MINISTÉRIO DA CIÊNCIA E TECNOLOGIA
INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS

Ciclo de Palestras Sobre Controle Térmico de Satélites

Sistemas criogênicos

Dr. Valeri Vlassov
Divisão de Mecânica Espacial e Controle - DMC

INPE-2003

Aplicações Espaciais de baixa temperatura

- Plano focais de CCD
- IR telescopes
- Amplificadores de baixo ruído
- Dispositivos super condutores
- Espectrômetro X-Ray
- Magnetômetros
- Sensores e instrumentos científicos

Requisitos térmicos do plano focal

TECNOLOGIA	PIXELS	RESPOSTA ESPECTRAL [µm]	TEMPERATURA DE OPERAÇÃO [K]	NETD [mK]
HgCdTe	320 x 256	1.0 - 2.5	190	40
QWIP	640 x 512	8.0 - 9.0	<90	<25
Microbolômetro	320 x 240	8.0 - 14.0	300	<120
HgCdTe	1500 x 1	MWIR / LWIR	80	11
HgCdTe	1000 x 256	1.0 - 2.5	200	S/R = 400
HgCdTe	15000 x 1	MWIR / LWIR	-	-
HgCdTe	640 x 480	3.7 - 4.8	<120	D* = 4.9×10^{11} Jones

TECNOLOGIA	PIXELS	RESPOSTA ESPECTRAL [µm]	TEMPERATURA DE OPERAÇÃO [K]	RUÍDO [e-]
InSb	512 x 512	2 - 5	-	<20
Si:As	256 x 256	2 - 5	-	<40
Microbolômetro	640 x 480	8 - 12	300	35mK
InSb	2048 x 2048	0.6 -5.4	30	<25
HgCdTe	2048 x 2048	0.85 -2.5	78	<15

Paiva,J. Bertolino,M. Detetores infravermelhos para aplicações espaciais, DEA-EO-001/2002

Requisitos térmicos do plano focal

TECNOLOGIA	PIXELS	RESPOSTA ESPECTRAL [μm]	TEMPERATURA DE OPERAÇÃO [K]	D* [Jones]
InGaAs	256 x 1	1.1 - 2.5	250	$7.5x10^{10}$
InGaAs	320 x 256	1.3 - 2.3	250	$7.5x10^{10}$

TECNOLOGIA	PIXELS	RESPOSTA ESPECTRAL [μm]	TEMPERATURA DE OPERAÇÃO [K]	RUÍDO [e-]
InSb	128 x 128	1.0 – 5.0	<80	<900
InSb	320 x 256	1.0 – 5.0	<80	<700
InSb	2048 x 16	3.5 – 4.8	78	NETD = 15mK

Paiva,J. Bertolino,M. Detetores infravermelhos para aplicações espaciais, DEA-EO-001/2002

Métodos para obtenção de baixas temperaturas

- Radiação de calor
- Expansão de gás ideal (reversível)
- Expansão irreversível (efeito de Joule-Thomson)
- Diluição em líquido
- De-magnetização adiabática

Métodos para manutenção de baixas temperaturas

- Mantas super-isolantes
- Evaporação de líquido
- Fusão sólido-líquido

Ciclos termodinâmicos utilizados

- Stirling (S)
- Brayton
- Joule-Thomson (J-T)
- Linde-Hampson (L-M)
- Gifford-McMahon (G-M)
- Vuilleumier (V-M)
- Claude
- Kleemenko

Técnicas mais usadas

- Radiador criogênico
- Peltier (TEC – termo-elétrico)
- Trocador de calor de evaporação aberta
- PCM – “phase change materials”
- Cryocoolers de ciclo L-M (J-T) aberto ou fechado
- Cryocoolers Stirling
- Cryocoolers de G-M, V-M, Claude
- Pulse tube (Cryocooler termo-acústico)
- Cryocoolers de sorpção
- Sistemas combinados

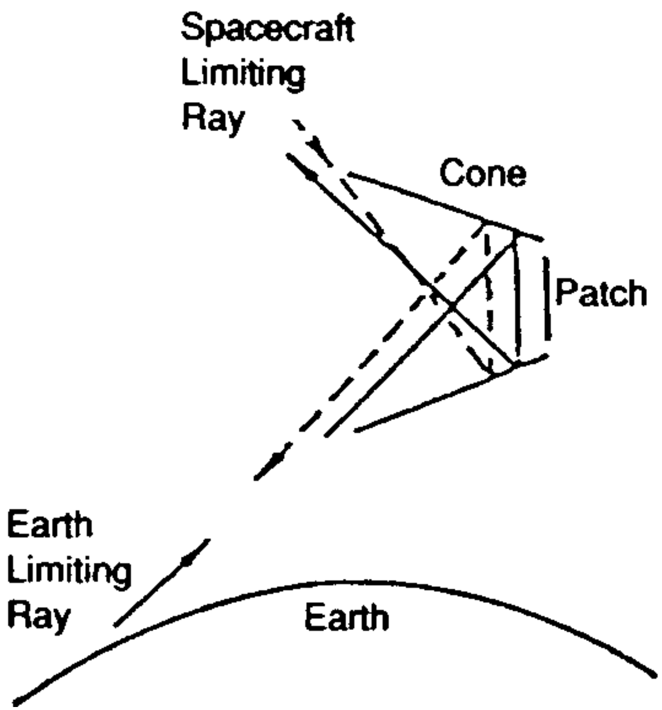
Como escolher? Responder a...

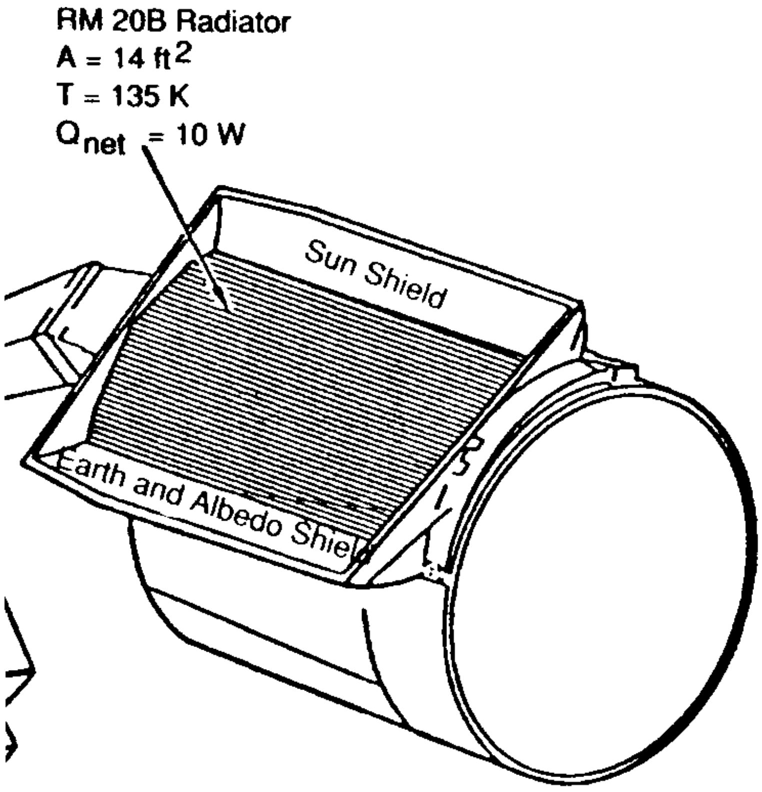
- Qual a temperatura necessária [K]?
- Qual a carga térmica para o cooler (calor gerado mais o calor proveniente da estrutura) [mW]?
- Quais são as limitações de massa p/ o sistema criogênico [kg] ?
- Qual o nível de vibração aceitável [μm: X,Y,Z] ?
- Qual a duração da missão [dias, anos]

Classificação pela Temperatura

- Radiadores criogênicos - 60K..200K (mínimo até 30 K)
- Peltier (TEC) – até 130K
- Cryocoolers mecânicos – de 100K até 6 K
- Sistemas de armazenamento – de 150K até 1.3 K
- "Adiabatic Demagnetization Refrigerator" (ADR) ou de diluição – menos de 1 K

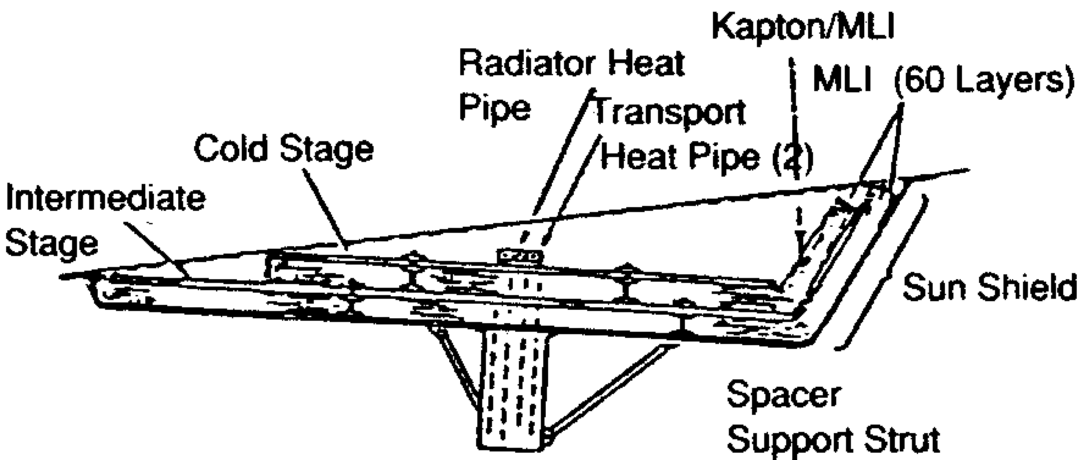
Radiador criogenico: "shielding"





Gilmore, D.G., Satellite Thermal Control Handbook, Aerospace, 1994

Radiador criogenico multi-estágio



f_p - fraction of parasitic leaks

f_x – fraction of absorbed external flux

Real radiators:

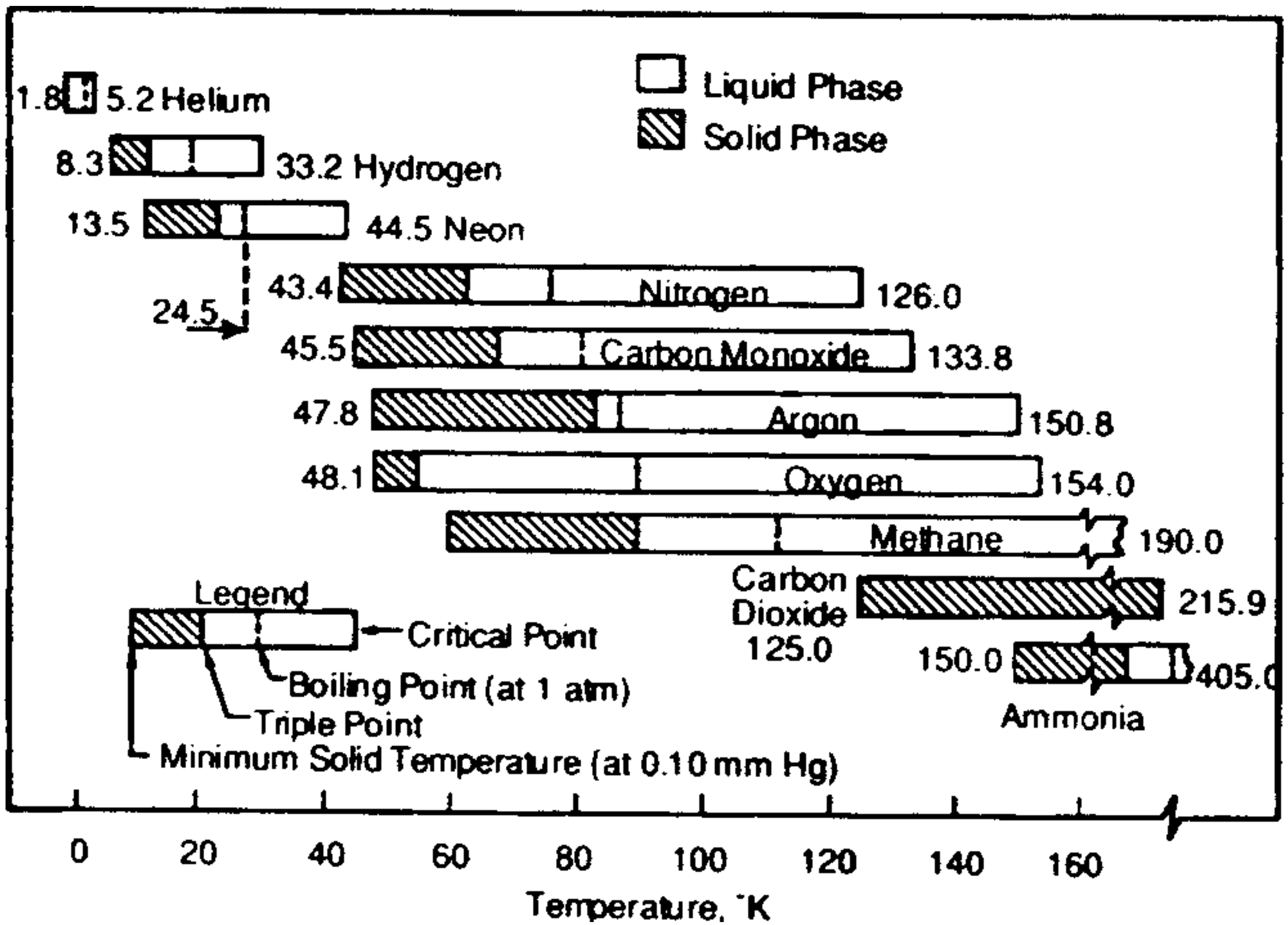
f_p – 0.290...0.973

Efetividade:

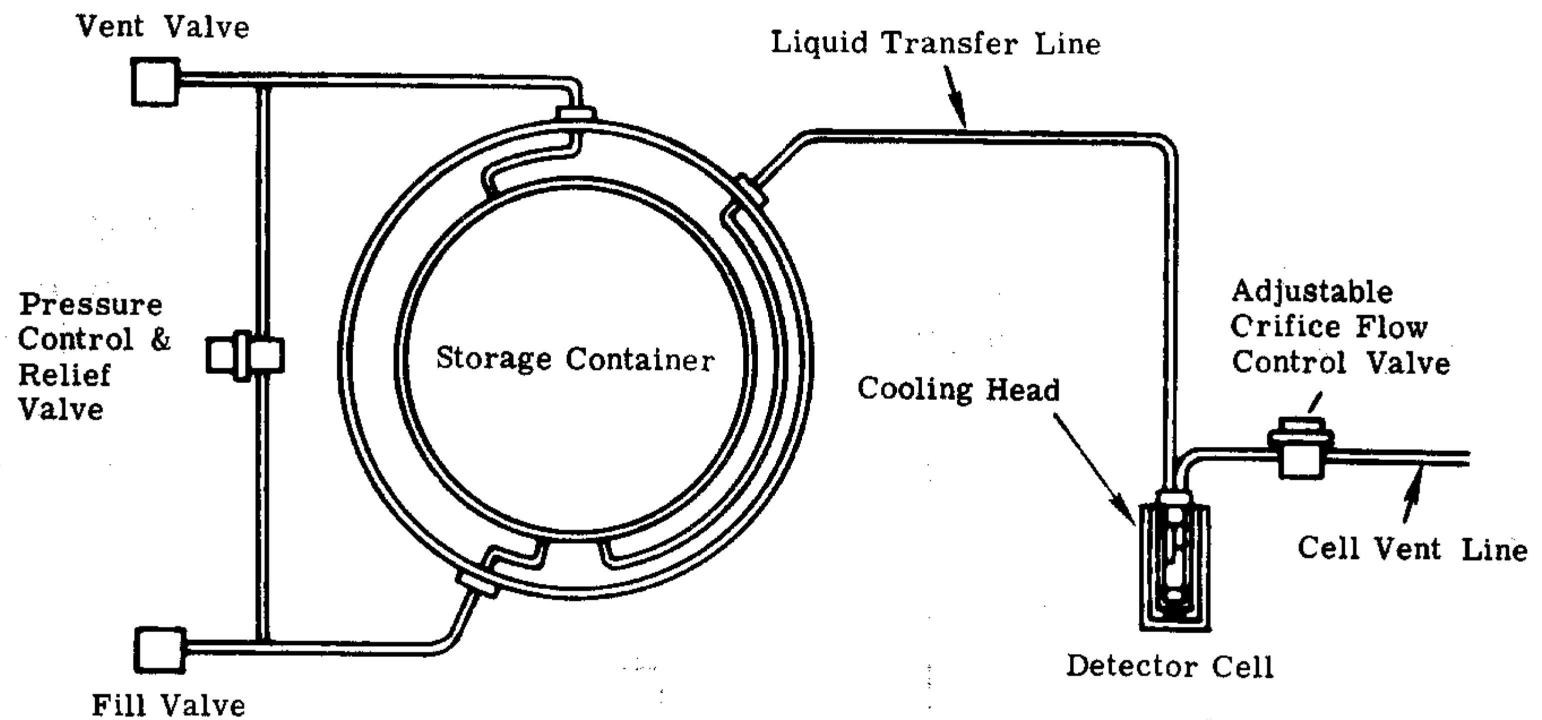
$$\eta(T) = \frac{A_{ideal}}{A_{real}} = \frac{\varepsilon\sigma T^4 - q_{ext} - q_p}{\varepsilon\sigma T^4} = 1 - f_x - f_p$$

Sistemas criogênicos de armazenamento

Missões de curto a médio prazo (até ~1 ano)
Temperatura - depende do líquido

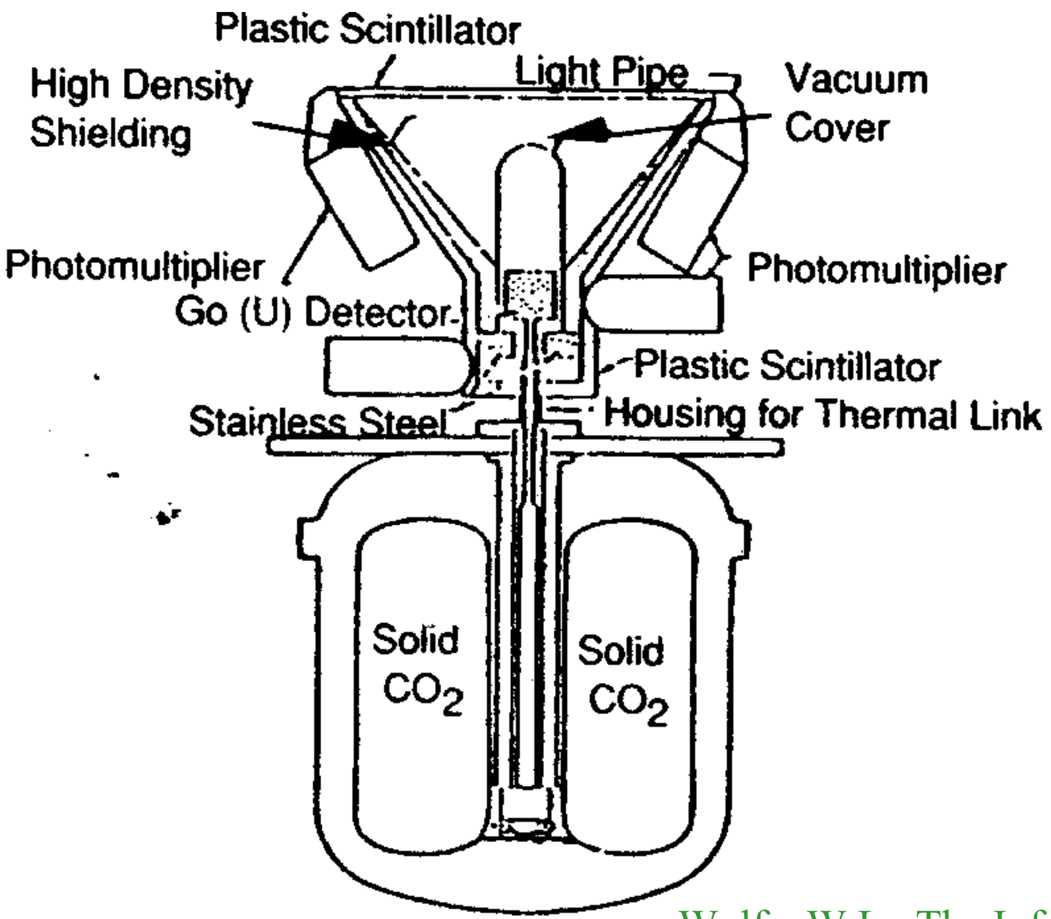


Sistemas criogênicos de armazenagem: evaporação de líquido



Wolfe, W.L., The Infrared Handbook, IRIA, Washington, 1978

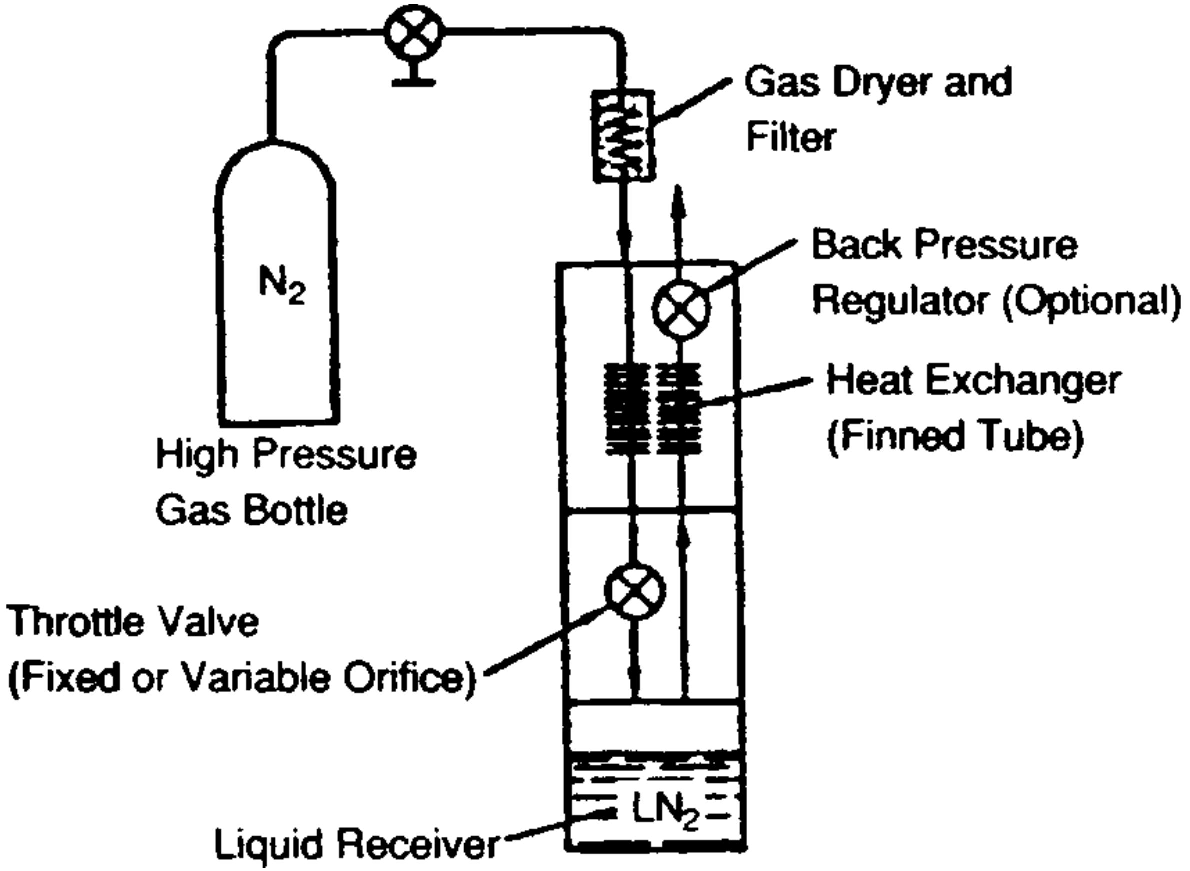
Sistemas criogênicos de armazenagem: fusão de sólido-líquido



SESPP 72-1: Gamma-ray detector solid cooler (Lockheed)

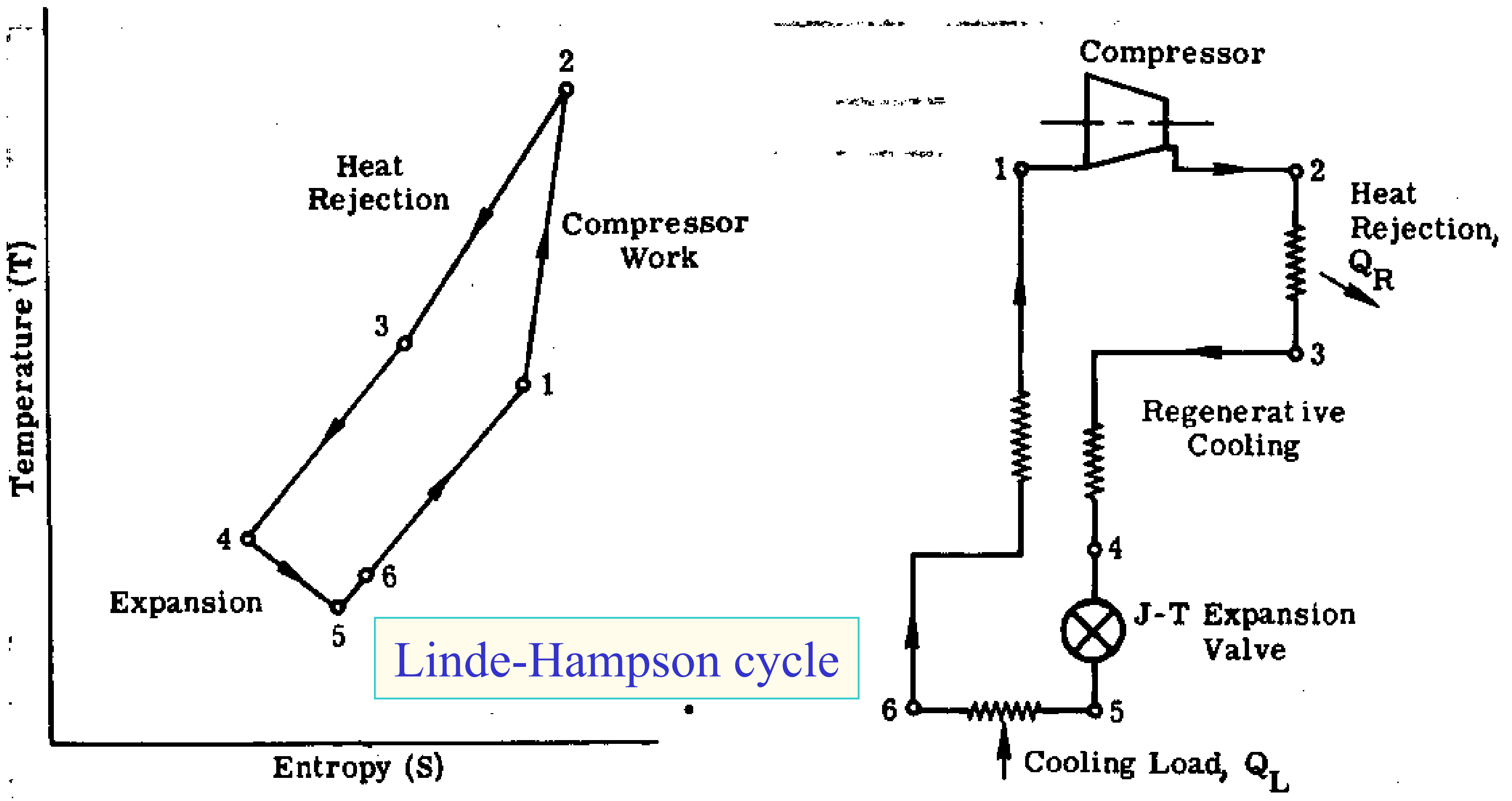
Wolfe, W.L., The Infrared Handbook, IRIA, Washington, 1978

Ciclo aberto de J-T



Gilmore, D.G., Satellite Thermal Control Handbook, Aerospace, 1994

Ciclo fechado de J-T



Linde-Hampson cycle

(a) Temperature-entropy diagram (b) System schematic

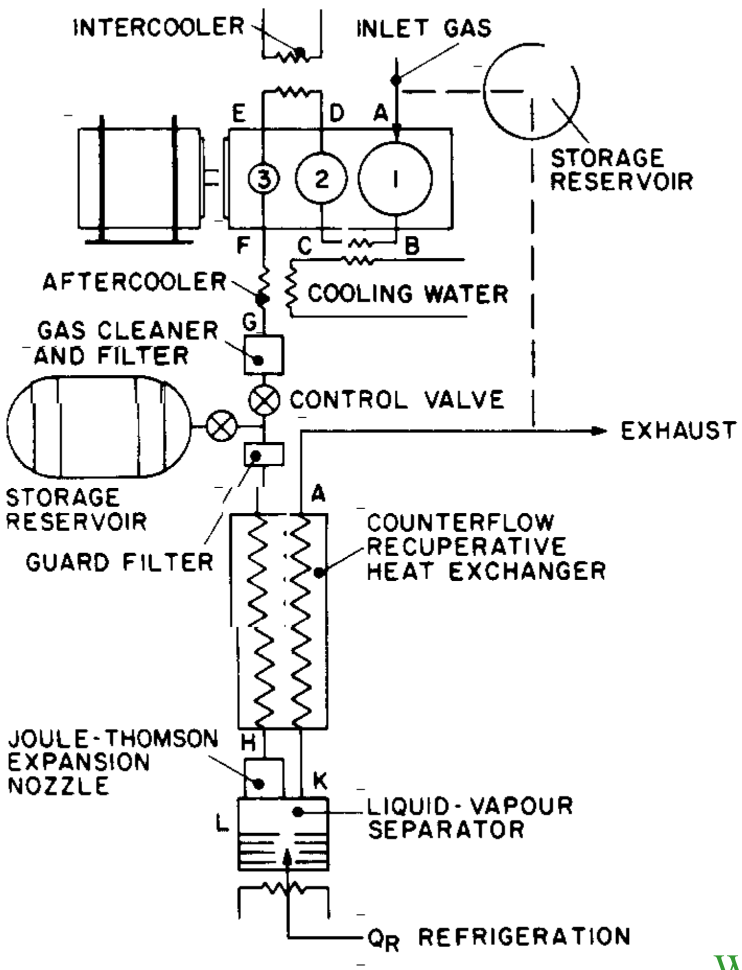
Wolfe, W.L., The Infrared Handbook, IRIA, Washington, 1978

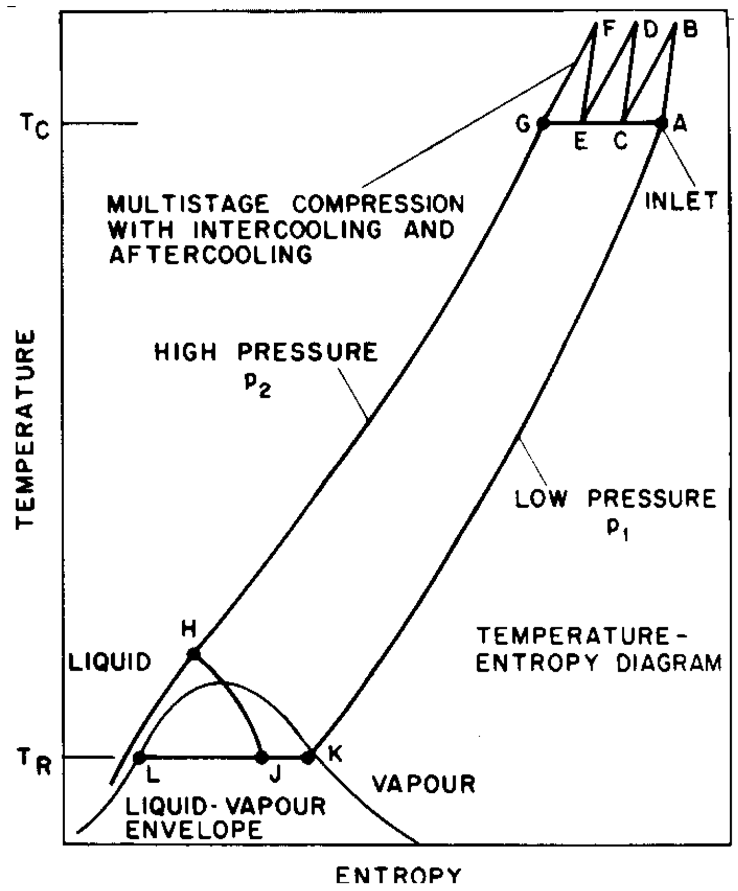
Temperaturas de inversão para J-T

Gas	Maximum inversion temperature (K)
Above ambient	
Ammonia	1994
Carbon dioxide	1500
Methane	939
Oxygen	761
Argon	794
Nitrogen	621
Air	603
Below ambient	
Neon	250
Hydrogen	205
Helium 4	40

Wolfe, W.L., The Infrared Handbook, IRIA, Washington, 1978

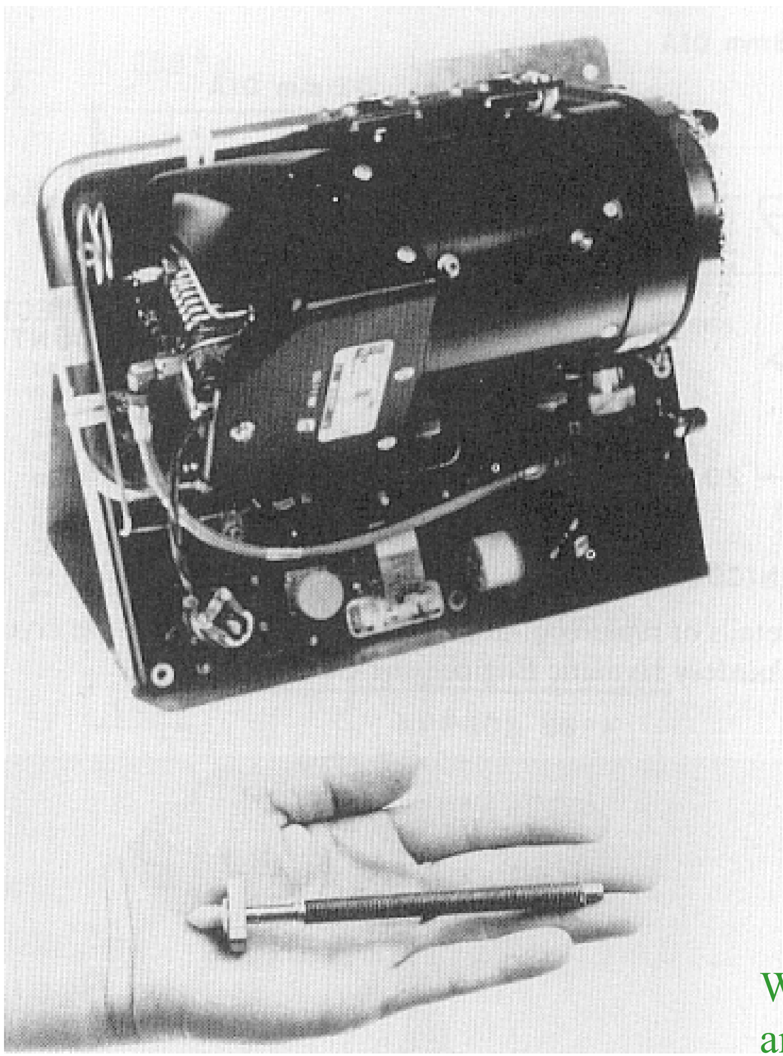
Linde-Hampson cryocooler (J-T)

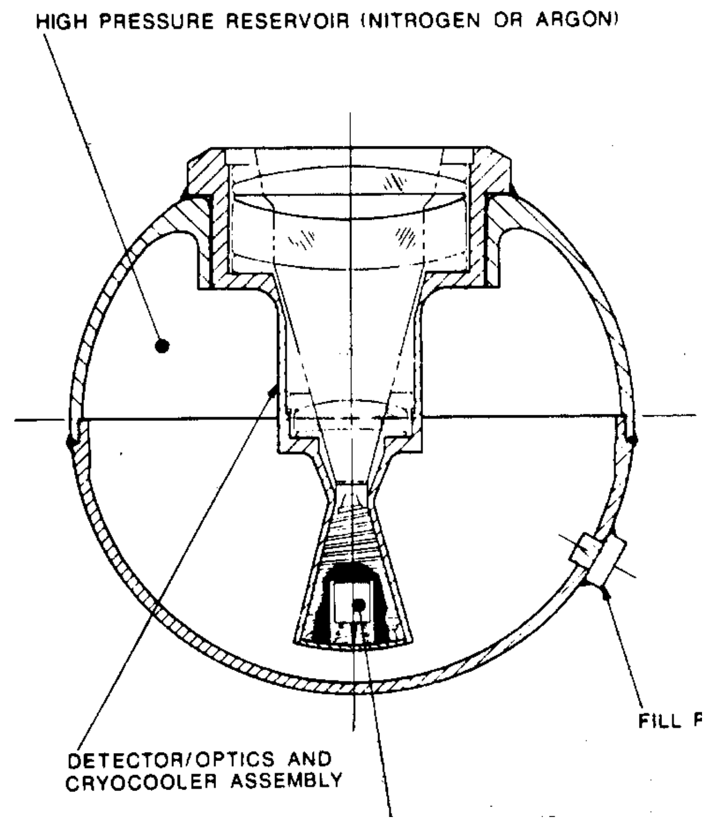




Walker, G., Miniature Refrigerators for Cryogenic Sensors and Cold Electronics, Oxford, 1989

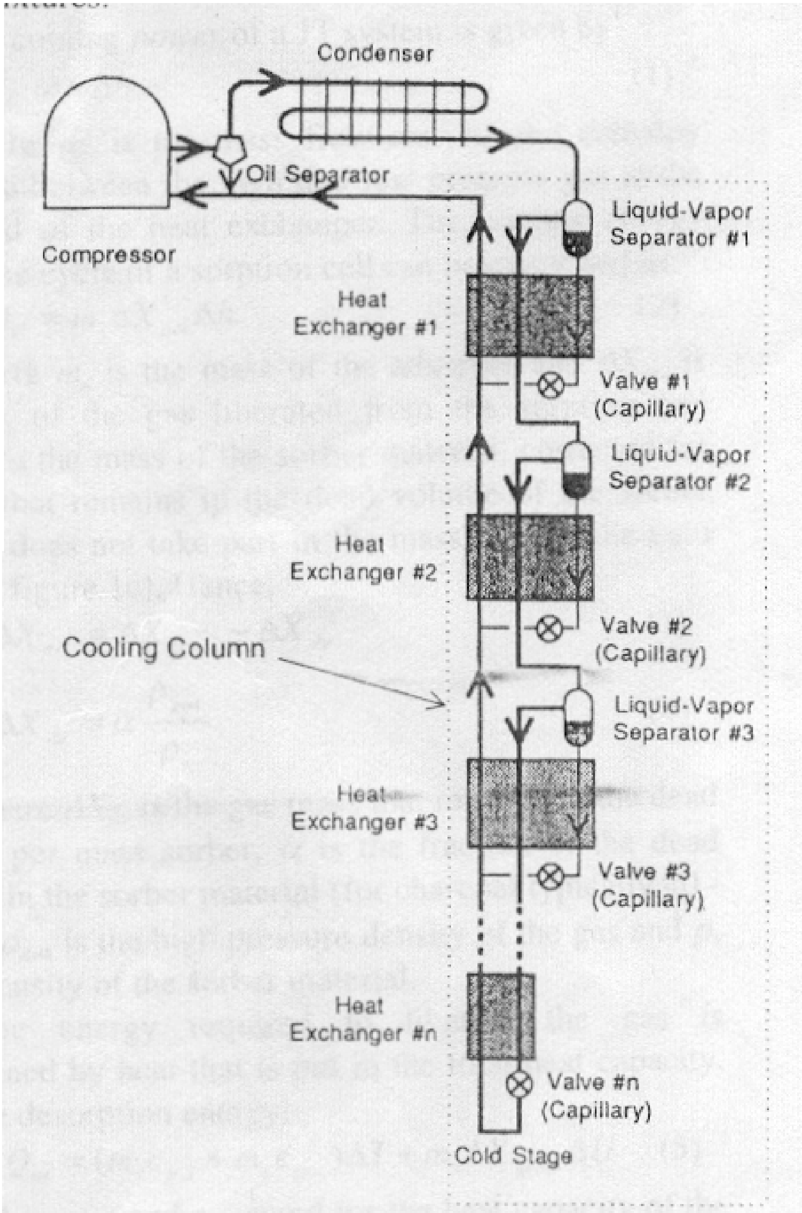
Linde-Hampson cryocoolers





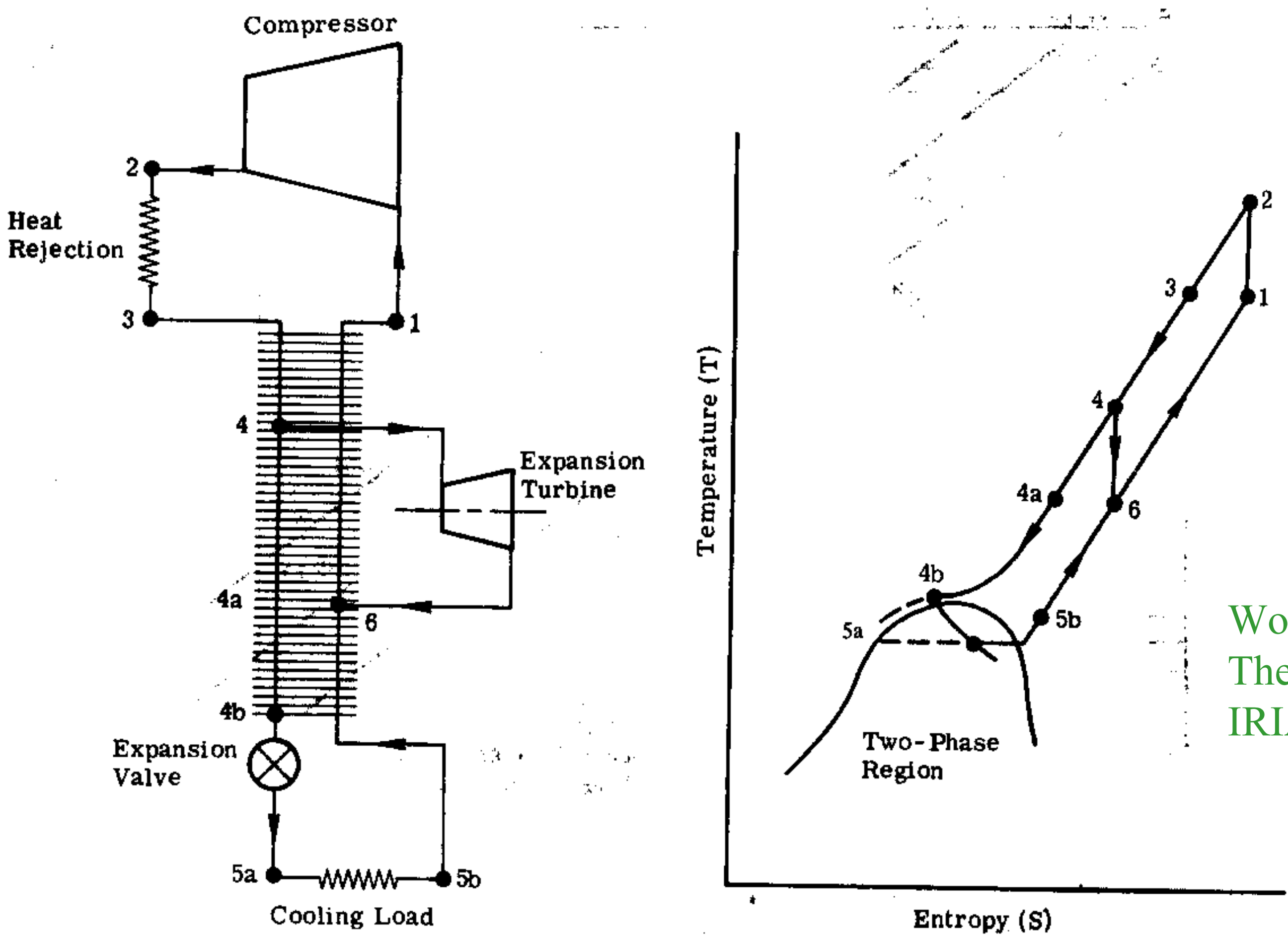
Walker, G., Miniature Refrigerators for Cryogenic Sensors and Cold Electronics, Oxford, 1989

Ciclo de Kleemenko



Burger, J., et al.
6th European Symposium on Space Environmental Control Systems, Noordwijk, The Netherland, 20-22 May 1997

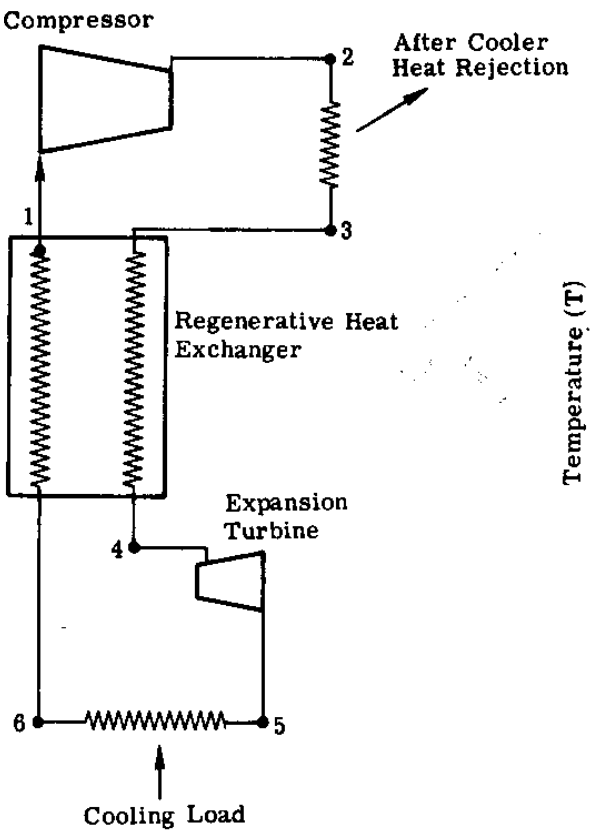
Ciclo de Claude



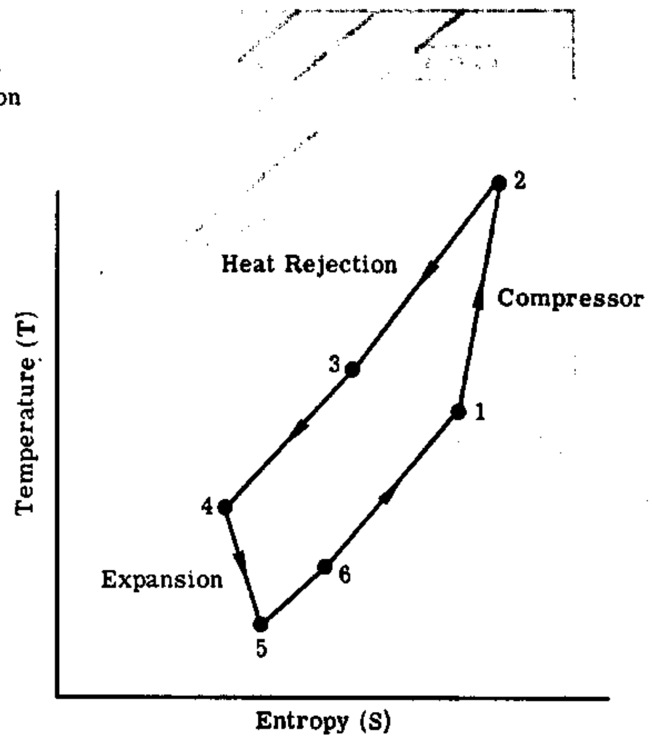
(a) System schematic (b) Temperature-entropy diagram

Wolfe, W.L.,
The Infrared Handbook,
IRIA, Washington, 1978

Ciclo de Brayton

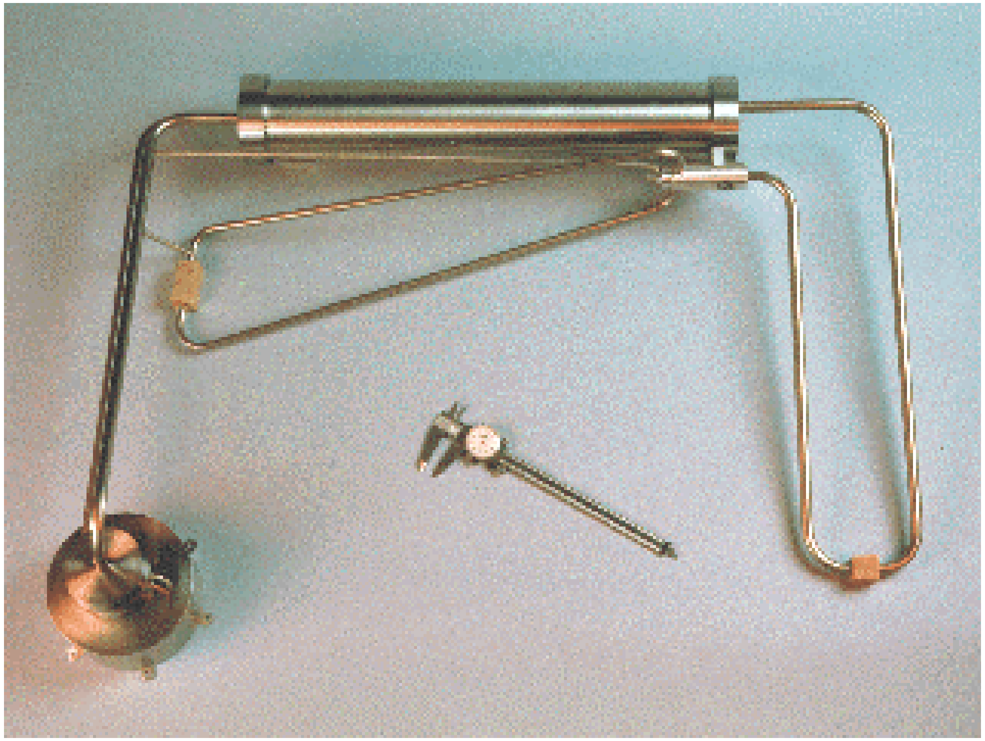


(a) System schematic



Wolfe, W.L., The Infrared Handbook, IRIA, Washington, 1978

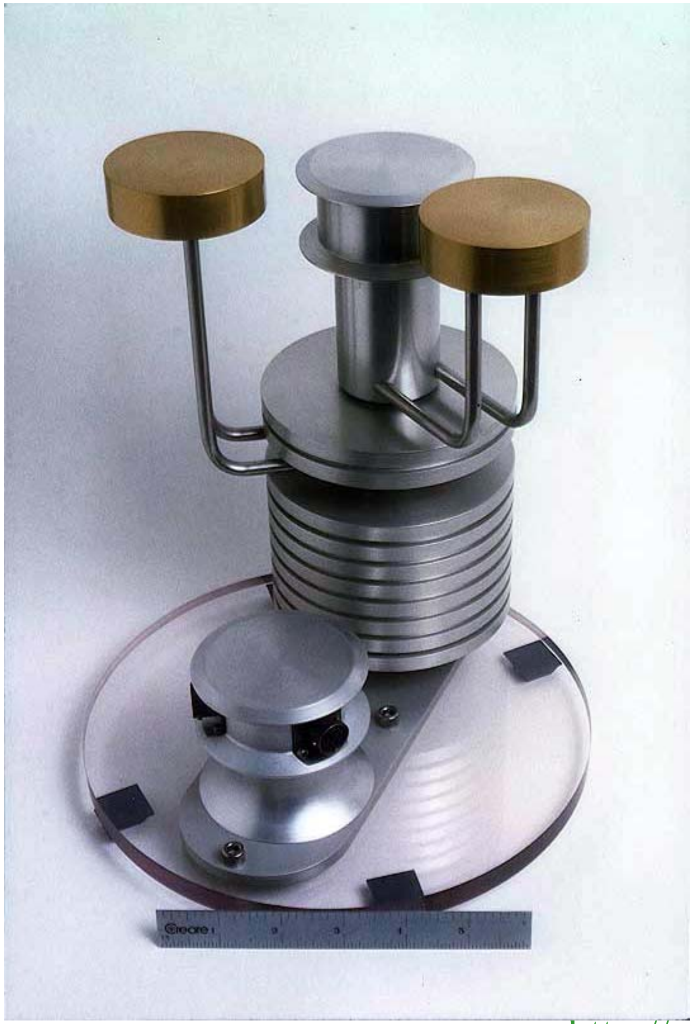
Micro-cryocooler de ciclo de Brayton



5 watt, 65 Kelvin
Turbo-Brayton cooler

http://cryowwwebber.gsfc.nasa.gov/coolers/Ball/Ball.html

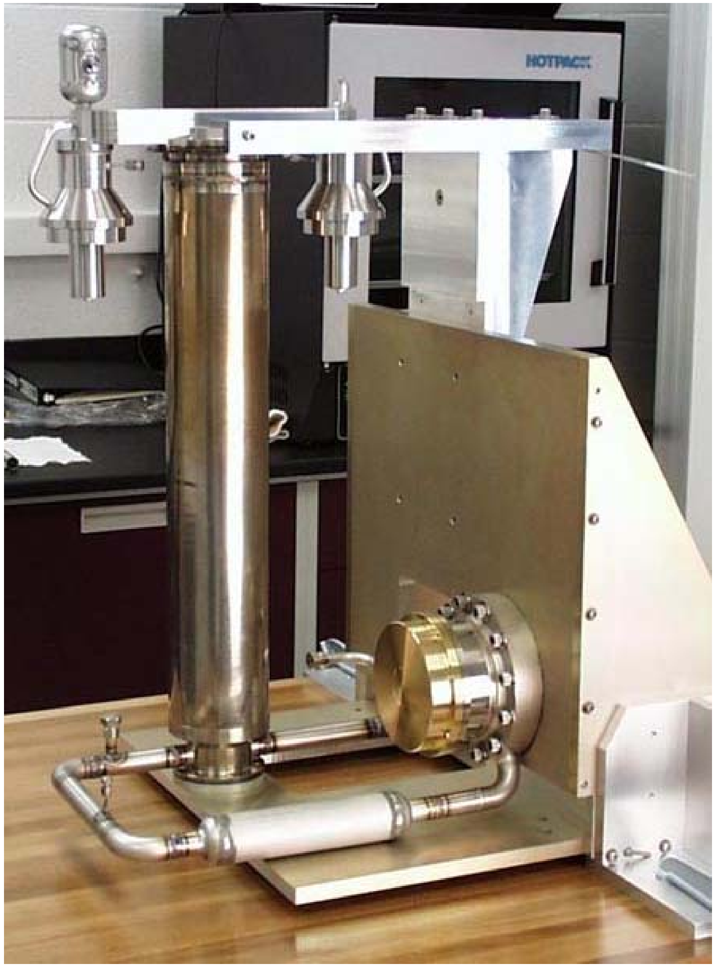
Micro-cryocooler de ciclo de Brayton



35/60 Kelvin Turbo-Brayton cooler

http://cryowwwebber.gsfc.nasa.gov/coolers/Ball/Ball.html

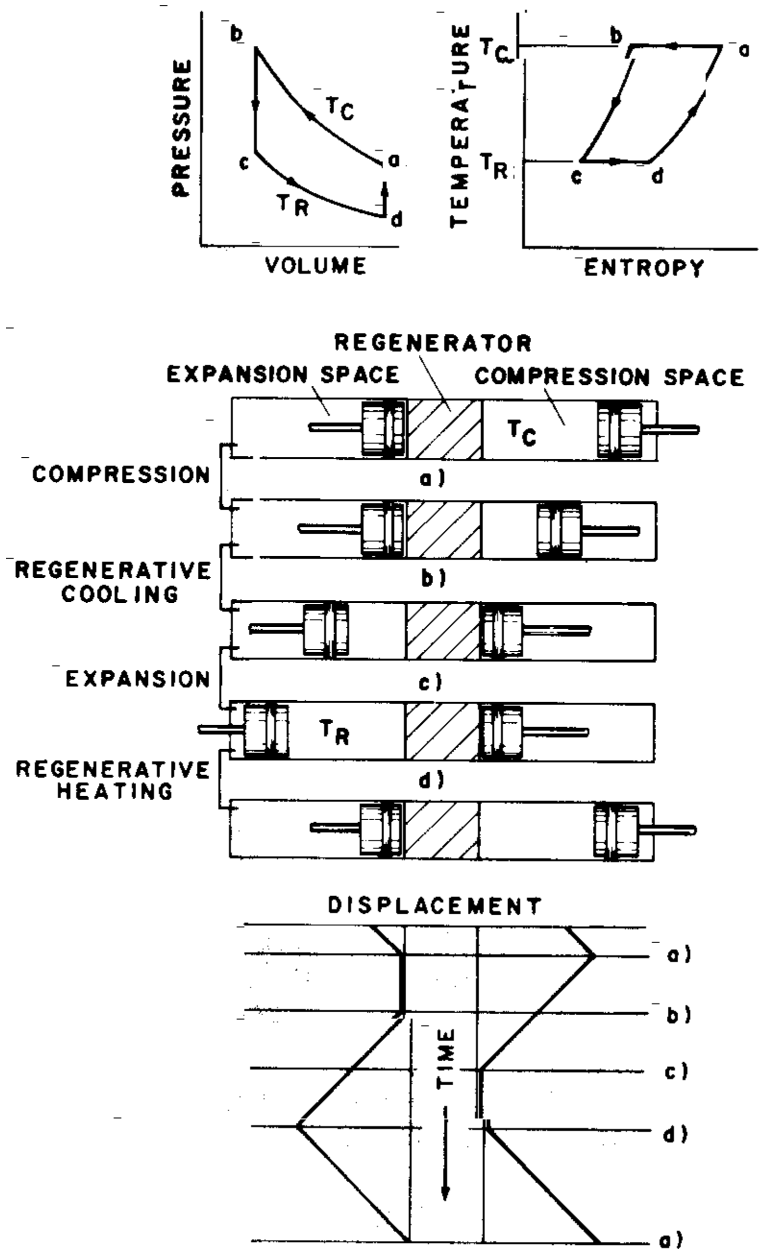
Micro-cryocooler de ciclo de Brayton



A Turbo-Brayton cooler has been installed on the Near Infrared Camera and Multi-Object Spectrometer (NICMOS) instrument of the Hubble Space Telescope. NICMOS's original solid nitrogen cooler exhausted its supply of solid nitrogen coolant earlier than planned.
The Turbo-Brayton cooler will allow the NICMOS instrument to continue studying the universe

http://cryowwwebber.gsfc.nasa.gov/coolers/Ball/Ball.html

Ciclo de Stirling



Walker, G., Miniature Refrigerators for Cryogenic Sensors and Cold Electronics, Oxford, 1989

Tipos de cryocoolers de Stirling

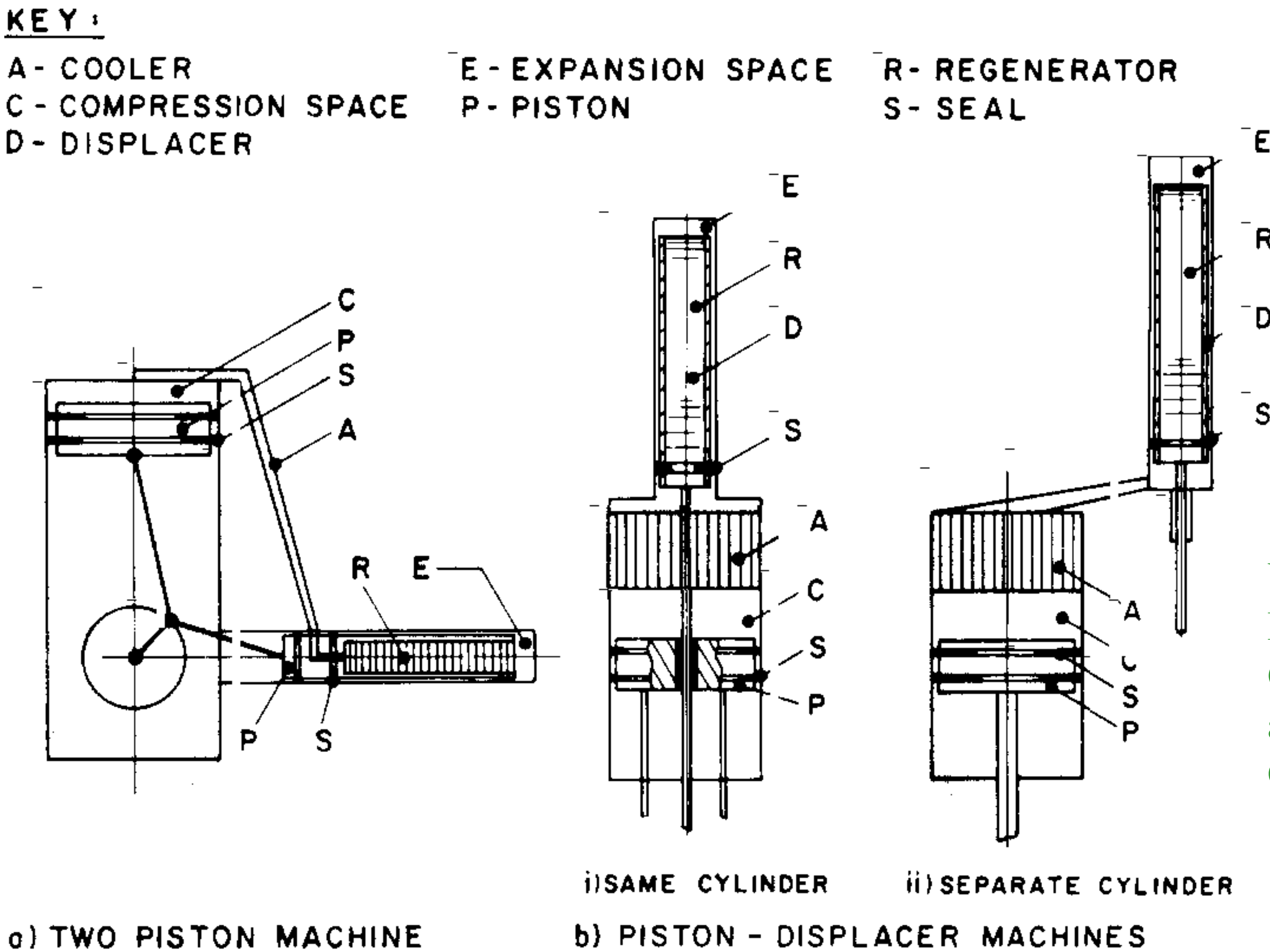
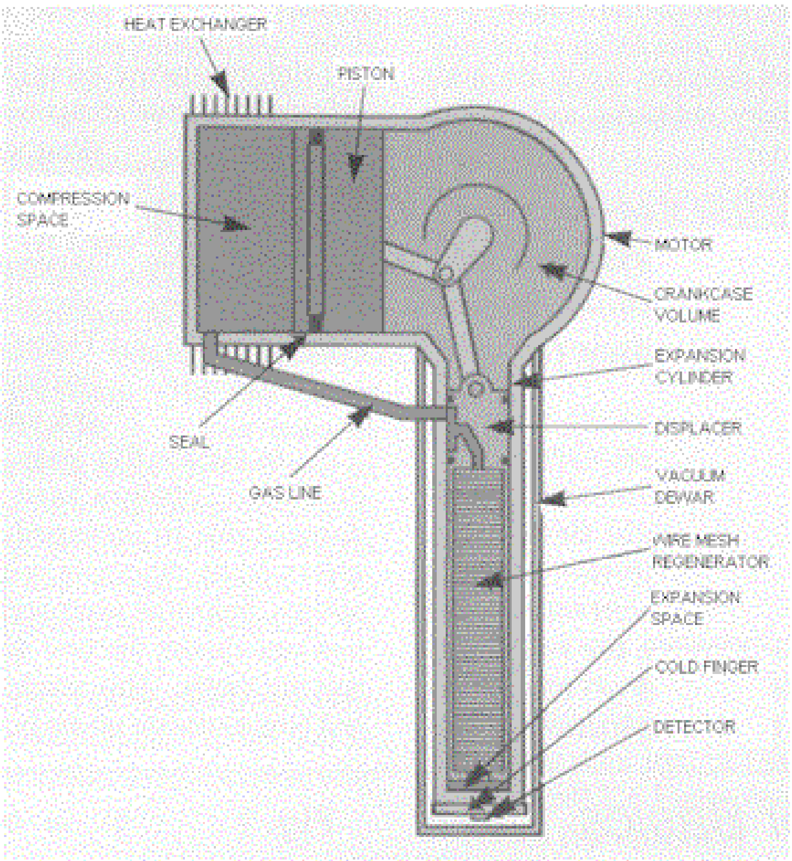
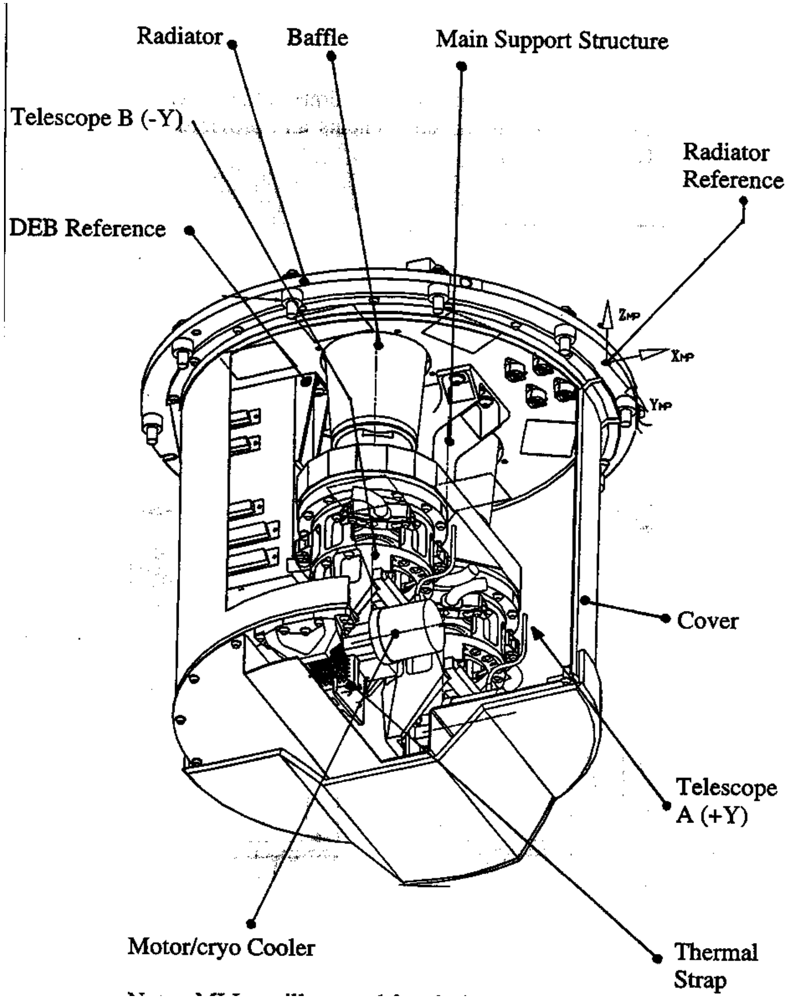


FIG. 3.11. Three basic arrangements for single-acting Stirling cryocoolers.

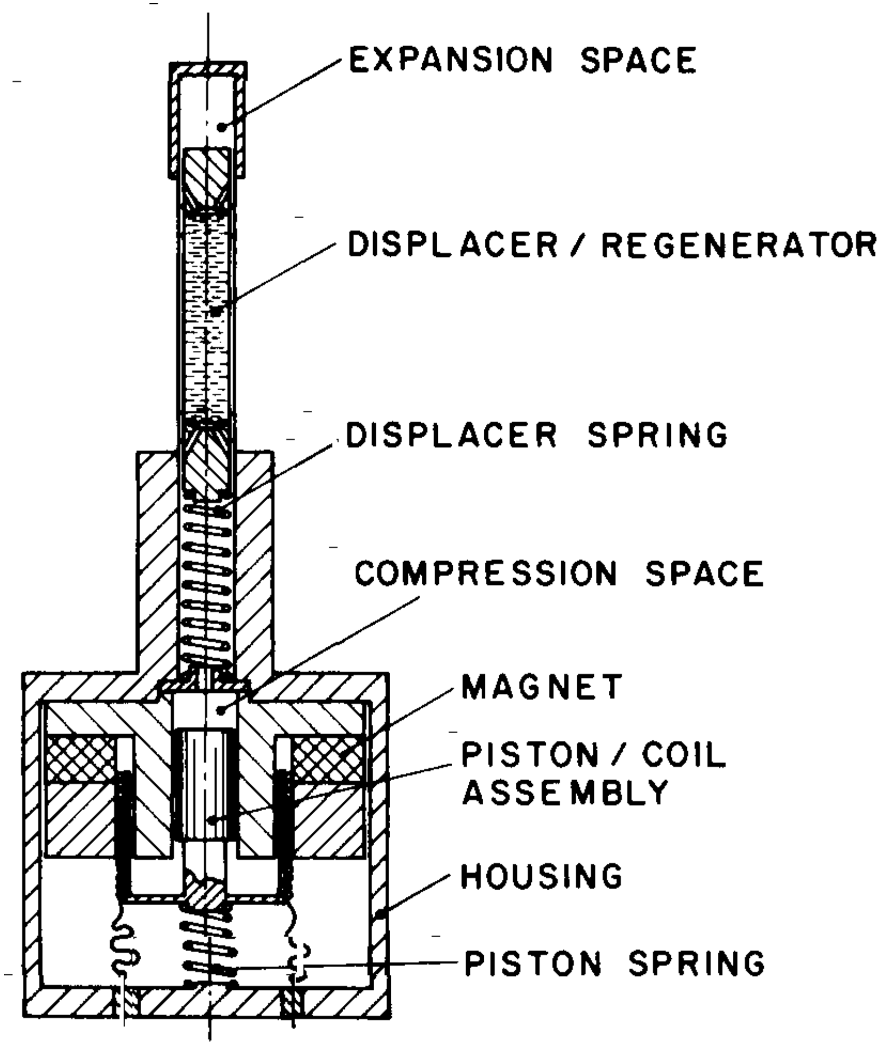
Walker, G., Miniature Refrigerators for Cryogenic Sensors and Cold Electronics, Oxford, 1989

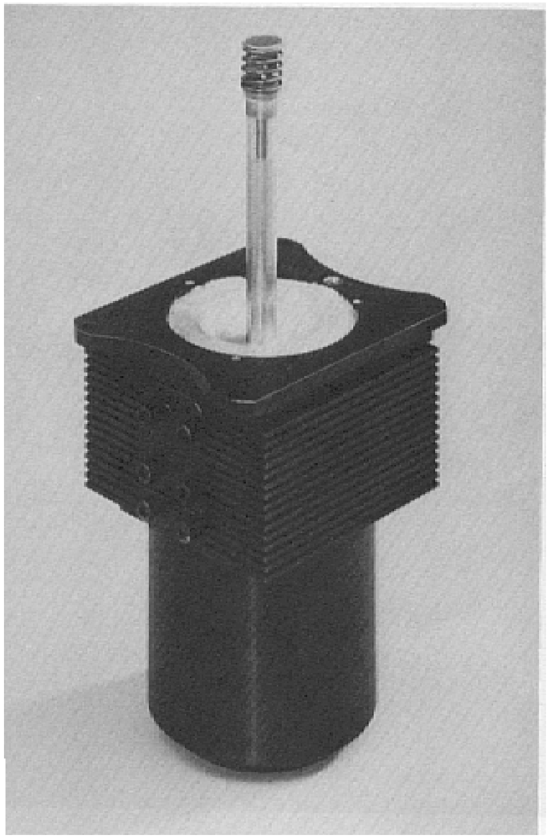
CIMEX cryocooler (INPE-NASA-Alcatel)





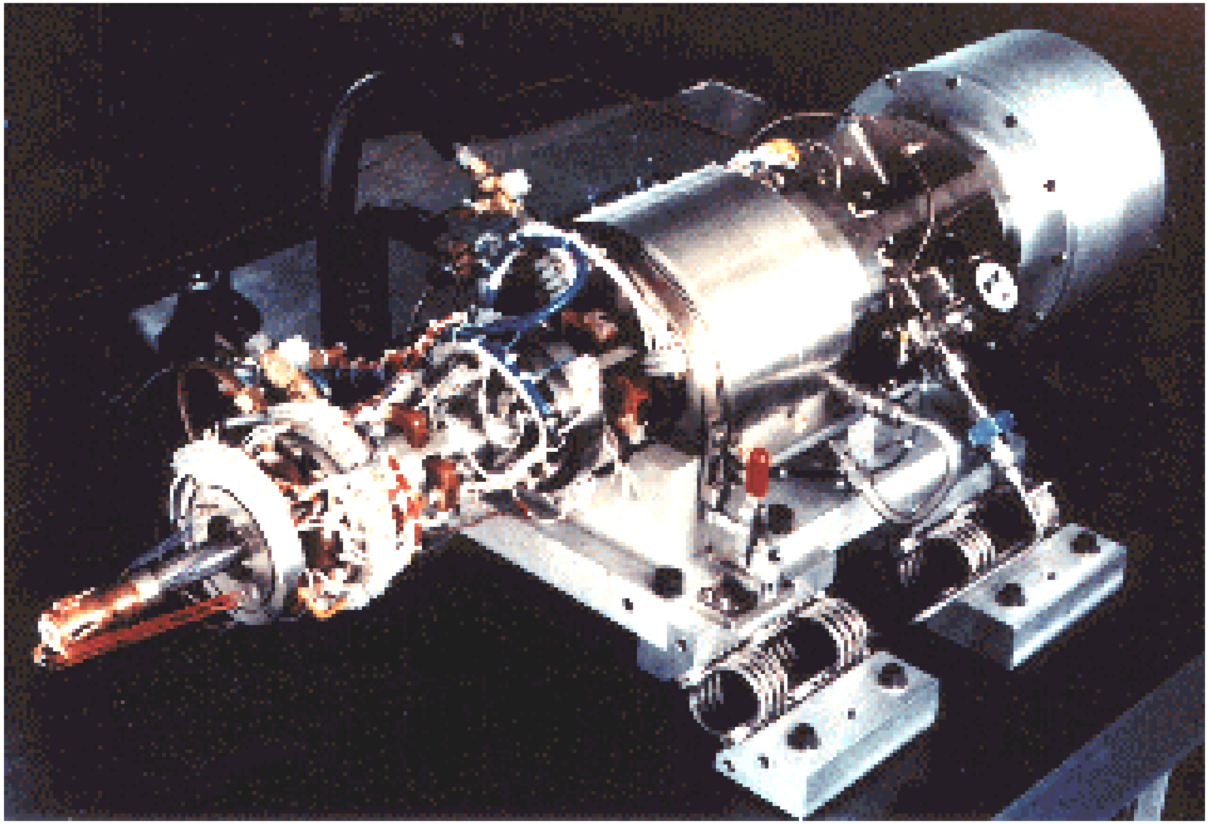
Linear Cryocooler de Stirling





Walker, G., Miniature Refrigerators for Cryogenic Sensors and Cold Electronics, Oxford, 1989

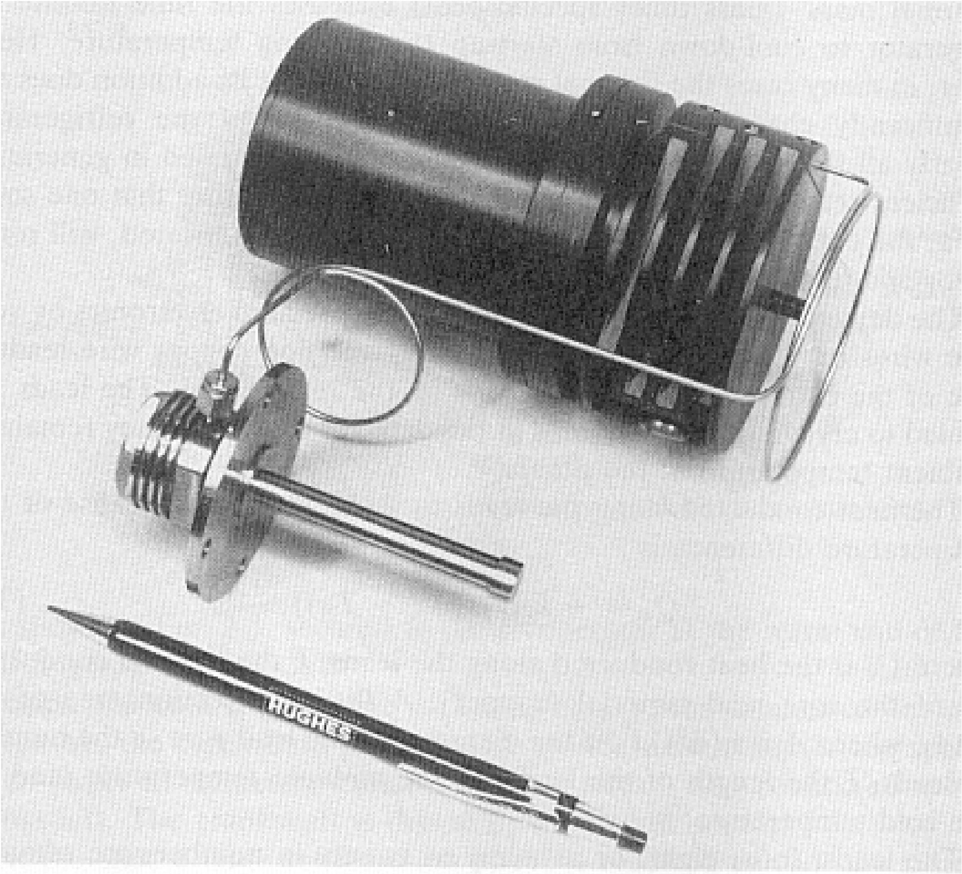
Linear Cryocooler de Stirling



This Stirling Cycle cooler, built by North American Phillips, tested the use of magnetic bearings and clearance seals in mechanical coolers. The cooler demonstrated the usefulness of these techniques by running for a total of 5 years

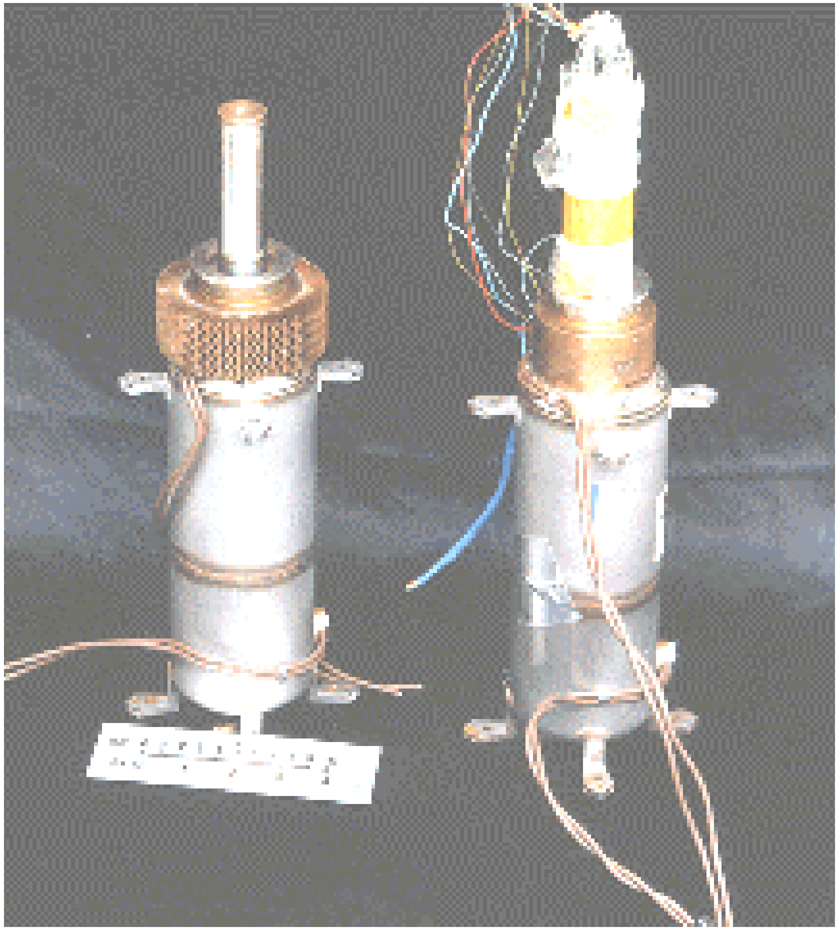
http://cryowwwebber.gsfc.nasa.gov/coolers/Ball/Ball.html

Split Cryocooler de Stirling



Walker, G., Miniature Refrigerators for Cryogenic Sensors and Cold Electronics, Oxford, 1989

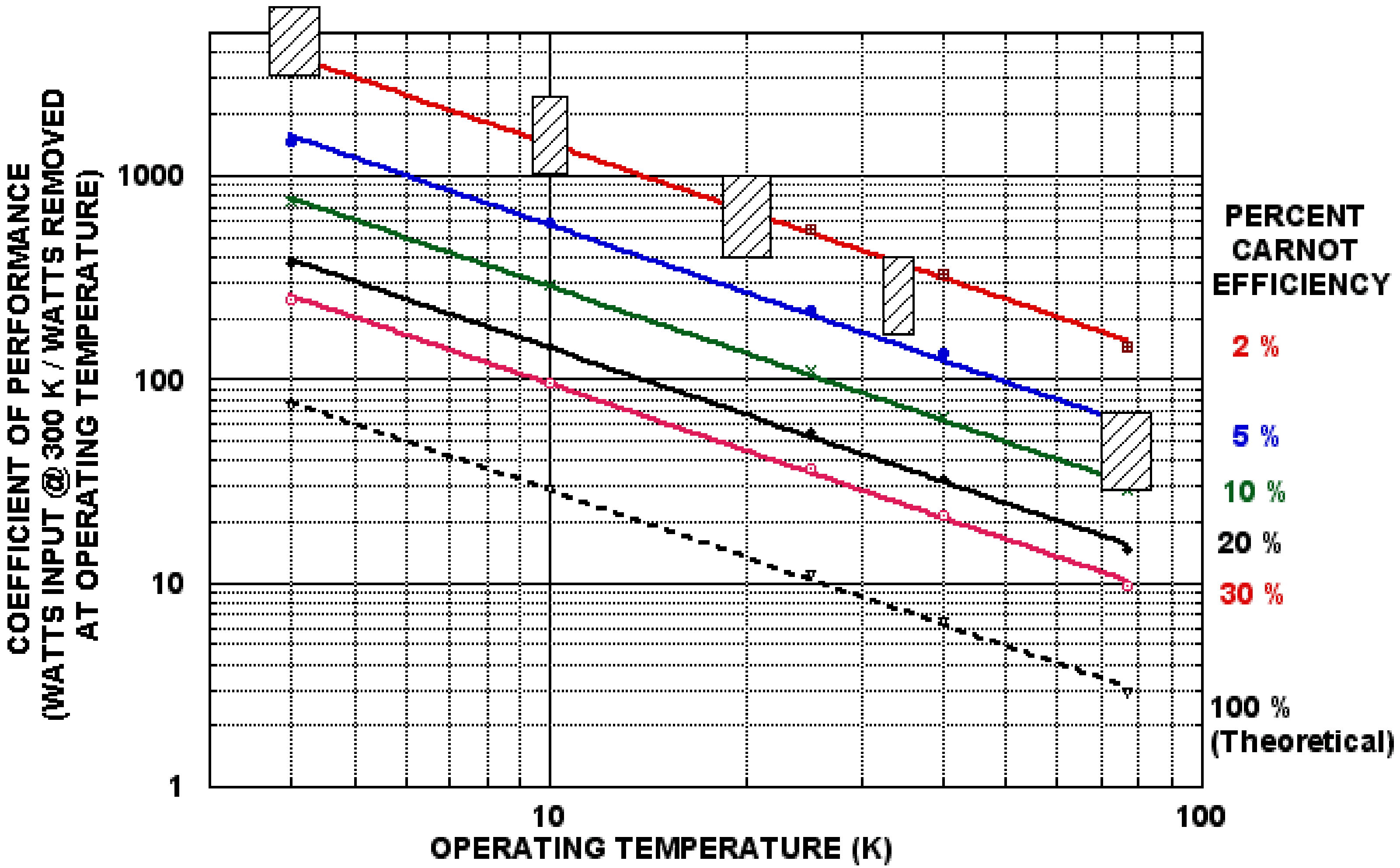
Split Cryocooler de Stirling



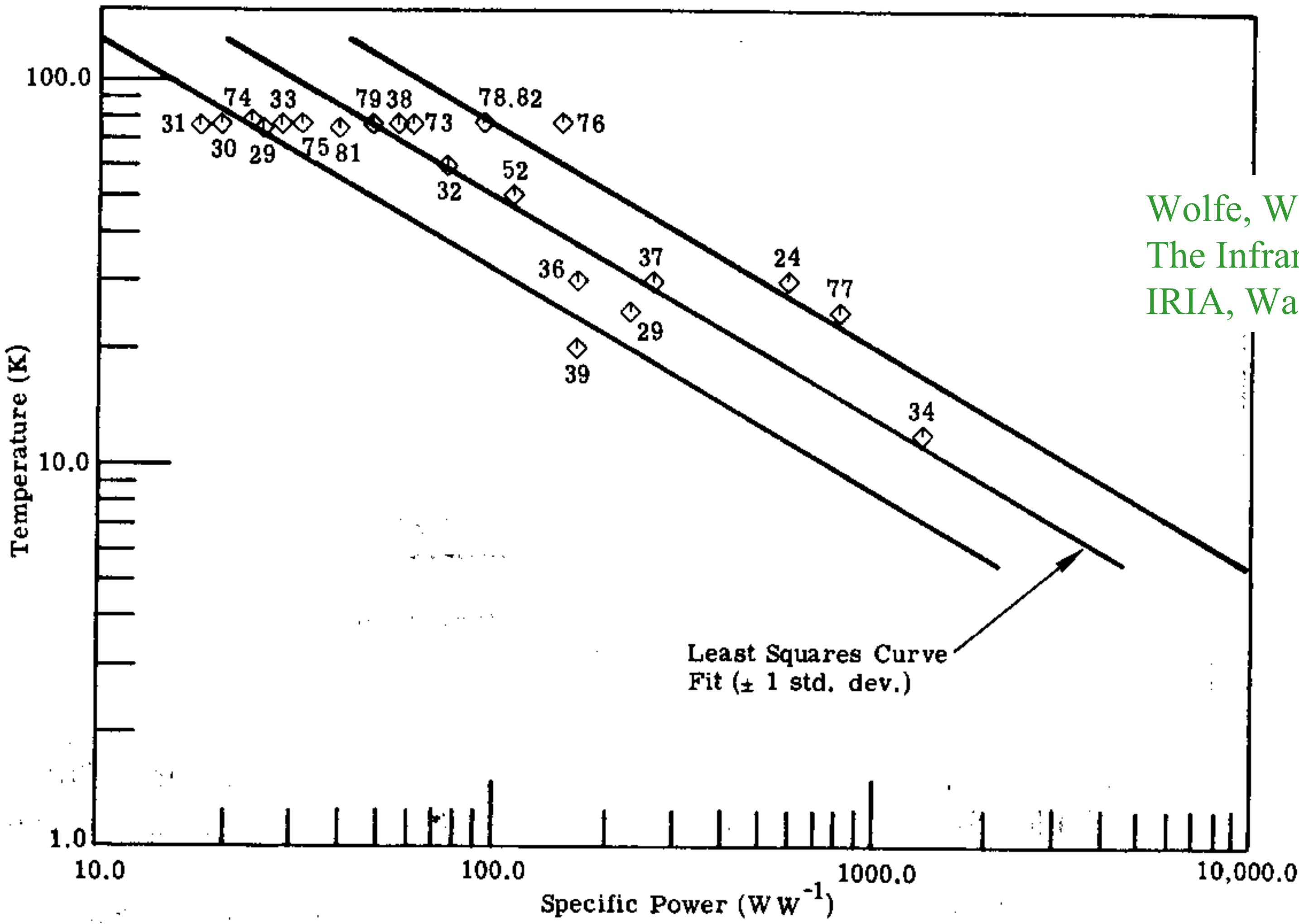
The Sunpower M77 cooler is a low cost, commercial Stirling cycle cooler. Goddard has procured 10 of these coolers that were designed to allow active vibration cancellation. It has operated 1.5 years since the last servicing of the cooler, with no degradation in performance

http://cryowwwebber.gsfc.nasa.gov/coolers/Ball/Ball.html

W/W característica cryocoolers

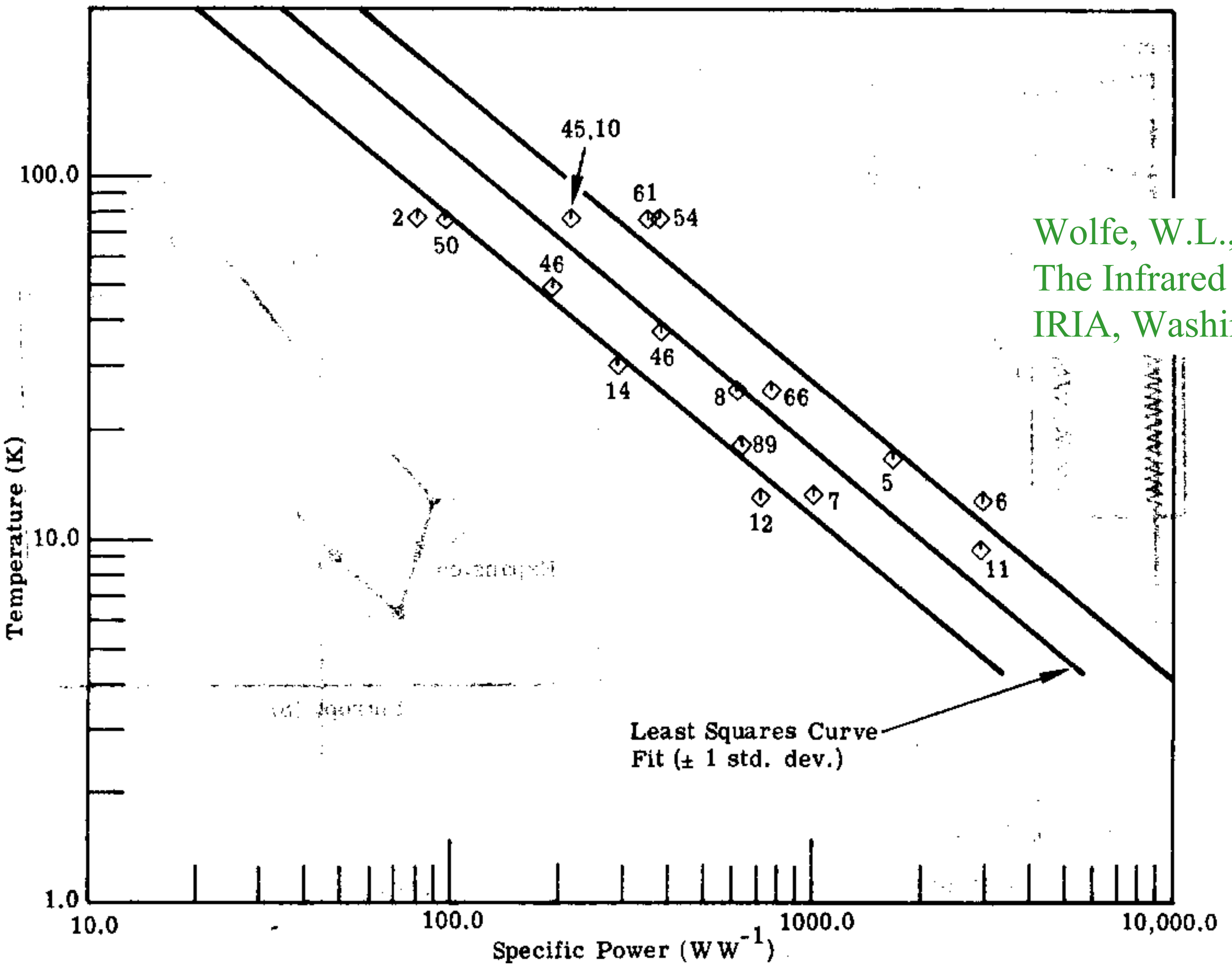


W/W característica de S-cryocoolers



Wolfe, W.L.,
The Infrared Handbook,
IRIA, Washington, 1978

W/W característica de G-M cryocoolers



Wolfe, W.L.,
The Infrared Handbook,
IRIA, Washington, 1978

V-M cryocoolers

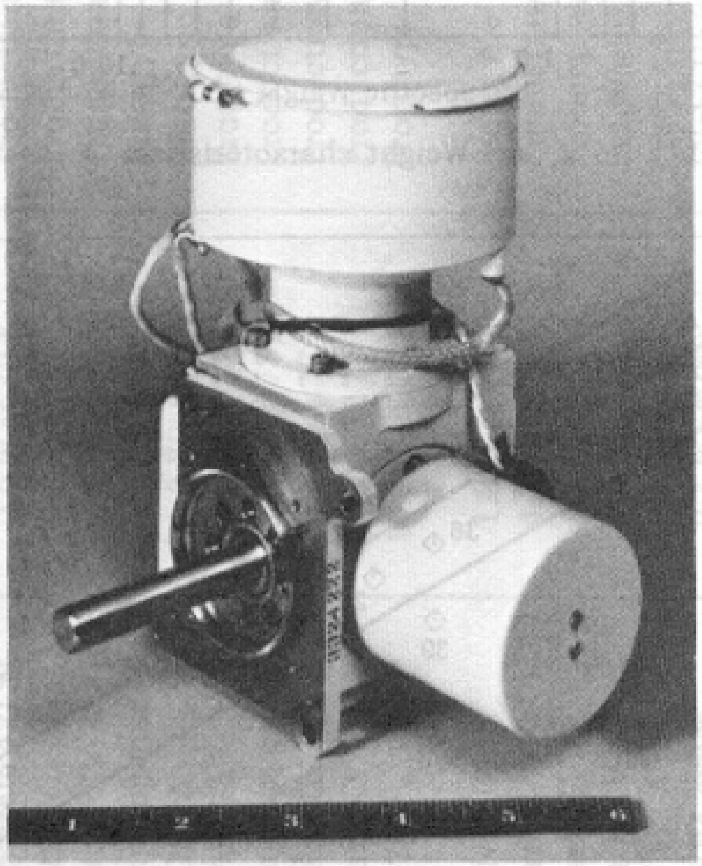
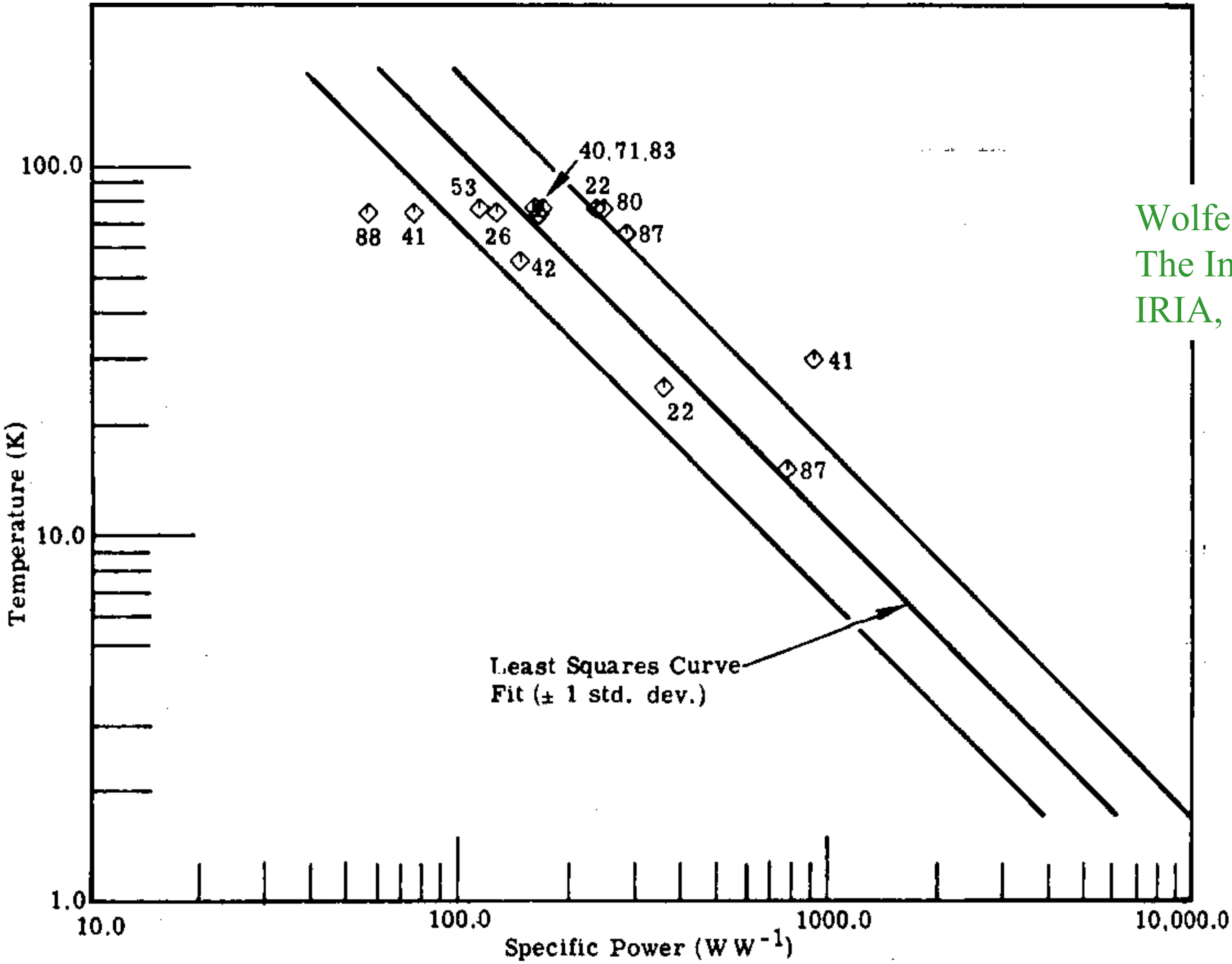


Fig. 15-18. A single-stage, VM cooler (1 W @ 77 K; Hughes Aircraft Co., Model 77 MVM-1-B) [15-25].

Wolfe, W.L.,
The Infrared Handbook,
IRIA, Washington, 1978

W/W característica de V-M cryocoolers



Wolfe, W.L.,
The Infrared Handbook,
IRIA, Washington, 1978

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Supressão de vibração em S-cryocoolers

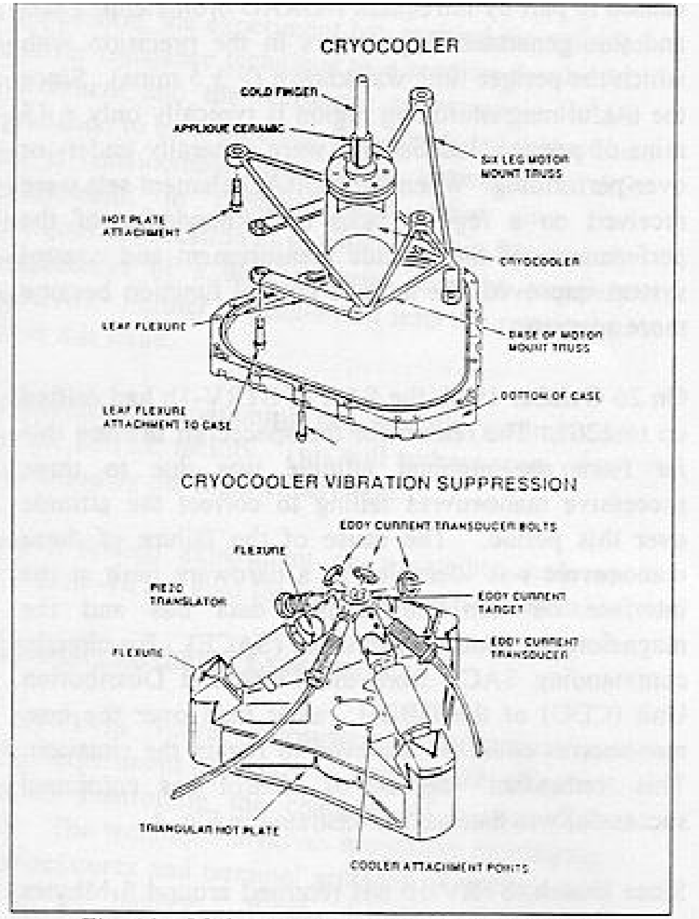
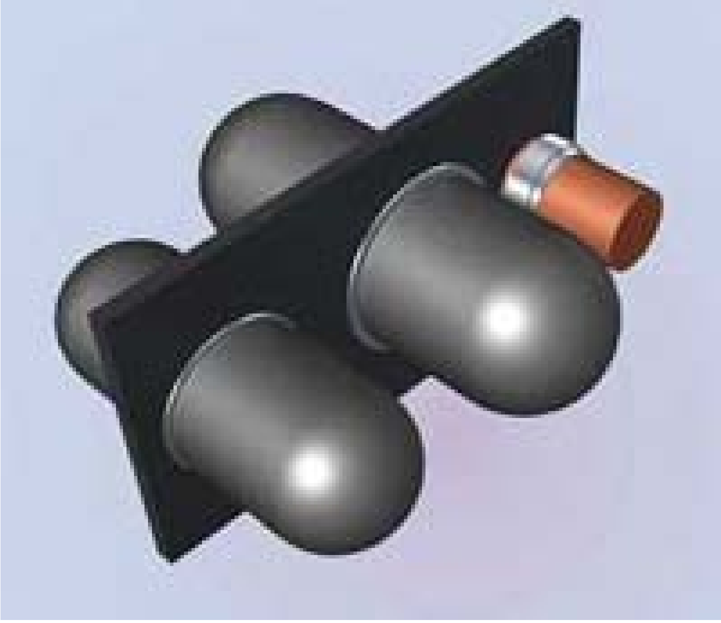


Fig. 16. Major components of the cryo-cooler
(courtesy of BMDO/JPL)

This BMDO experiment uses a novel vibration suppression technique comprising piezo materials to make the tip of the coldfinger stand stilk thus eliminating motion of the sensor mounted on the coldfinger. Piezo translators displace the entire cryocooler to cancel the motion of the tip of the cold finger, and three eddy current transducers detect tip motion

http://lasp.colorado.edu/strv/exp1b_strv.html

Combinação, Stirling + J-T

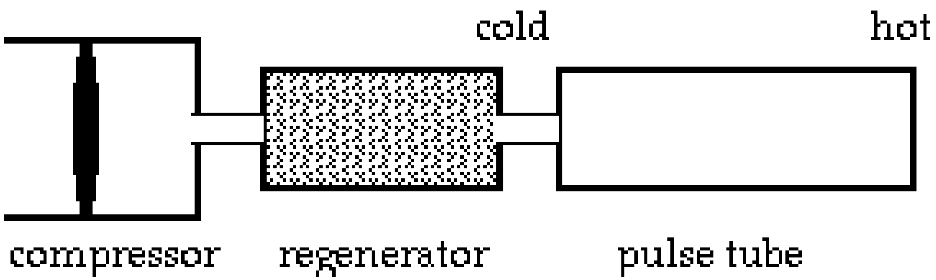


Ball Aerospace has combined its flight-qualified Stirling and Joule-Thomson (J-T) cryocooler technologies to create an efficient, low mass and versatile 10 K cryocooler.

The hybrid cryocooler consists of a Stirling precooler and a J-T fluid loop coupled by a thermal storage unit

http://www.ball.com/aerospace/p2prod.html

Cryocooler termo acústico "Pulse Tube – PT"

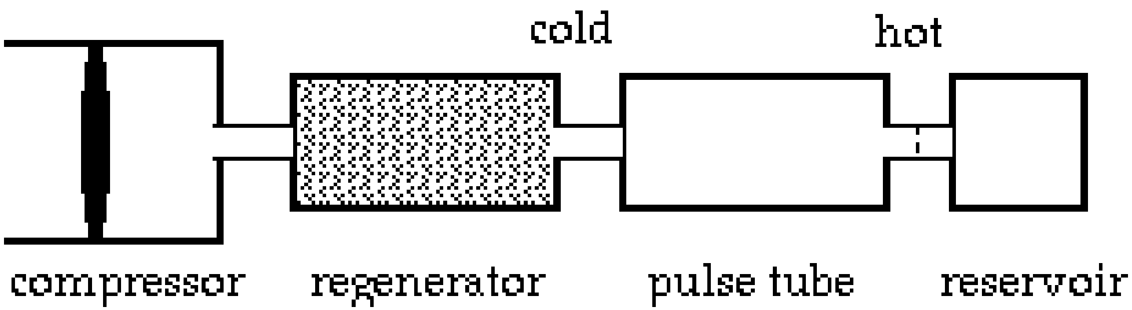


Basic Pulse Tube Refrigerator

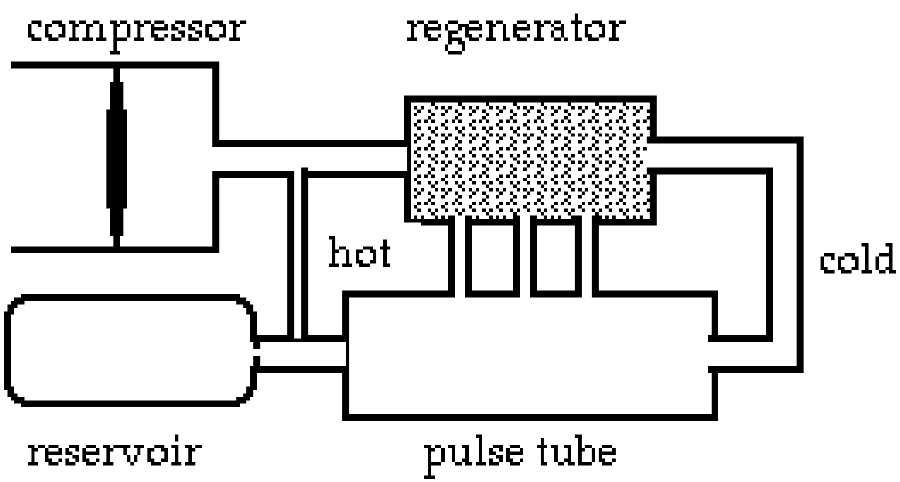
First reported by Prof. W. Gifford and his graduate student, R. Longsworth, of Syracuse University, 1963.

http://cryowwwebber.gsfc.nasa.gov/coolers/Ball/Ball.html

Modificações de PT



At the 1983, Dr. E. Mikulin (USSR) showed that the efficiency could be increased by inserting an orifice and reservoir at the hot end



The most important development has been the innovation of the double inlet Pulse Tube by Dr. Zhu et. al. of Xi'an Jiaotong University, China 1990.

http://cryowwwebber.gsfc.nasa.gov/coolers/Ball/Ball.html

PT para aplicações espaciais

Lockheed Pulse Tube Minicooler

The principal benefits are greater reliability and lower cost compared to the Stirling cooler and an order of magnitude lower mass, lower cost, and longer life than the current state of the art coolers: stored cryogens. Another benefit is that there are no cold moving parts which enhances life time and removes vibration causing components from the cold head. Additionally, Pulse Tubes use the same technologies as Stirling coolers.

http://cryowwwebber.gsfc.nasa.gov/coolers/Ball/Ball.html

PT para aplicações espaciais

TRW PT cryocooler: Low vibration, long life focal plane operation at 58 K . A fully redundant pulse tube refrigerator with each redundant assembly consisting of an actively balanced compressor, separate pulse tube coldhead, and independent control electronics

http://cryowwwebber.gsfc.nasa.gov/coolers/Ball/Ball.html

PT para aplicações espaciais

TRW PT cryocooler

Qdrive™ thermoacoustic cryocoolers are Stirling cycle machines that operate with no wearing parts and no lubrication needs. They are driven by two opposed balanced linear reciprocating CFIC STAR™ motors, giving them low-noise and low-vibration operation. 77K, 9kg, ~500W/8W

http://cryowwwebber.gsfc.nasa.gov/coolers/Ball/Ball.html

Cryocooler de sorpção

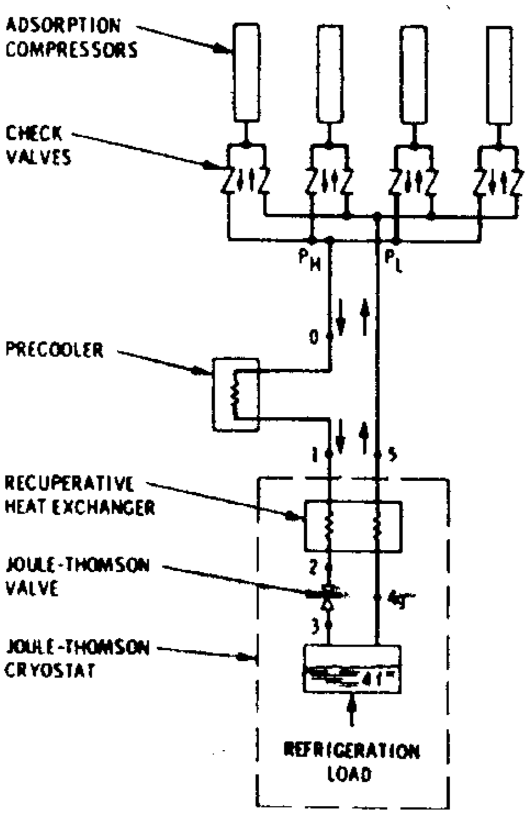


Figure 1a. Sorption cooler[1]

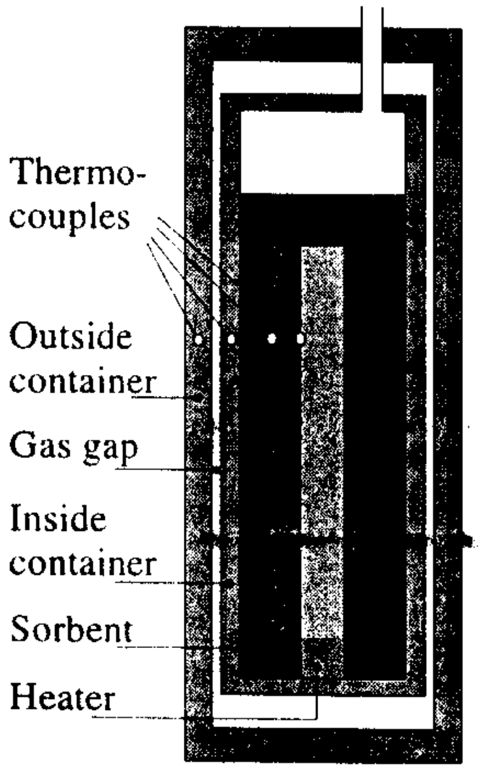


Figure 1b. Sorption compressor

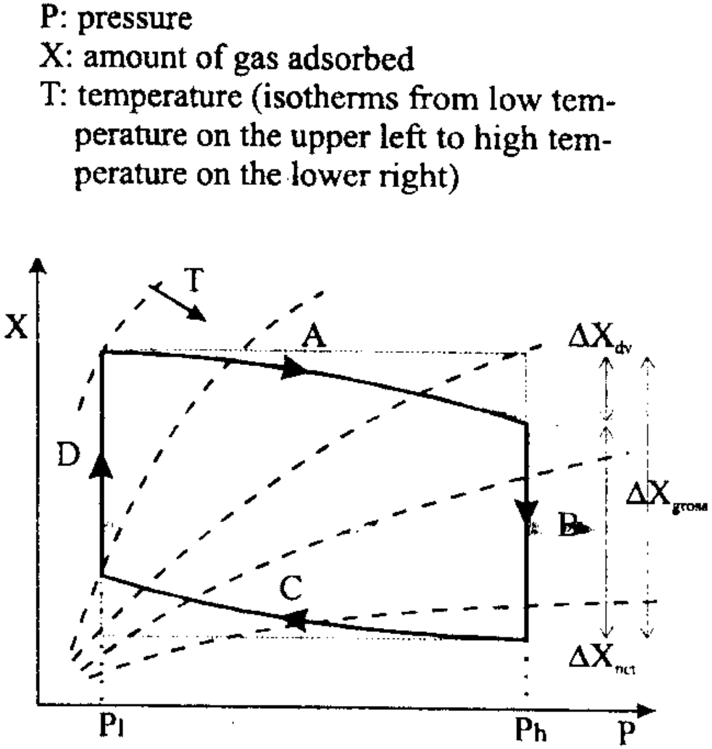
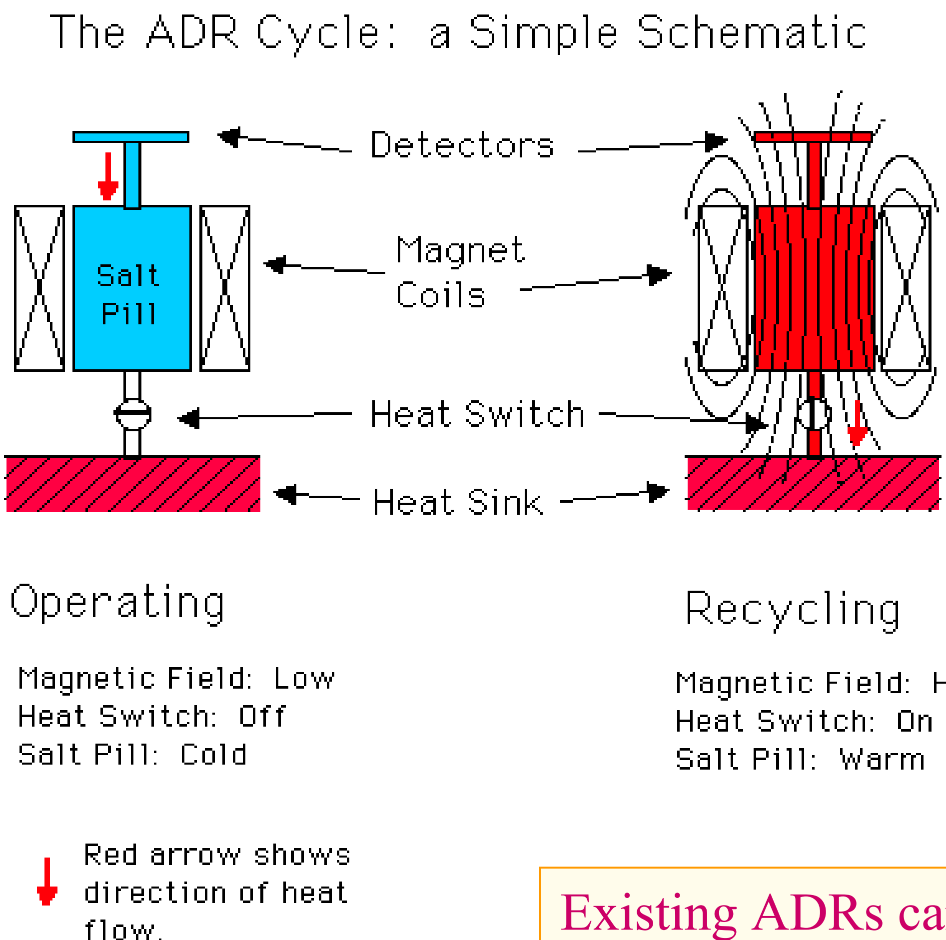
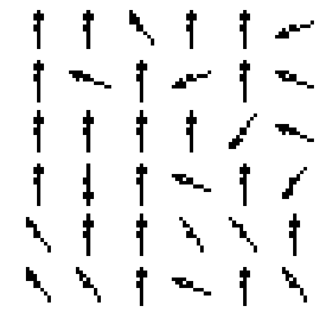


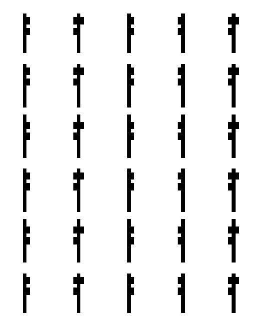
Figure 1c. Compressor cycle

1996 May 19 - STS-77... Brilliant Eyes Ten-Kelvin Sorption Cryocooler Experiment (BETSCE)

ADR Crycooler de <1.3 K

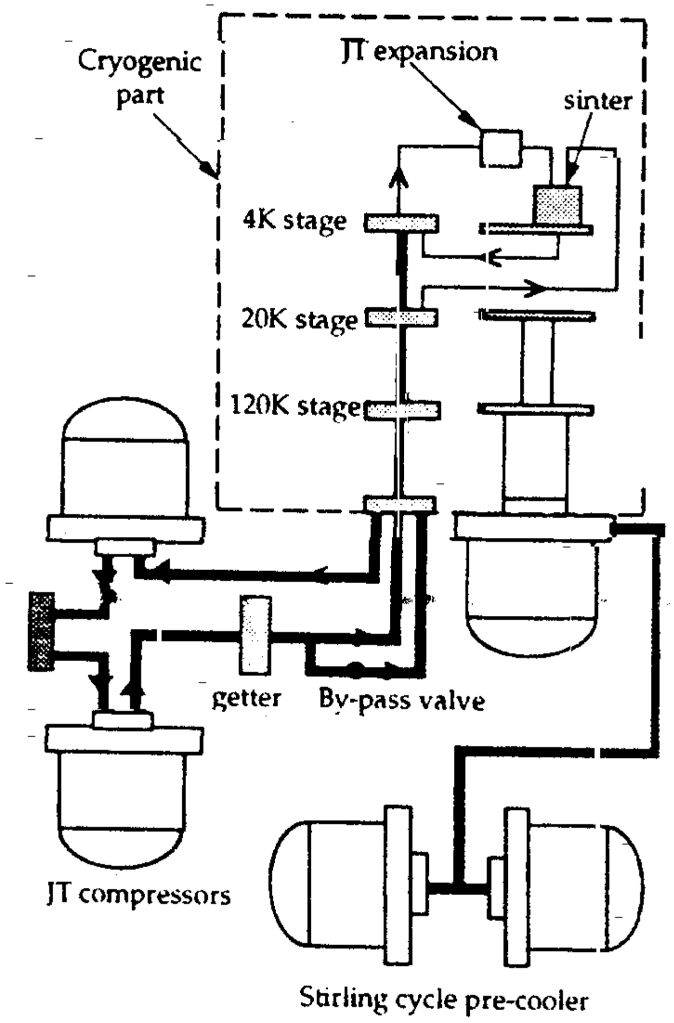




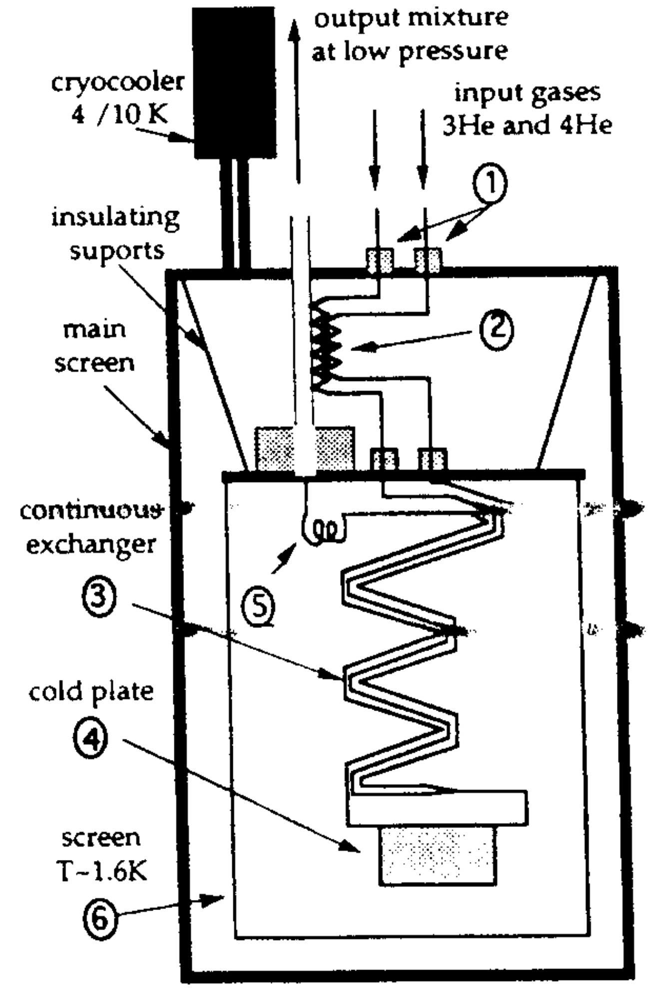


Existing ADRs can cool down to 70 millikelvin

Sistema de diluição de 0.1 K



Stirling ->
J-T fechado ->
diluição



Últimas tendências em desenvolvimento

- ADRs avançado
- Cryocoolers de sorpção
- PTs de Stirling
- Turbo-Bryton

Perspectives de aplicações

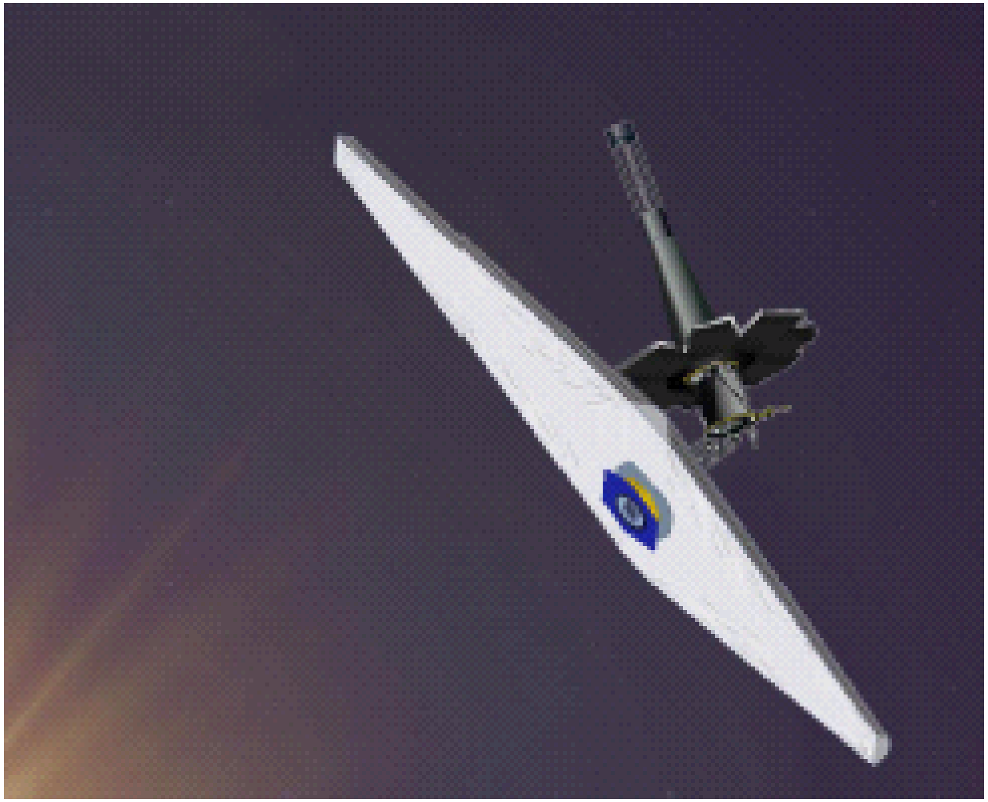


Figure 1. Concept drawing of a possible NGST configuration

Next Generation Space Telescope (NGST),
35K, 18K, 6K
L=~25m

NASA advanced cryocooler technology development program

Perspectives de aplicações

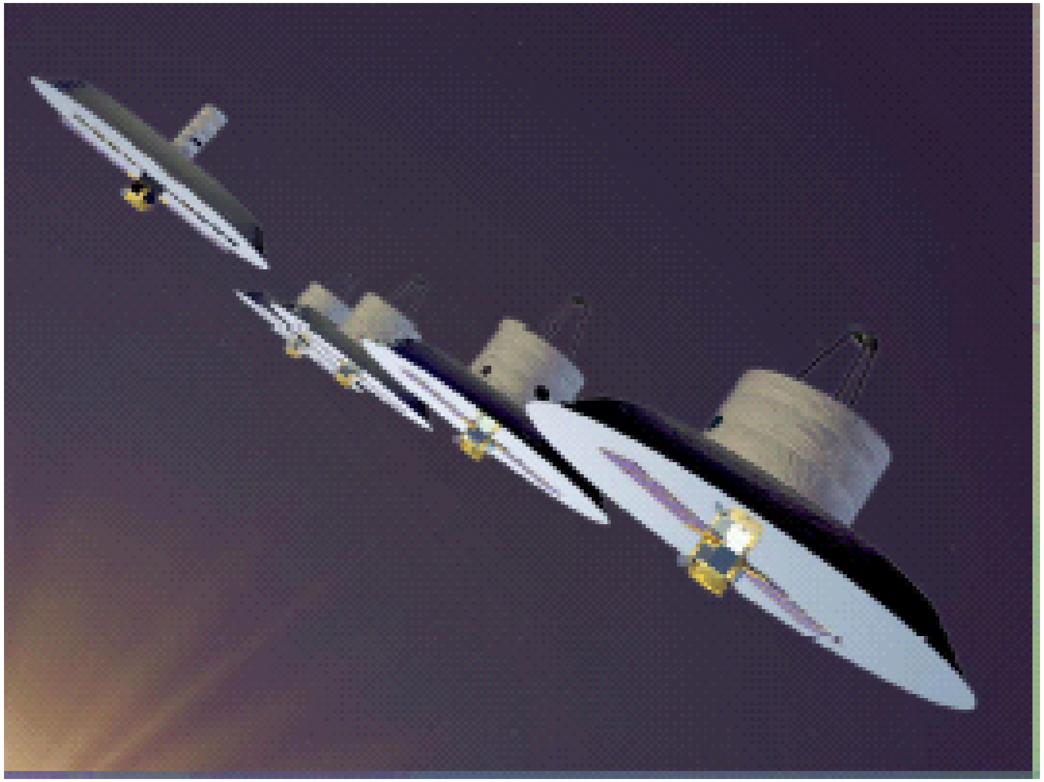


Figure 2. An artist's concept of the free-flying TPF constellation.

Terrestrial Planet Finder (TPF), 6K, 5..10 years

NASA advanced cryocooler technology development program

Programa avançado da NASA de cryocoolers

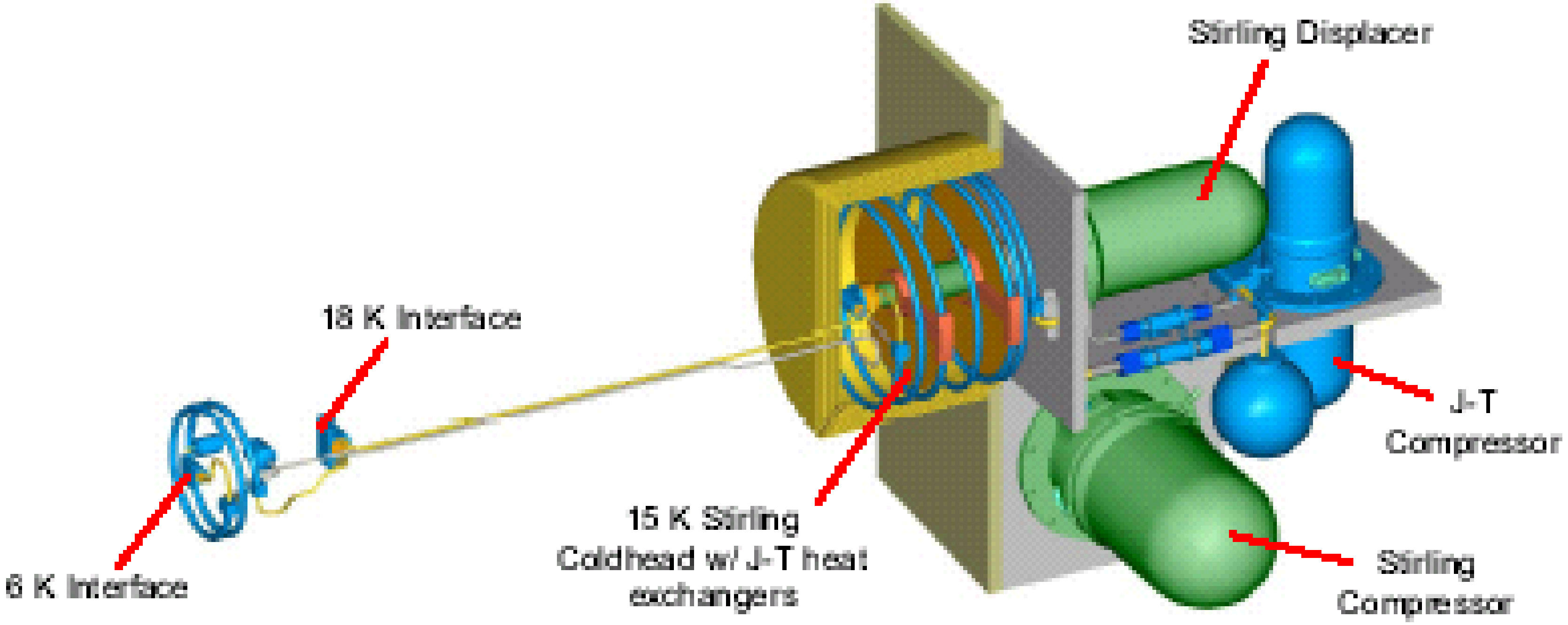


Figure 5. Ball Aerospace ACTDP Cryocooler Concept.

Programa avançado da NASA de cryocoolers

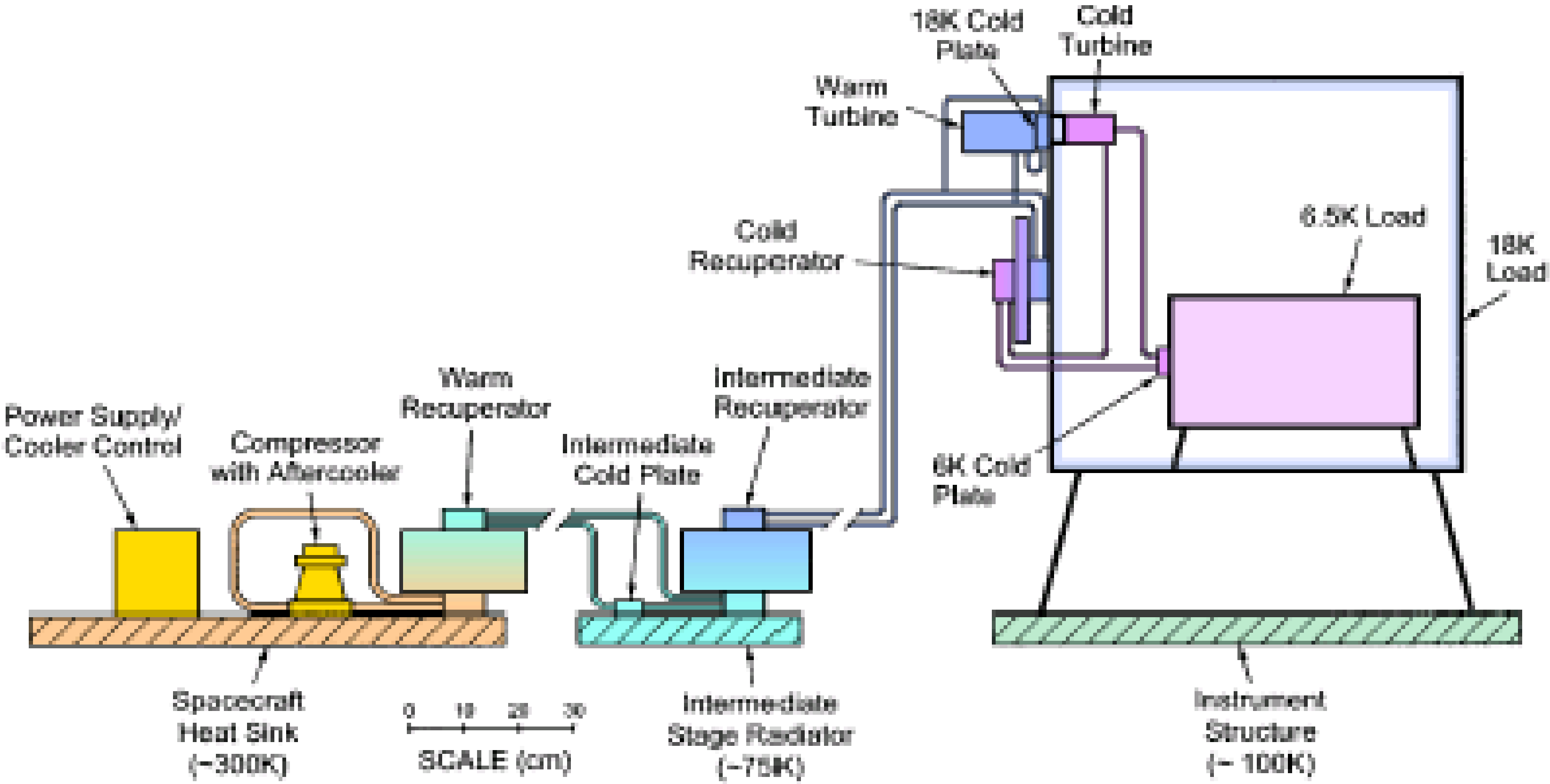


Figure 6. Creare turbo-Brayton ACTDP Cryocooler Concept.

Programa avançado da NASA de cryocoolers

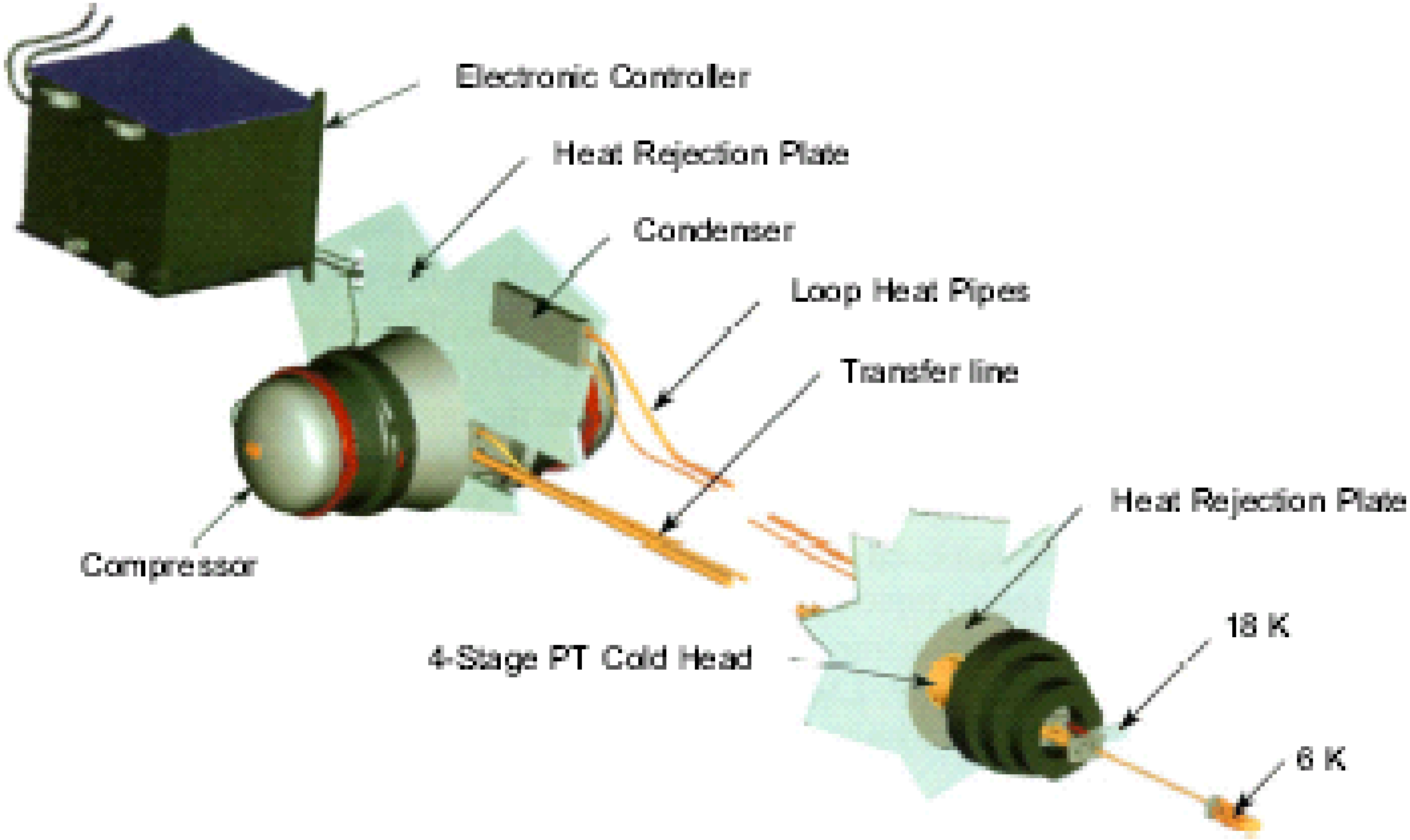


Figure 7. Lockheed Martin multistage pulse tube ACTDP cryocooler concept.

Programa avançado da NASA de cryocoolers

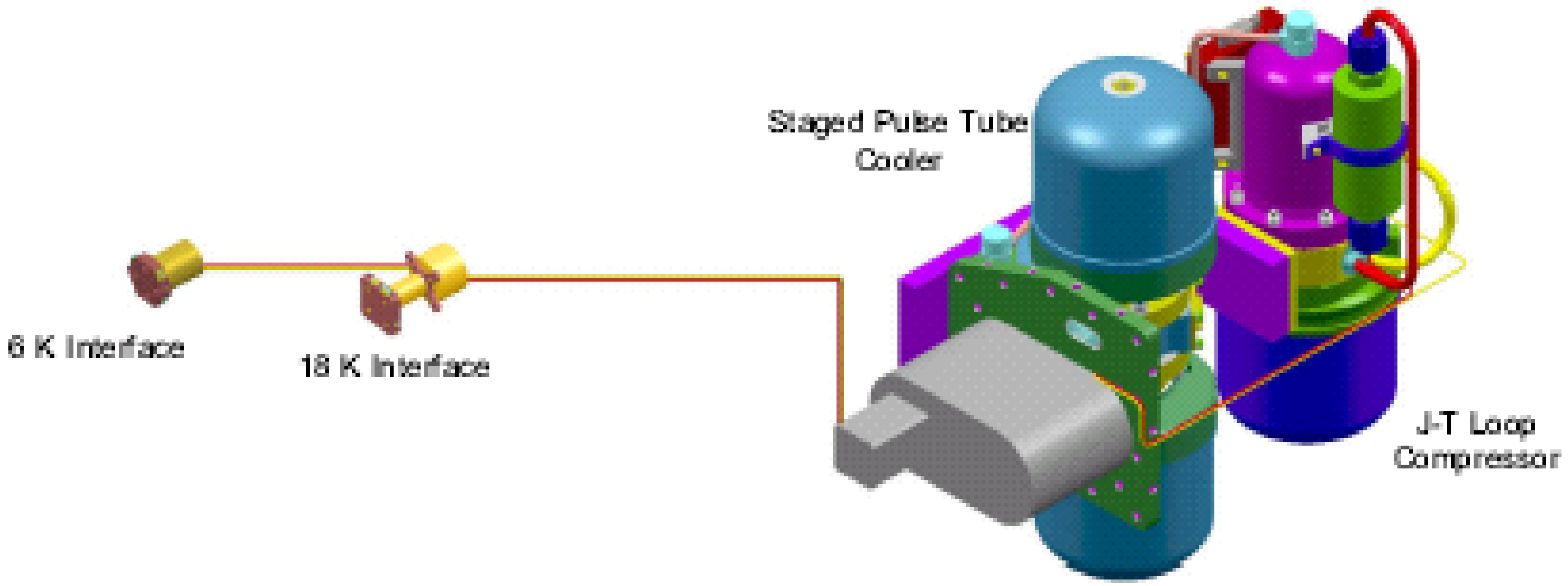
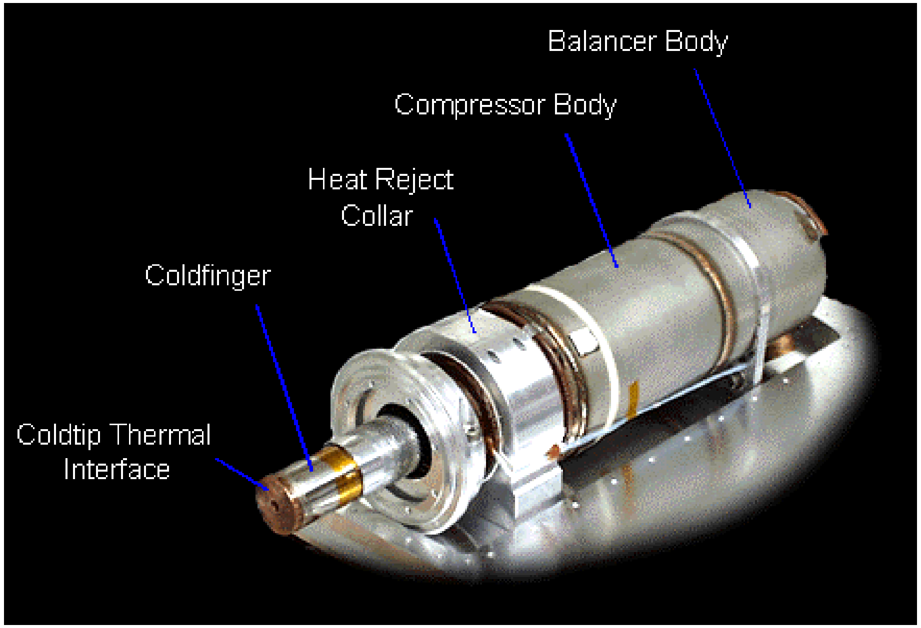


Figure 8. TRW ACTDP Cryocooler Concept.

PERGUNTAS



Sunpower Inc, Stirling linear, counterbalanced, 77K, 100W/4W