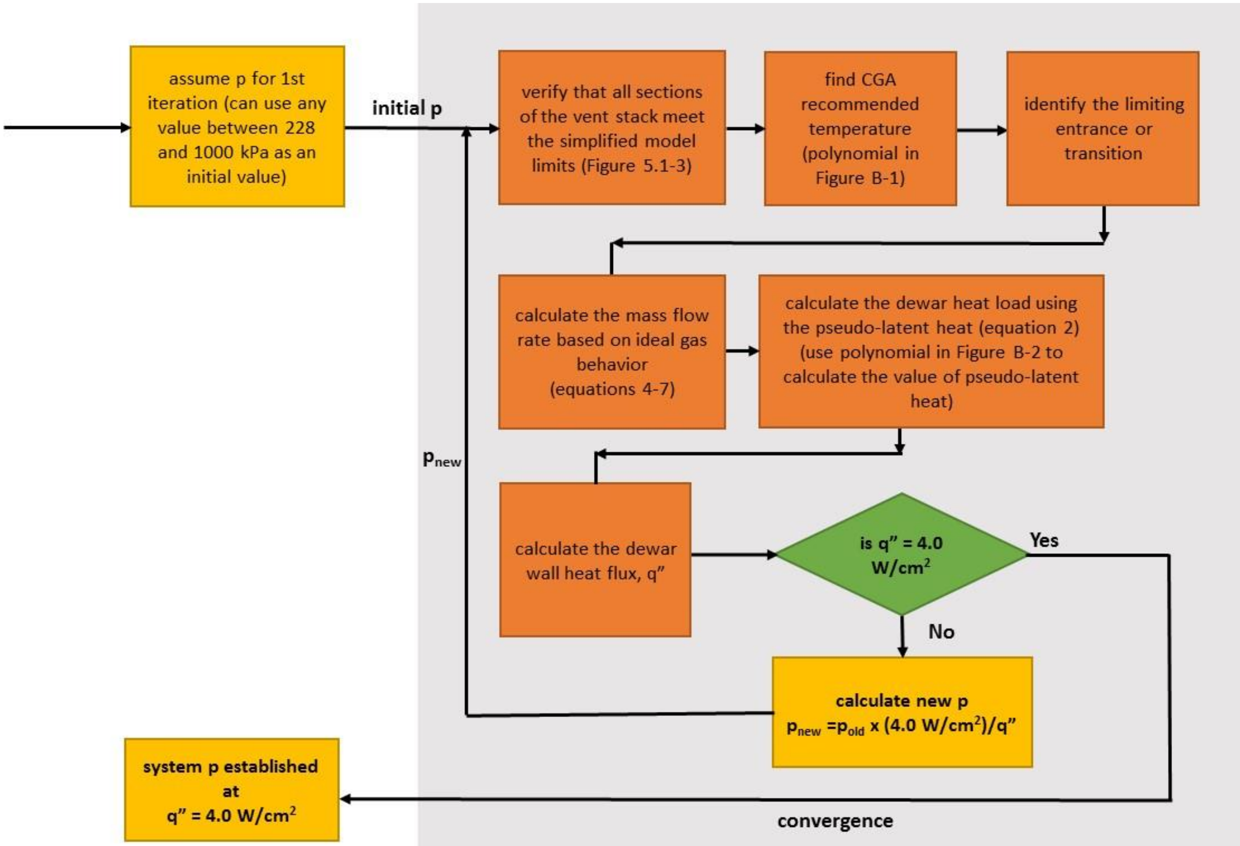

Figure B-3. Calculation Flow Chart

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14. ABSTRACT
The Safety and Mission Assurance Lead for the Stratospheric Observatory for Infrared Astronomy (SOFIA) Program at the Ames Research Center, requested that the NASA Engineering and Safety Center (NESC) develop a simplified method of predicting the maximum pressure in a cryogenic liquid helium (LHe) dewar after a sudden loss of vacuum jacket thermal insulation. The outcome of the NESC assessment is contained in this document.

15. SUBJECT TERMS
Liquid Helium; NASA Engineering and Safety Center; Stratospheric Observatory for Infrared Astronomy;SOFIA; Vacuum

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