

# SLOVENSKI STANDARD kSIST-TP FprCEN/CLC/TR 17603-31-14:2021 01-maj-2021

Vesoljska tehnika - Priročnik za toplotno zasnovo - 14. del: Kriogeno hlajenje

Space Engineering - Thermal design handbook - Part 14: Cryogenic Cooling

Raumfahrttechnik - Handbuch für thermisches Design - Teil 14: Kryogene Kühlung

Ingénierie spatiale - Manuel de conception thermique - Partie 14: Refroidissement cryogénique

(standards.iteh.ai)

Ta slovenski standard je istoveten z: FprCEN/CLC/TR 17603-31-14

https://standards.iteh.ai/catalog/standards/sist/f33c483b-f65e-4f65-a6bf-6b59789ff4eb/ksist-tp-fprcen-clc-tr-17603-31-14-2021

ICS:

49.140 Vesoljski sistemi in operacije Space systems and operations

kSIST-TP FprCEN/CLC/TR 17603-31en,fr,de 14:2021

kSIST-TP FprCEN/CLC/TR 17603-31-14:2021

# iTeh STANDARD PREVIEW (standards.iteh.ai)

kSIST-TP FprCEN/CLC/TR 17603-31-14:2021 https://standards.iteh.ai/catalog/standards/sist/f33c483b-f65e-4f65-a6bf-6b59789ff4eb/ksist-tp-fprcen-clc-tr-17603-31-14-2021

# TECHNICAL REPORT RAPPORT TECHNIQUE TECHNISCHER BERICHT

# FINAL DRAFT FprCEN/CLC/TR 17603-31-14

March 2021

ICS 49.140

#### **English** version

## Space Engineering - Thermal design handbook - Part 14: **Cryogenic Cooling**

Ingénierie spatiale - Manuel de conception thermique -Partie 14: Refroidissement cryogénique

Raumfahrttechnik - Handbuch für thermisches Design -Teil 14: Kryogene Kühlung

This draft Technical Report is submitted to CEN members for Vote. It has been drawn up by the Technical Committee CEN/CLC/JTC 5.

CEN and CENELEC members are the national standards bodies and national electrotechnical committees of Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Republic of North Macedonia, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey and United Kingdom.

Recipients of this draft are invited to submit, with their comments, notification of any relevant patent rights of which they are aware and to provide supporting documentation.

aware and to provide supporting documentation.

Warning: This document is not a Technical Report It is distributed for review and comments. It is subject to change without notice and shall not be referred to as a Technical Report.





**CEN-CENELEC Management Centre:** Rue de la Science 23, B-1040 Brussels

# **Table of contents**

Europ	ean Fo	reword	25
1 Sco	ре		26
2 Refe	rences		27
3 Tern	ns, defi	nitions and symbols	28
3.1	Terms	and definitions	28
3.2	Abbrev	viated terms	28
3.3	Symbo	ols	30
4 Gen	eral intı	roduction	42
4.1	Radiar	nt coolers ch. S.T.A.N.D.A.R.D. PREVIEW	43
4.2	Stored	solid-cryogen coolers (Standards.iteh.ai) liquid Helium (He4) coolers	44
4.3	Stored	liquid Helium (He4) coolers	44
4.4	Trends	toward lower temperatures CLC/TR 17603-31-14:2021.	45
4.5	Mecha	https://standards.iteh.ai/catalog/standards/sist/f33c483b-f65e-4f65-a6bf- nical refrigerators/4eb/ksist-tp-fprcett-clc-tr-17603-31-14-2021	46
4.6		mperature requirements to IR sensors	
	4.6.2	Radiation from the optical system	48
	4.6.3	Noise from the detector	49
5 Refr	igeratin	ng systems	51
5.1	Genera	al	51
5.2	Closed	l cycle	51
	5.2.1	Reverse-Brayton cycle	52
	5.2.2	Reverse-Brayton and Claude cycle refrigerators	54
	5.2.3	Gifford-McMahon/Solvay cycle refrigerators	55
	5.2.4	Joule-Thomson Closed Cycle Refrigerator	57
	5.2.5	Stirling cycle refrigerators	58
	5.2.6	Vuilleumier cycle refrigerator	66
	5.2.7	Existing systems	69
5.3	Open o	cycle	105
	5.3.1	Joule-Thomson open cycle refrigerators	105
	5.3.2	Existing systems	108

	5.3.3	Stored liquid or solid cryogen open refrigerators	114
6 VCS	Dewars	S	115
6.1	Genera	al	115
6.2	Theore	etical analysis	117
	6.2.1	Introduction	117
	6.2.2	The idealized model	118
	6.2.3	Evaluation of the restrictions involved in the idealized model	123
6.3	Suppor	rts	161
	6.3.1	Introduction	161
	6.3.2	Support materials	162
	6.3.3	Low thermal conductance tubing	164
	6.3.4	Tensile and flexural supports	169
	6.3.5	Compressive supports	174
6.4	Phase	separators	175
	6.4.1	Introduction	175
	6.4.2	Thermodynamic vent system	181
	6.4.3	Capillary barriers ANDARD PREVIEW	182
	6.4.4	Porous media(standards.iteh.ai)	189
	6.4.5	Baffled tanks	192
	6.4.6	Empirical data for design	204
	6.4.7	Testing 6b59789ff4eb/ksist-tp-fprcen-clc-tr-17603-31-14-2021	215
6.5	Existing	g systems	217
	6.5.1	Introduction	217
	6.5.2	Data on existing systems	219
7 Sup	erfluid H	Helium	233
7.1		ics of superfluids	
	7.1.1	Relevant equations of superfluid dynamics	
	7.1.2	Frictional effects	
	7.1.3	Counterflow heat transfer	
	7.1.4	Heat transfer at arbitrary combinations of vn and vs	256
	7.1.5	Vapor formation	257
	7.1.6	Superfluid Helium film	258
7.2	Kapitza	a conductance	266
	7.2.1	Measuring methods	268
	7.2.2	Experimental data	
7.3	Thermo	o-acoustic oscillations	302
7.4	The su	perfluid plug	304

		7.4.1	Phase separation in superfluid helium	304
		7.4.2	Simplified theory of the superfluid plug	305
		7.4.3	Characteristics of porous media	329
	7.5	Filling	a superfluid helium container	337
		7.5.1	Liquid loss because of pump down	337
		7.5.2	Pumping down requirements	339
		7.5.3	A typical filling sequence	339
8	Mate	rials at	cryogenic temperatures	342
	8.1	Norma	I cryogens	342
		8.1.1	General properties	342
		8.1.2	Entropy diagrams	390
	8.2	Superf	luid Helium-4	442
	8.3	Norma	l Helium-3	448
	8.4	Metalli	c materials	45
	8.5	Compo	osite materials	464
		8.5.1	Structural tubes	49′
	8.6	Miscell	aneous materials TANDARD PREVIEW	493
9	Safe	ty with	cryogenic systems ndards.iteh.ai)	494
	9.1	Genera	alksist-tp-fpicen/clc/tr-17603-31-14:2021	494
		9.1.1	Physiological spazards alog/standards/sist/f33c483b-f65e-4f65-a6bf-	
		9.1.2	6b59789ff4eb/ksist-tp-fprcen-ck-tr-17603-31-14-2021 Fire and explosion hazards	494
		9.1.3	Pressure hazards	495
		9.1.4	Materials hazards	495
		9.1.5	Safety provisions	496
	9.2	Hazard	ds related to properties of cryogens	497
		9.2.1	Combustion in an oxygen environment	499
		9.2.2	Combustible cryogens	500
		9.2.3	Fluorine	508
		9.2.4	O <sub>2</sub> deficiency	509
	9.3	Chang	e of properties of structural materials	
		9.3.1	Temperature embrittlement	509
		9.3.2	Hydrogen embrittlement	519
		9.3.3	Design codes and acceptance tests	
В	Bibliog	graphy.		527

# Figures

Figure 4-1:	He <sup>3</sup> cooler being developed by NASA. From Sherman (1978) [216]	.46
Figure 4-2:	Procedure to reduce the background flux from the optics. From Caren & Sklensky (1970) [37]	.48
Figure 4-3:	Detectivity, $D^*$ , of a photon noise-limited detector as a function of cutoff wavelength, $\lambda_c$ , for several values of the optics temperature, $T$ . From Caren & Sklensky (1970) [37].	.49
Figure 4-4:	Typical detector operating temperature, $T$ , vs. detectivity, $D^*$ . The detector is germanium doped either with mercury, with cadmium or with copper. From Caren & Sklensky (1970) [37].	.50
Figure 5-1:	Reverse-Brayton Cycle Refrigerator. From Sherman (1978) [216]	.52
Figure 5-2:	Compressor cross section of ADL rotary-reciprocating refrigerator. From Donabedian (1972) [59]	.53
Figure 5-3:	Claude Cycle Refrigerator. From Donabedian (1972) [59]	.54
Figure 5-4:	Solvay Cycle Refrigerator. From Donabedian (1972) [59]	.56
Figure 5-5:	Joule-Thomson Closed Cycle Refrigerator. From Donabedian (1972) [59]	.57
Figure 5-6:	Stirling Cycle Refrigerator Operation. From Sherman (1978) [216]	.58
Figure 5-7:	Stirling Cycle Refrigerator Ideal Pressure-Volume and Temperature- Entropy Diagrams. From Sherman (1978) [216]	.59
Figure 5-8:	Schematic representation of North American Philips refrigerator, showing rhombic drive mechanism. The drive has two counter-rotating crankshafts, each powered by a drive motor. By adjusting the mass of the reciprocating members of the drive and by adding appropriate counterweights to the crankshafts, the center of the gravity of all the moving parts can be kept stationary. From Balas, Leffel & Wingate (1978) [16]	.60
Figure 5-9:	https://standards.teh.ai/catalog/standards/sist/133c483b-f65e-4f65-a6bf-Schematic representation of North American Philips Magnetic Bearing refrigerator, showing the linear motors for piston and displacer and the magnetic bearing. The displacer rod passes through the piston. From Sherman, Gasser, Benson & McCormick (1980) [221]	.61
	2: Coupling of two refrigerator units to provide cooling of a single detector.  The complete refrigerator can be seen in Figure 5-8. Here, on the contrary, only the first and second stages of both refrigerators are shown. From Naes & Nast (1980) [160].	.62
Figure 5-11	E: Ground Test temperatures, of the first and second stage vs. Second stage heat transfer rate, $Q_2$ , for different values of the first stage heat transfer rate, $Q_1$ , and motor rpm. The data correspond to refrigerator 2 but are typical of the four units. From Naes & Nast (1980) [160]. ○ first stage, $Q_1$ = 1,5 W, 1000 rpm; □ first stage, $Q_1$ = 1,5 W, 1150 rpm; △ second stage $Q_1$ = 1,5 W, 1150 rpm; ▷ first stage, $Q_1$ = 2 W, 1000 rpm; ○ first stage, $Q_2$ = 2 W, 1000 rpm	.63
Figure 5-12	2: In orbit temperature, $T$ , of several components of Gamma 004 systems vs. Orbital time, $t$ . From Naes & Nast (1980) [160]. $\bigcirc$ cold tip of refrigerator 3; $\square$ cold tip of refrigerator 4; $\triangle$ shroud; $\bigcirc$ ground test value of cold tip of refrigerator 3; $\blacktriangle$ ground test value of shroud	.63
Figure 5-13	3: In orbit temperature, <i>T</i> , of several components of Gamma 003 systems vs. Orbital time, <i>t</i> . From Naes & Nast (1980) [160]. ○ cold tip of refrigerator 2; □ cold tip of refrigerator 1; △ shroud; ● ground test value of cold tip of refrigerator 2; ▲ ground test value of shroud	.64

; !	: In orbit heat transfer rates, $Q$ , from Gamma 003 detector to refrigerators 1 and 2, vs. orbital time, $t$ . From Naes & Nast (1980) [160]. $\bigcirc$ detector heat load. Refrigerator 2 on; $\square$ heat load through meter 1, $Q_1$ . Refrigerator 1 off; $\triangle$ heat load through meter 2, $Q_2$ . Refrigerator 2 on; $\blacksquare$ refrigerators 1 and 2 on; $\blacksquare$ refrigerators 1 and 2 on	64
-	: Schematic of the Vuilleumier-Cycle Refrigerator. From Sherman (1978) [216]	67
Figure 5-16:	: Vuilleumier-Cycle Refrigerator. From Sherman (1971) [218]	67
	: Pressure-Volume Diagrams, for the Cold Cylinder, Hot Cylinder and Total Gas, of the Vuilleumier-Cycle Refrigerator. From Sherman (1971) [218]	67
	: Inverse efficiency (required power per unit of refrigeration power) $\eta$ -1, vs. operating temperature, $T$ , for several closed cycle refrigerators. a - Brayton refrigerators (Turbo machinery Systems). b - Stirling refrigerators. c - Vuilleumier refrigerators. d - Gifford-McMahon/Solvay refrigerators. From Donabedian (1972) [59]. Also shown are curves for closed cycle refrigerators operating with the quoted efficiencies (in percentages of Carnot) through the whole temperature range. From Haskin & Dexter (1979) [83]. The Carnot efficiency for a machine working between $T_C$ and $T_H$ temperatures is given by $\eta_C = 1 - T_C/T_H$ . Very low operating temperatures result in a reduced efficiency for a given cooling load and a given cycle.	70
1	: System mass per unit of refrigeration power, $M_p$ , vs. operating temperature, $T$ for several closed cycle refrigerators, a - Gifford-McMahon/Solvay refrigerators, b - Stirling refrigerators. From Donabedian (1972) [59]	71
- I	: System mass per unit of refrigeration power (or cooling load), $M_p$ , for representative closed cycle refrigerating systems and for passive radiant coolers. O Closed cycle refrigerators, $Q = 0.13$ Wl. Closed cycle refrigerators, $Q = 10$ W. Closed cycle refrigerators, $Q = 10$ W. Passive radiant coolers; $Q = 0.1$ W. Passive radiant coolers; $Q = 10$ W. Passive radiant coolers; $Q = 10$ W. From Haskin & Dexter (1979) [83]. Smallest temperature attained by closed cycle refrigerators in orbit. Smallest temperature attained by passive radiant coolers in orbit. From Sherman (1982) [217]	72
- ( ( ( ( ( ( ( ( (	: System area per unit of refrigeration power (or cooling load), $A_p/M_p$ , for closed cycle refrigerating systems and for passive radiant coolers. O Closed cycle refrigerators, $Q = 1$ W. $\square$ Passive radiant coolers; $Q = 1$ W. From Haskin & Dexter (1979) [83]. Although the areas, $A_p$ , have been calculated for 1 W cooling, they could be scaled in approximately direct proportion to the cooling load. $A_p/Q = 7,13x10^7$ $T^{-4}$ is the best fitting, by the least squares method, to the data for passive radiant coolers. $\square$ Smallest temperature attained by closed cycle refrigerators in orbit. $\square$ Smallest temperature attained by passive radiant coolers in orbit. From Sherman (1982) [217]	75
Figure 5-22:	: 80 K cooler schematic. From Jewell (1991) [103]	.101
	: Cooler heat lift performance vs. gross compressor input power. From Scull & Jewell (1991) [211]	.102
Figure 5-24:	: 20 K cooler schematic. From Jones et al. (1991) [110]	.103

Figure 5-25	From Jones et al. (1991) [110].	104
Figure 5-26	S: 4 K cooler layout. From Bradshaw & Orlowska (1988) [27]	104
Figure 5-27	7: Cooling power/mass flow vs. precooler temperature. From Bradshaw & Orlowska (1991) [28]	105
Figure 5-28	8: Isenthalps and inversion curve for different gasses. a Hydrogen. b Helium. c Nitrogen. From Zemansky (1968) [272]. Data in b, after Hill & Loumasmaa (1960) [89], are no longer valid for above 20 K. Upper isenthalps are instead from Angus & de Reuck (1977) [6], pp. 64-127 . The locus of the maxima has been drawn by the compiler as a dotted line	106
Figure 5-29	9: Schematic of a typical JT cryostat-dewar system. From Hellwig (1980) [86]	107
Figure 5-30	9: Schematic of a self-demand flow JT cryostat-dewar system. From Oren & Gutfinger (1979) [175]. The sketch of the variable-orifice controlling device is from Buller (1970) [35].	108
Figure 6-1:	Schematic representation of a solid gryogen cooler. From Breckenridge (1972) [29]	116
Figure 6-2:	Sketch of a typical VCS Dewar. From Niendorf & Choksi (1967) [169]	117
	Heat transfer mechanism through a normal attachment VCS Dewar. From Niendorf & Choksi (1967) [169].	117
Figure 6-4:	Insulation model geometry NDARD PREVIEW	119
Figure 6-5:	Ratio $m/m_0$ against the cryogen sensibility, S, for different values of the heat additions to the cryogen other than those across the insulation. No cooled supports $(m_{si} = 0)$ . Calculated by the compiler.	121
Figure 6-6:	Corrective factor $a_k$ for the dependence of insulation thermal conductivity, $k$ , on temperature, $T$ , against the sensibility, $S$ , of the cryogen, for several values of the temperature ratio, $T_{\mathcal{C}}/T_{\mathcal{H}}$ . A linear thermal conductivity vs. temperature dependence has been assumed. Calculated by the compiler	128
Figure 6-7:	Insulation model with finite number of shields	129
Figure 6-8:	Corrective factor, $\omega_n$ , accounting for the influence of the finite number, $n$ , of shields, vs. the sensibility $S$ of the cryogen, for several values of $n$ . Calculated by the compiler.	
Figure 6-9:	Contours of constant values of the ratio of the heat flux through the VCS system to the uncooled shield heat flux, mapped as functions of the dimensionless distances, $\xi_1$ and $\xi_2$ , of the two vapor cooled shields to the cold face of the insulation, for several values of the sensibility, $S$ , of the cryogen. Uniform insulation thermal conductivity. The numerical values labelling the contours corresponds to $\omega_n/\omega_{nopt}$ – 1. Calculated by the compiler.	139
Figure 6-10	Contours of dimensionless displacements of a single shield from its optimum position ( $\xi_1$ = 0,25) which produce a 10% increase in the heat flux through a three shield system. The contours are mapped as functions of the remaining two shields dimensionless positions. Numerical values are	140
Figure 6-11	: Contours of constant values of the ratio of the heat flux through the VCS system to the uncooled shield heat flux, mapped as functions of the dimensionless distances, $\xi_1$ and $\xi_2$ , of the two vapor cooled shields to the	

	cold face of the insulation, for several cryogens in typical cases. Temperature dependent insulation thermal conductivity ( $k = k_1 T$ ). The numerical values labelling the contours corresponds to $\omega_n/\omega_{nopt}$ —1. Calculated by the compiler.	.141
Figure 6-12	2: Factor $\omega_{Nu}$ , accounting for finite convective heat transfer in the venting duct, vs. coefficient $r$ , for several cryogens. $T_H$ = 300 K. Calculated by the compiler.	. 141
Figure 6-13	3: Factor $\omega_{Nu}$ , accounting for finite convective heat transfer in the venting duct, vs. coefficient $r$ , for several cryogens. $T_H$ = 200 K. Calculated by the compiler.	. 145
Figure 6-14	1: Factor $\omega_{Nu}$ , accounting for finite convective heat transfer in the venting duct, vs. coefficient $r$ , for several cryogens. $T_H$ = 150 K. Calculated by the compiler.	.146
Figure 6-15	5: Helium vapor bulk temperature, $T_b$ , vs. insulation temperature, $T$ , for different values of the dimensionless heat transfer coefficient, $r$ . $T_H$ = 300 K. Calculated by the compiler.	. 147
Figure 6-16	6: Temperature, $T$ , across the insulation for different values of the dimensionless heat transfer coefficient $r$ . Helium vapor cooling. $T_H$ = 300 K. Calculated by the compiler.	.148
Figure 6-17	7: Sketch of a VCS insulation in the nearness of the venting duct. Normal attachment. After Paivanas et al. (1965) [177]	.148
Figure 6-18	3: Sketch of the insulation and of the simplified configurations used to analyze the influence of the finite thermal conductivity of the shields. (a) Insulation. (b) Simplified configuration in the physical coordinates $x$ , $y$ . (c) Simplified configuration in the stretched coordinates, $\xi$ , $\eta$	.150
Figure 6-19	2: Sketch of a typical spaceborne Dewar All the dimensions are in mm	.151
Figure 6-20	6b59789ft4eb/ksist-tp-fprcen-clc-tr-17603-31-14-2021 D: Coefficient, $(\omega_{y^-} 1)/\varepsilon$ , of the first order correction accounting for the influence of the finite thermal conductivity of the VCSs on the cryogen boiloff rate, as a function of the cryogen sensibility, $S$ , for two values of the dimensionless outer radius of the venting duct, $\alpha$ . The results have been obtained by means of a perturbation scheme in the small parameter, $\varepsilon$ , which measured the ratio of normal to lateral heat flux, and are valid provided that terms of order $\varepsilon$ 3/2 can be neglected. Calculated by the compiler.	.159
Figure 6-2 <sup>-</sup>	1: Cryogenic supports tubes. a) Composite. b) All-metal. All dimensions are in mm. From Hall & Spond (1977) [81]	
Figure 6-22	2: Heat transfer rate, $Q_s$ , through fiber-glass overwrapped and through all-stainless-steel supports vs. support length, $L$ , for several values of liner wall thickness, $t_0$ , and overwrap thickness, $t_0$ . (a) Inner diameter of the tube, $d = 12.7 \times 10^{-3}$ m. (b) $d = 50.8 \times 10^{-3}$ m. From Hall et al. (1971) [80]	.166
Figure 6-23	3: Heat transfer rate, $Q_s$ , through fiber-glass overwrapped supports vs. liner wall thickness, $t_i$ , for several support lengths, $L$ and overwrap thickness, $t_o = 0.762 \times 10^{-3}$ m. Hoop wrapping. (a) Inner diameter of the tube, $d = 12.7 \times 10^{-3}$ m. (b) $d = 50.8 \times 10^{-3}$ m. From Hall et al. (1971) [80]	.167
Figure 6-24	4: Heat transfer rate, $Q_s$ , through fiber-glass overwrapped stainless-steel supports vs. overwrap thickness, $t_o$ , for several supports lengths, $L$ , and liner wall thickness $t_l = 0.51 \times 10^{-3}$ m. Hoop wrapping. (a) Inner diameter of the tube, $d = 12.7 \times 10^{-3}$ m. (b) $d = 50.8 \times 10^{-3}$ m. From Hall et al. (1971) [80]	

	5: Heat transfer rate, $Q_s$ , through fiber-glass overwrapped stainless-steel supports vs. warm boundary temperature, $T_H$ , for several values of the cold boundary temperature, $T_C$ . Tube length, $L$ , liner wall thickness, $t_l$ , and overwrap thickness, $t_0$ , as indicated in the insert. Hoop wrapping. (a) Inner diameter of the tube, $d = 12.7 \times 10^{-3}$ m. (b) $d = 50.8 \times 10^{-3}$ m. From Hall et al. (1971) [80]	169
	5: Typical supporting methods. Notice how the rods shown in (a) are crossed to minimize the effect of thermal contraction and to increase the length of the heat flow path. In (b), long suspension rods are accommodated in standoffs. From Barron (1966) [18]	170
	7: Tensile support of a liquid helium tank. From Lemke, Klipping & Römisch (1978) [131]	170
Figure 6-28	8: Spacing discs. From Bennett et al. (1974) [23]	171
-	9: Support tube for a liquid helium Dewar. From Bennett et al. (1974) [23]	
Figure 6-30	Two ways of supporting cryogenic containers by means of tensile ties.  After Glaser et al. (1967) [75].	
	: Sketch of the Superfluid Helium Cryostat for Space Use (CRHESUS) showing the tensile ties used for supporting the helium tank. From Lizon-Tati & Girard (1978) [134]	173
	2: CRHESUS heat flow diagram. From Lizon-Tati & Girard (1978) [134]	
•	3: Composite column compressive support. From Heim & Fast (1973) [85]	
Figure 6-34	: Schematic of thermodynamic vent system. a) Forced convection. From Mitchell et al. (1967). b) Pulsed constant pressure. From Müller et al.	
Figure 6-35	(1983) [157]	181 182
_	3: A capillary barrier in static equilibrium. From McCarthy (1968) [144]	
Figure 6-37	Container with a capillary-barrier partition. From McCarthy (1968) [144].  (a) An angular acceleration appears when the interface is formed at the barrier. (b) The configuration reaches a steady angular velocity before interaction of the interface with the barrier. See Table 6-12 for the definition of the experimental conditions.	
J	3: Results of barrier dynamic stability tests. Bond number-controlled mode. Tests were insufficient for determining the effect on barrier stability of the various dimensionless parameters. From McCarthy (1968) [144]	185
	9: Results of dynamic stability tests with different barriers. Bond number-controlled mode. The acceleration, $g$ , is parallel to the barrier. From Fester (1973) [67]. A Reynolds number through the hole has been plotted vs. the critical Bond number	186
	P: Results of barrier dynamic stability tests. Weber number-controlled mode. From McCarthy (1968) [144]. The Weber number in abscissae is normalized with an analytical critical Weber number $We_c$ , which is given in Figure 6-41 below.	187
•	: Critical Weber number, $We_c$ , as a function of geometry, $I/D$ , and position of the axis of rotation, $L/D$ . These results have been obtained by use of a potential (incompressible, inviscid, irrotational flow) theory with $O_p \rightarrow 1$ , although assuming that the barrier induces a capillary pressure difference. From Gluck (1970) [76].	187

Figure 6-42	2: Damping performance of selected barriers. From Fester (1973) [67]. The damping categories A to G are associated to the flow patterns resulting after impingement of the liquid with the barrier, from orderly (A) to irregular (G)	.188
Figure 6-43	3: Compartmented tank device. From Fester, Eberhardt & Tegart (1975) [68]	
_	4: Sustained liquid height in a capillary tube	
•	5: Sustained ethanol height, <i>I</i> , vs. diameter of fiber, <i>d</i> <sub>o</sub> . Gravity level 40 <i>g</i> <sub>o</sub> . From Enya, Kisaragi, Ochiai, Sasao & Kuriki (1981) [64]	
Figure 6-46	6: Sustained liquid height, $l$ , vs. gravity level, $g/g_o$ . Liquids are: Ammonia (circle), underfilled Ammonia (square), and ethanol (triangle). Matrix is glass wool, $d_o = 10^{-6}$ m. Solid lines have been deduced from Eq. [6-91] with $\theta = 0$ and the quoted values of $d$ . From Enya, Kisaragi, Ochiai, Sasao and Kuriki (1981) [64]	.191
Figure 6-47	7: Criterion for the onset of nucleation in subcooled boiling. After Collier (1981) [46]	.192
Figure 6-48	8: Post height, <i>I</i> , required to position a given ullage, <i>U</i> , under reduced gravity. See Clause 6.4.5.2 for explanation of curves <i>d/R</i> =/0, B and C	.193
Figure 6-49	9: Experimental glass tank with a standpipe. From Petrash, Nussle & Otto (1963) [184]. All the dimensions are in mm	.194
•	0: Minimum ullage centering capability of the standpipe	195
Figure 6-5	1: Liquid acquisition by the standpipe for large ullages. From Petrash, Nussle & Otto (1983) [184] (standards:item.ai)	.195
Figure 6-52	2: Central post with thin, off axis, posts (fingers). From Tegart et al. (1972)  [233]ksist.tp.fprcen/clc/tr.i7603-31-142021	
Figure 6-50	3: Criteria to deduce vane profile limits From Tegart et al. (1972) [233]	197
Figure 6-54	4: Limiting vane profiles, $R_{min}/R$ and $R_{max}/R$ for $n = 6$ , 8 and 12 vanes. $R_{min}/R$ has been calculated for an ullage $U = 0,05$ . $R_{max}/R$ is ullage-independent. After Tegart et al. (1972) [233].	. 198
Figure 6-5	5: Simplified bubble geometry. The bubble is held by two contiguous vanes and shapes up as if it were held by the "effective" vane. From Tegart et al. (1972) [233]	.199
Figure 6-56	6: The ideal distorted axisymmetrical bubble	
	7: Angle $\theta_a$ which measures the distortion of the bubble vs. ratio, $R_o/R$ , of	.201
Figure 6-58	8: Typical effective vane profiles, $Ro/R$ , and dimensionless restoring force, $R\Delta K$ , vs. displacement angle, $\theta$ . The Figure has been replotted by the compiler after a representation in polar coordinates by Tegart et al. (1972) [233]	.202
Figure 6-59	9: Typical effective vane profiles, $R_0/R$ , and dimensionless restoring force, $R \triangle K$ , vs. displacement angle, $\theta$ . The vane profiles have been calculated by Eq. [6-99] with the shown values of $k$ and $m$ . Forces have been deduced from Eqs. [6-96] to [6-98]	.203
Figure 6-60	0: Bond length, $L_b$ , as a function of $T$ , for saturated Argon, Methane, Nitrogen and Oxygen	.205
Figure 6-6 <sup>-</sup>	1: Bond length, $L_b$ , as a function of $T$ , for saturated Ethane, Carbon Dioxide and Ammonia.	.206

Figure 6-6	2: Bond length, $L_b$ , as a function of $T$ , for saturated Hydrogen, Helium and Neon	.207
Figure 6-6	3: Relation between contact angle, $ heta$ , and surface tension, $\sigma$ , for several liquids on the quoted surfaces	.209
Figure 6-6	4: Sketch of a dual stage solid cooler. From Nast et al. (1976) [161]	.217
Figure 6-6	5: Liquid helium (He⁴) coolers. a) Single stage. b) Dual stage. From Sherman (1978) [216]	.218
Figure 6-6	6: Normal attachment of the VCSs to the cooling duct through heat stationis.  From Glaser et al. (1967) [75]	.218
Figure 6-6	7: Tangential attachment of the cooling duct to the shields. Sketched by the compiler after Hopkins & Chronic (1973) [94].	.219
Figure 6-6	8: Detector, $T_1$ , and optics, $T_2$ , temperature vs. orbital time	.224
Figure 6-6	9: JPL-Caltech IR detector cooler arrangement	.226
Figure 6-7	0: Heat Flow diagram of the Ball Brothers Liquid helium Dewar	.231
Figure 7-1	: Phase diagram for He⁴ (not to scale). From Arp (1970) [10]	.233
Figure 7-2	: Schematic of the apparatus used by the Leiden group to produce helium flow through capillaries with independent variation of superfluid and normal velocities. a) From Van der Heijden, Van der Boog & Kramers (1974) [247]. b) From De Haas & Van Beelen (1976) [55]	.241
Figure 7-3	The superfluid friction, $\angle F_s$ , vs. relative velocity, $v_n$ - $v_s$ , for various runs with $\rho_s v_s + \rho_n v_n$ = Const. From van der Hejden, van der Boog & Kramers (1974) [247]	.243
Figure 7-4	: The mutual friction, 4F <sub>sn,1</sub> vs_relative velocity,3vntvs.from various constant mass flux <sub>1</sub> runs <sub>m</sub> From van der Hejden, van der Boog &4Kramers (1974) [247]	.244
Figure 7-5	: Mutual friction to superfluid friction ratio, $F_{sn}/F_s$ , vs. relative velocity, $v_n$ - $v_s$ , from various runs with $v_s \ge 0$ and $v_n \ge 0$ . From van der Heijden, van der Boog & Kramers (1974) [247]	.244
Figure 7-6	: Isothermal and iso chemical-potential flows in the $v_n, v_s$ plane. The shaded region corresponds to subcritical flow ( $\Delta \mu$ =0). From van der Heijden, van der Boog & Kramers (1974) [247]	.245
Figure 7-7	Correlations between the critical superfluid velocity, $v_{sc1}$ , and the tube diameter, $D_E$ . The experimental data have been re-plotted by the compiler after van Alphen et al. (1969) [246]. They correspond to widely different flow conditions. * Clow and Reppy, $T_{\lambda}$ - $T$ 50 x 10 <sup>-3</sup> K. $\bullet$ Fokkens, film flow. $\bullet$ Pellman, "superfluid wind tunnel". $\Box$ Chase, heat conduction $T \rightarrow T_{\lambda}$ ; $v_n \rightarrow 0$ . $\triangle$ Van Alphen, adiabatic flow rate. $\bigcirc$ Van Alphen, energy dissipation technique. $\blacktriangledown$ Kramers, second sound attenuation in pure superfluid flow. $\bullet$ Van Alphen, critical flow through jeweller's rouge. $\triangledown$ Keller and Hammel, isothermal flow. $\bullet$ Data from reviews of Atkins, and Hammel and Keller	.247
Figure 7-8	: Schematic of pressure and temperature drop data as a function of heat flux	.248
Figure 7-9	: Schematic of $L_v^{1/2}D_E$ vs. $v_sD_E$ under steady-state conditions. From Childers & Tough (1976) [44].	.250
Figure 7-1	0: Critical Reynolds number for counterflow heat exchange, <i>Re<sub>c</sub></i> , as a function of temperature, <i>T</i> . From Arp (1970) [10]	.252

Figure 7-11	counterflow heat exchange. <i>T</i> =1,5 K to 2 K. Calculated by the compiler after Arp (1970) [10]	.253
Figure 7-12	2: Temperature profile along a channel filled with He II at atmospheric pressure in conterflow heat exchange. From Bon Mardion, Claudet & Seyfert (1979) [26]	. 255
Figure 7-13	3: Tube and He II bath arrangement	.257
Figure 7-14	1: Film and bulk liquid configuration	.258
Figure 7-15	5: Bernoulli thinning. The full line corresponds to Eq. [7-46]. The dotted line is the Kontorovich (1956) [125] solution. Neither solution gives the correct transition of the film interface to the horizontal free surface in the reservoir, because capillary pressure has been neglected. Curves labelled with the values of <i>Bo</i> correspond to Eq. [7-49].	. 261
Figure 7-16	6: Cell used to perform reduced-gravity test. The film thickness experiments were performed in the left hand side compartment. From Yang & Mason (1980) [268]	.266
Figure 7-17	7: Kapitza conductance, $h_k$ , of low Debye temperature metals, Mercury, Lead, Gold and Silver in contact with Liquid Helium, vs. temperature, $T$ . See Table 7-2 below	.272
Figure 7-18	B: Kapitza conductance, $h_k$ , of Copper in contact with various low acoustic impedance materials vs. temperature, $T$ . See Table 7-2 and Table 7-41 below. Theoretical results are also shown in this figure	.273
Figure 7-19	9: Kapitza conductan <b>ce, h., of Tungsten, Aluminium</b> , Molybdenum and Beryllium, in contact with Liquid Helium, vs. temperature, <i>T</i> . See Table 7-2 below	.274
Figure 7-20	D: Kapitza conductance, h, of Nonmetals in contact with Liquid helium vs. temperature 7. See Table 7-32 below - tr-17603-31-14-2021	.274
Figure 7-21	1: The neutral stability curve for Taconis oscillations when $\xi = 1$ . $\bigcirc D_E = 2,4$ x $10^{-3}$ m, $T_H = 288$ K; $\bigcirc D_E = 2,4$ x $10^{-3}$ m, $T_H = 77,3$ K; $\bigcirc D_E = 4,4$ x $10^{-3}$ m, $T_H = 288$ K; $\bigcirc D_E = 4,4$ x $10^{-3}$ m, $T_H = 77,3$ K From Yazaki, Tominaga & Narahara (1979) [269].	. 303
Figure 7-22	2: Device for preventing Taconis oscillations. All the dimensions are in mm.	. 304
Figure 7-23	3: Superfluid plug arrangement. The intake face of the plug is located at <i>x</i> = 0	.305
Figure 7-24	4: Backward pressure, $p_2$ , as a function of mass flow rate, $m$ , through the plug. Experimental points are from smooth curves by Karr & Urban (1978, 1980) [113] & [114]. The curve shown in the figure and the Reynolds number in the abscissae axis correspond to turbulent flow (neglecting entrance effects, see ECSS-E-HB-31-01 Part 13 clause 7.2.5) in a straight tube of circular cross-section, under the validity of Blasius formula, for the data shown in the insert. Calculated by the compiler.	.311
Figure 7-25	5: Quadrangle of data required in porous plug performance evaluation	.312
Figure 7-26	6: Mass flow rate, $m$ , vs. pressure drop, $p_1$ - $p_2$ , for slits of various lengths, $t$ , and two different bath temperatures, $T_1$ . From Denner et al. (1980) [56]	.323
Figure 7-27	7: Active Phase Separator (APS). From Denner et al. (1982) [57]	.324

3: Three typical positions of the liquid-vapor interface. a) Ideal flow separation. b) Choking. c) Gorter-Mellink flow. From Schotto (1984) [209]	.326
9: Temperature distribution within a 4 x $10^{-2}$ m thick. Ceramic plug for several pressure differences. $p_2 = 2,55 \times 10^{-3}$ Pa in any case. From Elsner (1973) [63]	.328
D: Time constant, <i>b</i> , as a function of heating power, <i>Q</i> , for the plug described by Karr & Urban (1978,1980) [113] & [114] in clause 7.4.2.6. Position of the heaters, <i>H</i> , is also shown in the figure. White circle: upstream heater power-on; blackcircle: upstream heater power-off; white square: heater at the plug exit power-on; black square: heater at the plug exit, power-off. From Karr & Urban (1978,1980) [113] & [114]. There is no consistent difference between power-on and power-off.	.328
1: Fraction, <i>f</i> , of liquid mass lost because of pump down vs. final temperature, <i>T<sub>f</sub></i> . Curves labelled REVERSIBLE correspond to Eqs. [7-80] and [7-81] respectively. Experimental results are also shown. From Nicol & Bohm (1960) [168]	.338
2: Mass flow rate, $m/\rho$ , required for a refrigerating load of $10^{-2}$ W as a function of final temperature, $T_f$ , under three different situations. (a) Liquid He <sup>4</sup> is continuously supplied at 4,2 K for evaporation. (b) No supply of He <sup>4</sup> . (c) Liquid He <sup>3</sup> is continuously supplied at 3,2 K for evaporation. From Nicol & Bohm (1960) [168]	.339
3: Superfluid helium filling assembly. Explanation: NV1 to NV4, ruby needle valve; NV5, standard needle valve; V1, remote controlled QSB for flap valve; V2 to V8, standard valves; F1 and F2, external fittings to maintain cleanliness; T1, 120° flexible transfer tube continuous with filling cryostat and having a 4,2 K radiation shield; T2, long flexible transfer tube for filling 4,2 K tank; R1, 4,2 K reservoir and header tank, R2, 1,5 K reservoir. (NV2 is the porous plug seal. NV3 is the gas vent hole seal). From OXFORD INSTRUMENTS (1976) [176].	.340
Density, $\rho$ , of Saturated Liquid Argon vs. temperature, $T$ . From Johnson (1961) [109]	.347
Density, $\rho$ , of Saturated Solid Argon vs. temperature, $T$ . From Johnson (1961) [109]	.348
Density, $\rho$ , of Saturated Liquid Methane vs. temperature, $T$ . From Johnson (1961) [109]	.348
Density, $\rho$ , of Saturated Solid Methane vs. temperature, $T$ . From Johnson (1961) [109]	.349
Density, $\rho$ , of Saturated Liquid Ethane vs. temperature, $T$ . From Johnson (1975) [107]	.349
Density, $\rho$ , of Saturated Liquid Carbon Dioxide vs. temperature, $T$ . From LEFAX [130]	.350
Density, $\rho$ , of Saturated Solid Carbon Dioxide vs. temperature, $T$ . From LEFAX [130]	.350
Density, $\rho$ , of Saturated Liquid Hydrogen vs. temperature, $T$ . From Vargaftik (1975) [253]	.351
Density, $\rho$ , of Saturated Liquid Helium-4 vs. temperature, $T$ . From Johnson (1961) [109]	.351
	separation. b) Choking. c) Gorter-Mellink flow. From Schotto (1984) [209]