Cryocoolers for Space Applications

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Topics

- Space Cryocooler Historical Overview and Applications
- Space Cryogenic Cooling System Design and Sizing
- Space Cryocooler Performance and How It's Measured
- Cryocooler-Specific Application and Integration Example: The AIRS Instrument

Topics

- Technical Challenges to Achieving Long-life Cryocoolers
  - Operating needs of typical space detectors
  - Space cryocooler technology and reliability challenges
- Space Stirling Cryocooler Developments
  - The Oxford cooler and its spinoffs
  - Recent long-life space Stirling cooler developments
- Pulse Tube Cryocooler Developments
  - Operating principle and integration advantages
  - Recent developments and flight applications
- Closed-cycle J-T Cryocooler Developments
  - J-Ts based on mechanical compressors
  - J-Ts based on sorption compressors
- Brayton Cryocooler Developments

References

- Ross, R.G., Jr., "Aerospace Coolers: a 50-Year Quest for Long-life Cryogenic Cooling in Space," Chapter 11 of *Cryogenic Engineering: Fifty Years of Progress,* Ed. by K. Timmerhaus and R. Reed, Springer Publishers, New York, 2007, pp. 225-284 (130 references).

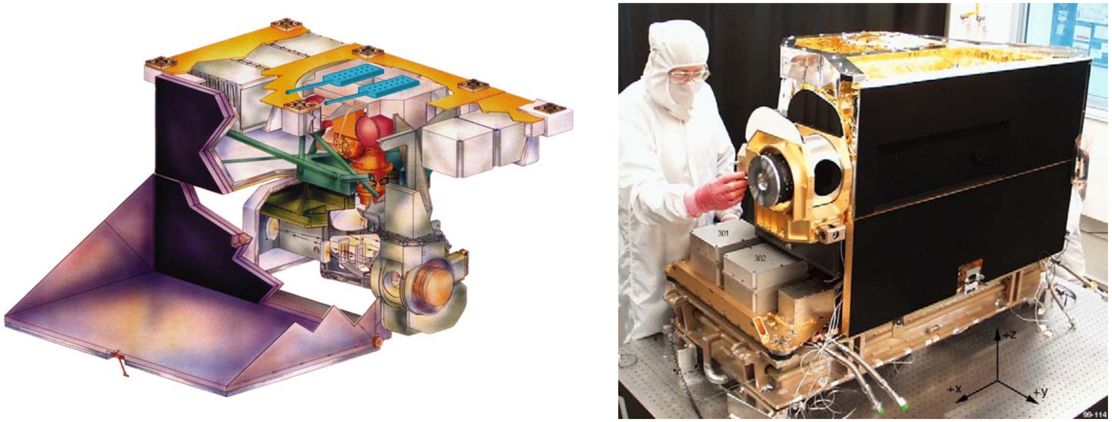
- http://www2.jpl.nasa.gov/adv_tech/ JPL website with 103 JPL cryocooler references as PDFs (R. Ross, webmaster)

- Donabedian, M., *Spacecraft Thermal Control Handbook, Vol. II: Cryogenics*, The Aerospace Press, El Segundo, CA, (2003). (641 pages)

- Donabedian, M., "Chapter 15: Cooling Systems," *The Infrared Handbook*, revised edition, IRIA Series in Infrared & Electro-Optics, George J. Zissis (Editor), William L Wolfe (Editor) (1993), pp. 15-1 to 15-85 (good history but dated).

Typical Cryogenic Uses in Space

- **Cryocoolers are an enabling technology for space missions viewing in the Infrared, gamma-ray and x-ray spectrums**
  - **Earth science (weather, atmospheric chemistry, air and ocean temperature distributions)**
  - **Planetary science (mineral distribution)**
  - **Space Astronomy (star formation, planet detection, origin of the universe studies, CMB, black holes)**
  - **Reconnaissance and missile defense**

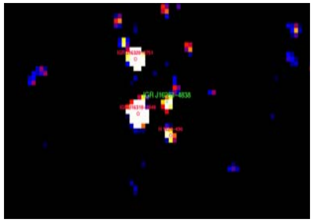


AIRS Earth-science instrument

SIRTF IR space telescope

Detector Technologies and Temperatures

Radiation Type	Wavelength (microns)	Blackbody Temp. (K)	Detector Technology	Detector Oper. Temp. (K)
γ-rays	10^{-5}	3×10^{8} K	Ge Diodes	80 K
γ-rays	10^{-4}	3×10^{7} K	Ge Diodes	80 K
x-rays	10^{-3}	3×10^{6} K	micro calorimeters	0.050 K
x-rays	10^{-2}	3×10^{5} K		0.050 K
UV	0.1	30,000 K	CCD/CMOS	200-300 K
visible	1	3000 K	CCD/CMOS	200-300 K
IR	2	1500 K	HgCdTe	80-130 K
IR	5	600 K	HgCdTe	80-120 K
LWIR	10	300 K	HgCdTe	35-80 K
LWIR	15	200 K	HgCdTe	35-60 K
LWIR	20	150 K	Si:As	6 -10 K
LWIR	50	60 K	Ge:Ga	2.0 K
LWIR/μwaves	100	30 K	Ge:Ga	1.5 K
microwaves	200	15 K	Bolometers	0.100 K
microwaves	500	6 K	Bolometers	0.100 K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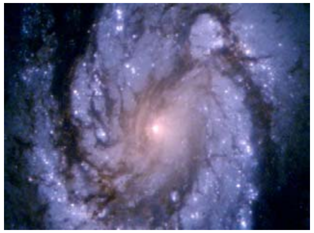
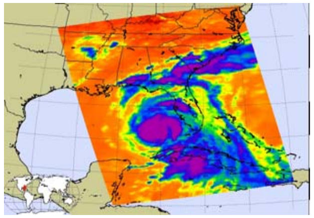
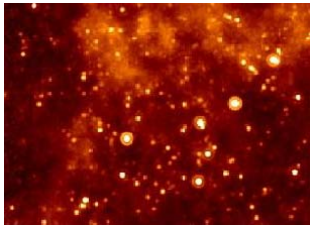
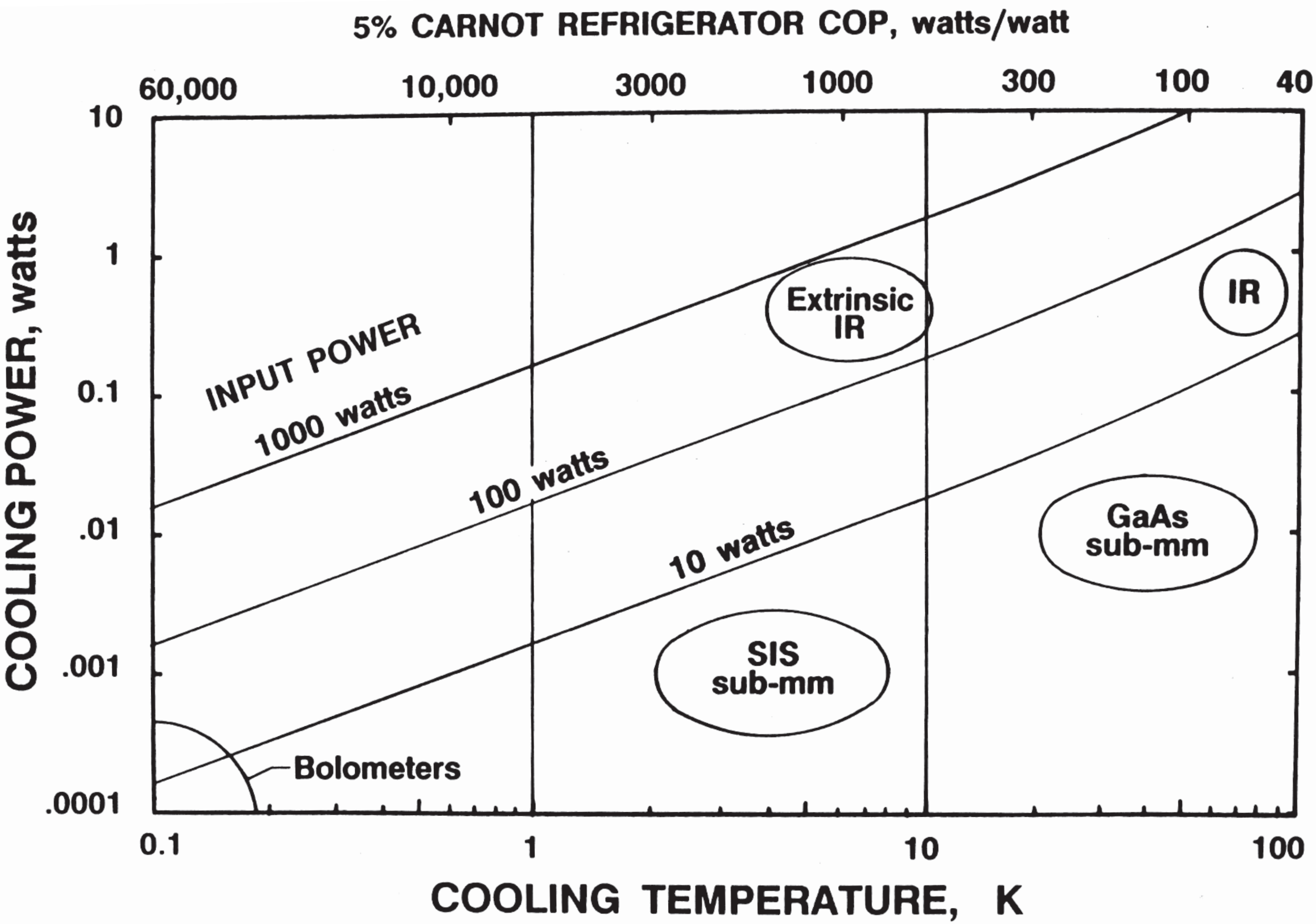

HST

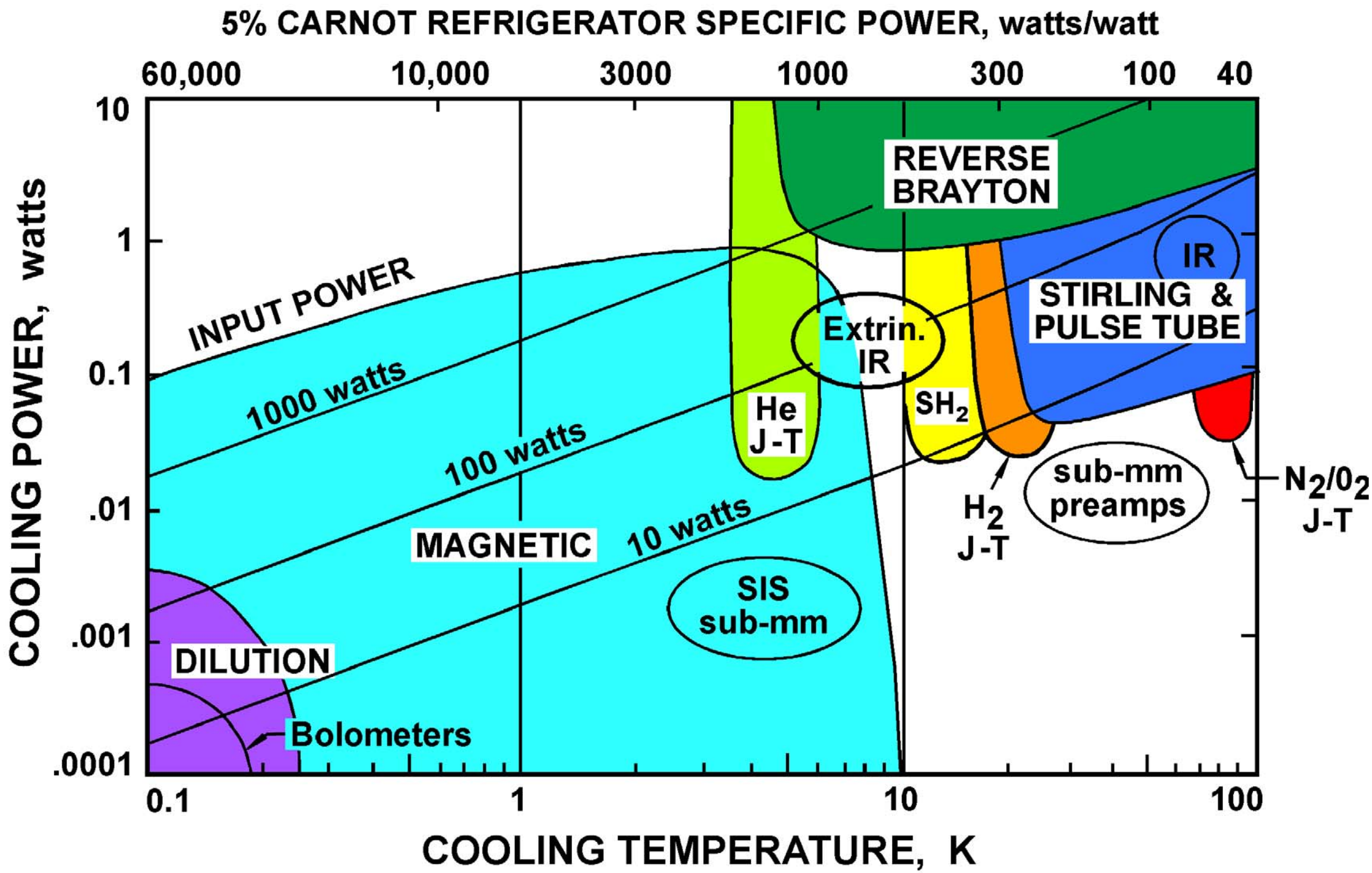

AIRS


SIRTF

Detector Cooling Requirements vs Cooler Temperature/Power Performance



Operating Regions of Cryocoolers vs Detector Cooling Requirements



Principal Space Cryocooler Development Challenges

- 5 to 10 YEAR LIFE with 0.95 RELIABILITY
  - This corresponds to 2,000,000 miles for an automobile with no breakdowns or servicing
- MINIMAL VIBRATION and EMI
  - Imaging instruments demand low levels of vibration and EMI
  - Goals are for induced vibratory forces to be below 0.05 lbs
- EFFICIENT THERMAL PERFORMANCE

Principal Reliability Issues

- Contamination and plugging of the cold-end by condensables
  - Contaminants in the as-filled working fluid
  - Desorbed gases from interior surfaces
  - Outgassing from polymers and porous materials
  - Products of wear and chemical decomposition
- Fatigue of structural elements
  - Piston and displacer support flexures
  - Electrical power leads to moving motor windings
  - Thin displacer cold-finger walls
- Wear due to misalignment of clearance seals
  - Assembly errors
  - Thermal deformations due to differential temperatures
  - Dynamic structural excursions
  - Structural warping from external loads and residual stresses
- Wear due to particulate contaminants
- Leakage of the working fluid

Stirling and Pulse Tube Cryocooler Technology Drivers

- Sensitive mechanical construction
  - Precision part fit and alignment
  - Fragile cold end construction
  - Strong sensitivity to leakage of working fluids (Helium)
  - Potential for cyclic mechanical fatigue

- High sensitivity to contamination
  - Lubricants or rubbing surfaces generate contaminants
  - Cold surfaces getter contaminants from all sources

- AC drive generates vibration and EMI

- Complex drive electronics to provide AC waveforms and closed-loop control of piston motions, vibration, and coldtip temperature

- Difficult failure analysis
  - Operation obscured by pressure vessels and vacuum jackets
  - Observation and rework require resealing, decontamination, and refilling -- generally requiring several weeks

Brief History of Cryocoolers in Space

- **50 Years to Achieve Long-Life Cryocoolers in Space**

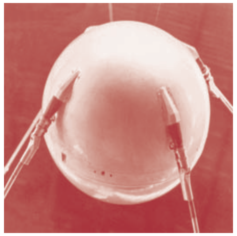
  1955 to 1965 — The Birth of the Space Program, First Satellites: Sputnik and Explorer

  1965 to 1975 — Man on the Moon; First cryogenics in space

  1975 to 1985 — Launch of the Shuttle; Struggle to achieve long-life coolers

  1985 to 1995 — Great Observatories in Space; Long-life coolers arrive

  1995 to 2005 — Mission to Planet Earth; Long-life cryocoolers achieve acceptance

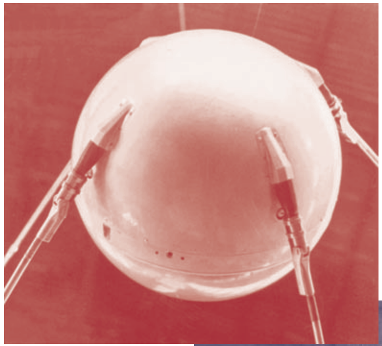




1955 to 1965

The birth of the space program — 50 years ago

- **The First Satellites Reach Orbit**
  - Sputnik launched in October 1957
  - Explorer launched in January 1958
- **Ranger Moon Shots 1961 to 1965**
- **First Earth Science Missions**
  - Nimbus 1 in 1964
- **First Planetary Flybys**
  - Mariner Venus 1962
  - Mariner Mars 1964
- **Advance Planning for Future Missions**
  - Fundamental physics (Gravity Probe B)
  - Earth science (weather, atmos. chemistry)
  - Planetary science (Mercury, Jupiter, etc)
  - Space Astronomy (IR, γ-ray, x-ray)
  - Reconnaissance and missile defense

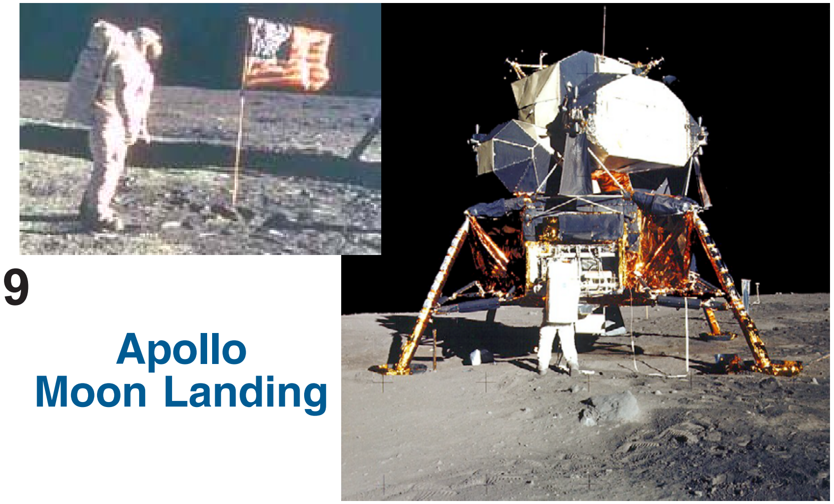


Sputnik 1

Explorer

1965 to 1975

Man on the Moon — First Space Laboratories



Apollo Moon Landing

- **To the Moon by 1970**
  - **Surveyor lander in 1967**
  - **Apollo moon orbiter in 1968**
  - **Apollo 11 "Man on the Moon" in 1969**
  - **Apollo 13 to 17 from 1970-72**

- **First Cryocoolers and Cryostats**
  - **First Stored Cryogen 1968 (Apollo Fuel Cell LH_2 and LO_2 Dewars)**
  - **First Cryogenically cooled Instruments**

    1969—Mariner 6 and 7 to Mars (N_2/H_2 22 K open-cycle J-T cooler)

    1971—Malaker Stirling and Hughes VM coolers on DoD flights

    1972—Lockheed Solid CO_2 on DoD's SESP 72-2

    1973—Malaker Stirlings on S-191 & S-192 Skylab instruments

    1975—Lockheed 2-stage CH_4/NH_3 cryogen on Nimbus 6

- **1975 Viking Mars Landing**

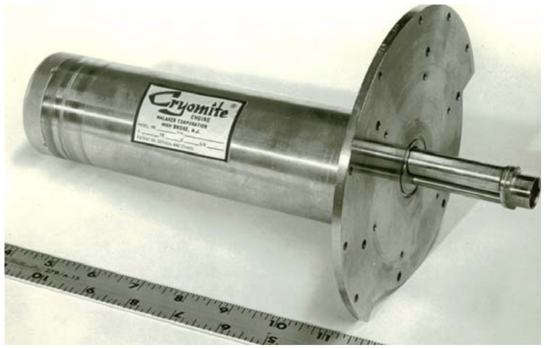
Viking Lander on Mars

First Coolers to Fly in Space

(1971 to 1975 — 40 years ago)

1971
Malaker Stirling

(2 W at 100 K)
(1000 hr Life)

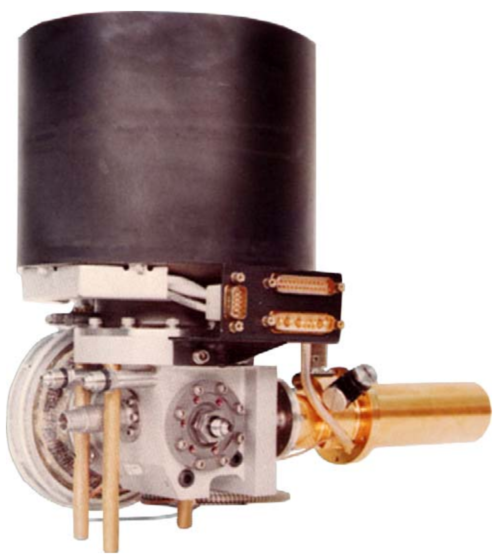


1972
Lockheed Solid CO_2

(230 mW at 126 K)
(7 month Life)

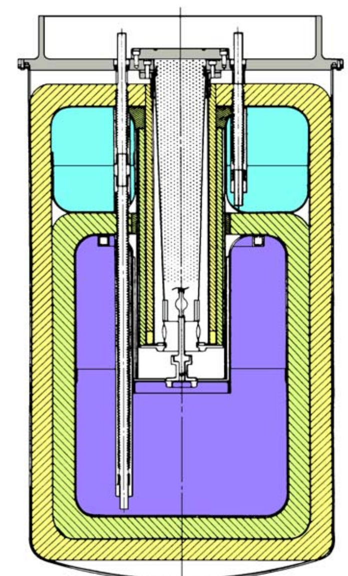
1971
Hughes 2-stage VM

(3.5 W at 60 K + 0.15W at 13K)
(500 hr Life)



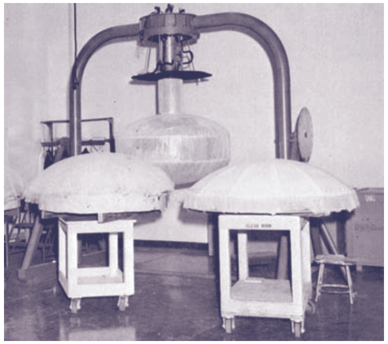
1975
Lockheed Solid CH_4/NH_3

(52 mW at 65 K)
(91 mW at 152 K)
(7 month Life)



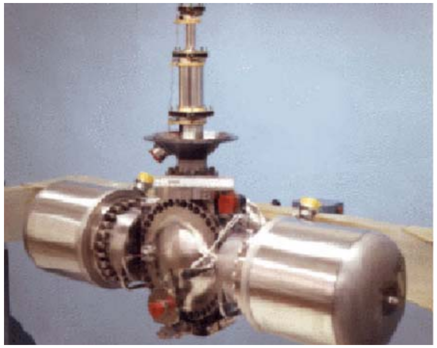
Primary R&D Emphasis
1965-1975

- **Solid cryogen dewars for 50-75 K**
  - **Thermal performance of MLI for dewars**



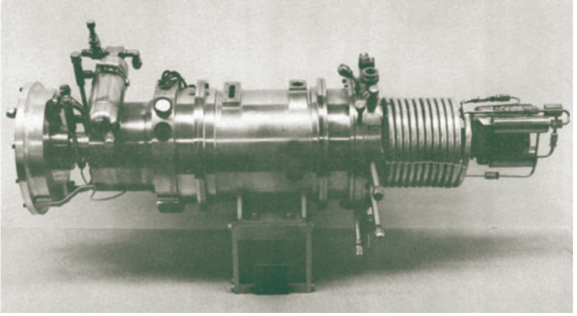
Lockheed MLI Testing

- **Long-life 1 and 3-stage Vuilleumier coolers for NASA and DoD**
  - **5 W at 75 K**
  - **Input power: Up to 2700 W**
  - **Developers: Garrett AiResearch, Philips and Hughes**



Hughes VM Cooler

- **Long-life turbo and Rotary Reciprocating Brayton coolers for DoD**
  - **1.5 W at 12 K + 30 W at 60 K**
  - **Input power: 2500 to 4000 W**
  - **Developer: General Electric and A.D. Little**

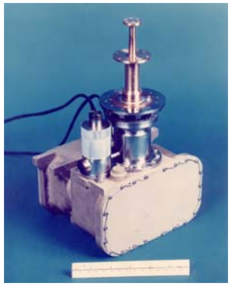


A.D. Little 77 K R^3 Brayton

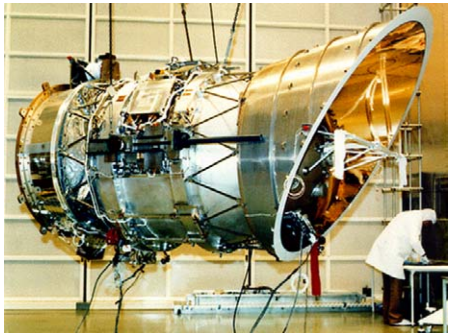
1975 to 1985

Launch of the Shuttle — Struggle for Long-Life Coolers

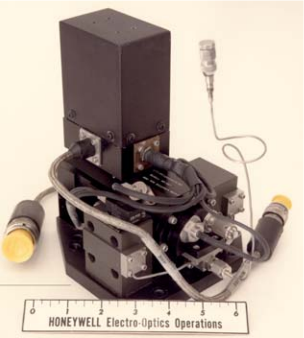
- **Continued Earth Science Cryogenic Missions**
  - **1978 Nimbus 8 (Lockheed 2-stage cryogen CH_4/NH_3)**
  - **1978 HEAO (Ball 2-stage cryogen CH_4/NH_3)**
  - **1979 STP 78-1 (Philips rhombic drive Stirling** (0.3W at 90 K + 1.5 W at 140 K ...13,000 hr Life)**)**
- **First Space Shuttle Launch (1981)**
- **First Super Fluid Helium Dewar**
  - **IRAS IR telescope (1983): 190 day life**
- **Spacelab Launch and Cryogenic Experiments**
  - **Spacelab 2 (1983): IRT SHe dewar**
  - **Spacelab 3 (1985): ATMOS (CTI Stirling Cooler** (3.5 W at 60 K + 0.15W at 13K (several 7-day flights)



Philips Rhombic Drive



IRAS SHe Dewar



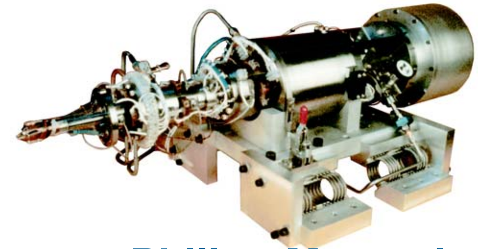
ATMOS CTI Cooler

Primary R&D Emphasis (1975 - 1985)

The Struggle for Long-Life Coolers Continues

Long-life Stirling Coolers for 60- 80 K

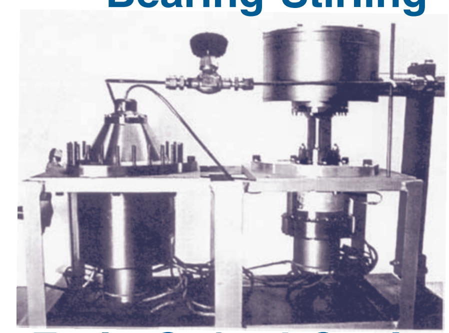
- Philips magnetic-bearing Stirling (5W at 60K)
- Flexure Stirling coolers at Oxford Univ. and RAL (0.5 W at 80K)



Philips Magnetic Bearing Stirling

Large Long-Life Missile Defense Coolers for 10-20 K

- 10K Turbo Brayton (1.5 W at 12K)
- 10K Rotary Reciprocating Refrigerator (R^3) (1.5 W at 12K + 40 W at 60 K; power < 2500 W)
- 3-stage Vuilleumier (0.3 W at 11.5 K + 10 W at 33 K + 12W at 75K; power: 2700 watts)
- Large Rotary Magnetic Refrigerators (Bridge cooling between 10 and 20 K)



Early Oxford Cooler

Long-life Sorption Coolers

- Charcoal/H_2 sorption refrigerators for 20 K
- LaNiH sorption refrigerators for 20 K

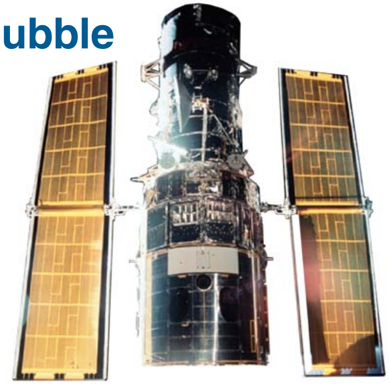
Garrett Turbo Brayton

1985 to 1995

Great Observatories & Long-life Coolers Arrive

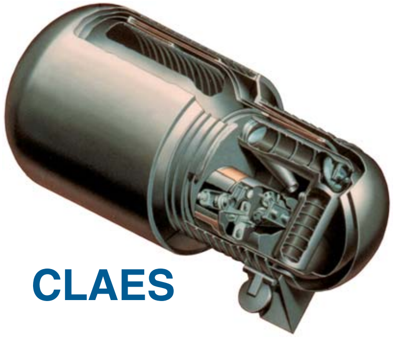
- **Hubble Space Telescope Launched (1990)**
- **First Long-Life Oxford Coolers in Space**
  - July 1991: ATSR-1 on ERS-1 (RAL 80K Stirling)
  - Sept 1991: ISAMS on UARS (Oxford 80K Stirling)
  - 1995: ATSR-2 on ERS-2 (RAL 80K Stirling)
- **Shuttle SF Helium Experiments (Lambda Point)**
- **Continued Large Stored Cryogen Telescopes**
  - 1989: COBE (Ball SF He dewar)
  - 1991: UARS CLAES (Lockheed 15K Ne/CO_2 cryostat)
  - 1995: ESA ISO (SF He dewar)

Hubble



Oxford cooler

COBE



CLAES

ISO

Primary R&D Emphasis (1985 - 1995)

A Dramatic Change in R&D Emphasis

Development Focus Takes a major turn toward smaller coolers

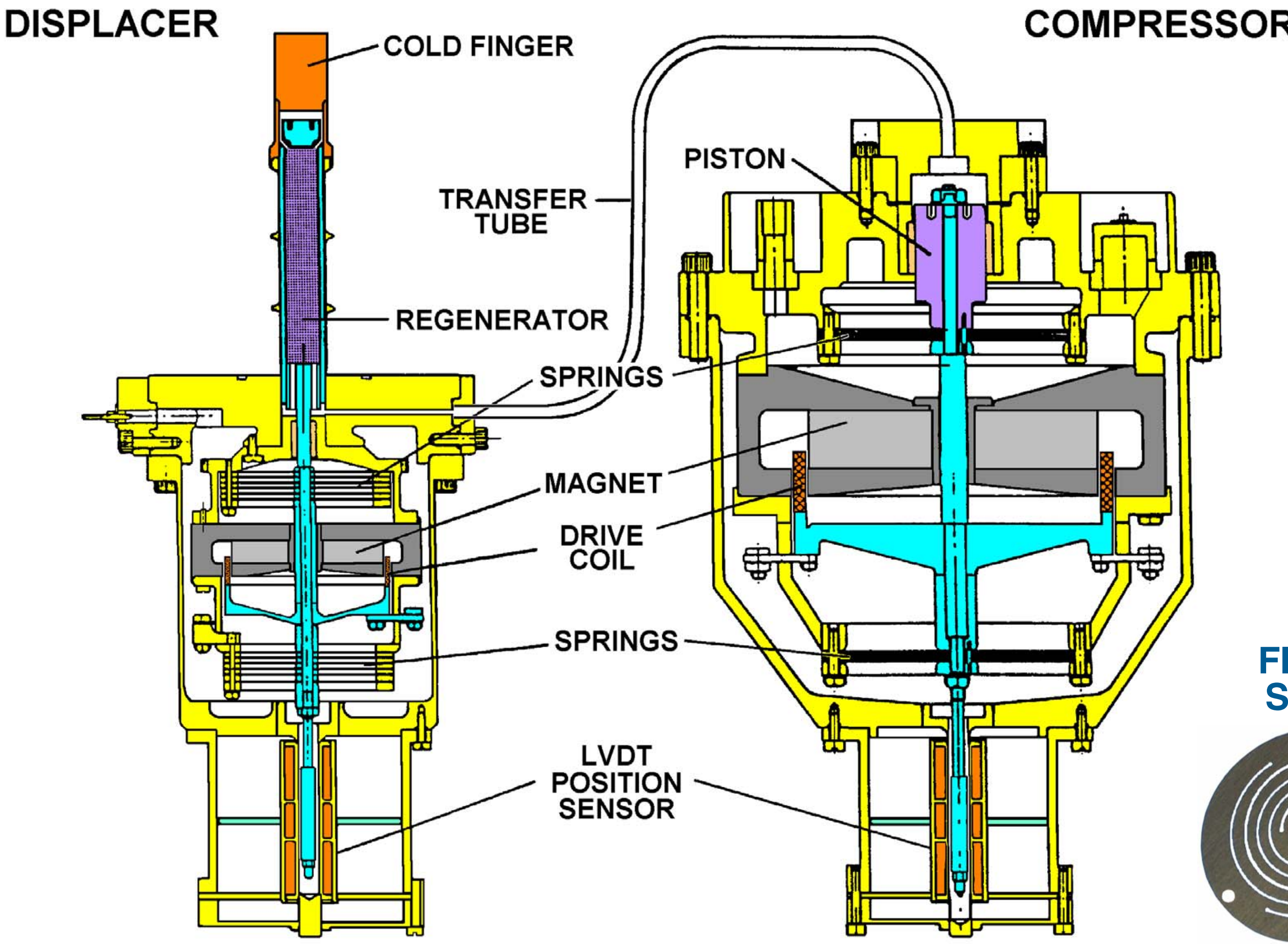
- **Large 10-20 K cooler efforts are abandoned**
- **BMDO starts Standard Spacecraft Cryocooler (SSC) effort (2W at 65 K)**
- **NASA prepares for up to 75 coolers needed for its "Mission to Planet Earth"**

Development Items:

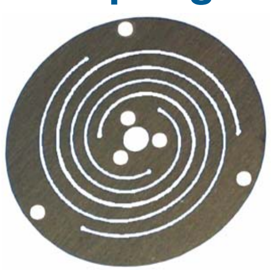
- **50-80K Oxford Stirling derivatives at BAe, Lockheed/Lucas, Ball, TRW, Hughes, Mitsubishi and Fujitsu**
- **Multi-Stage Oxford Stirling derivatives at RAL and Ball**
- **High-efficiency Pulse Tubes (TRW)**
- **65 K Turbo Brayton and Diaphragm Stirling at Creare**
- **65K (PCO) and 10K (LaNiH) Sorption (JPL, Aerojet)**

The Oxford Cooler

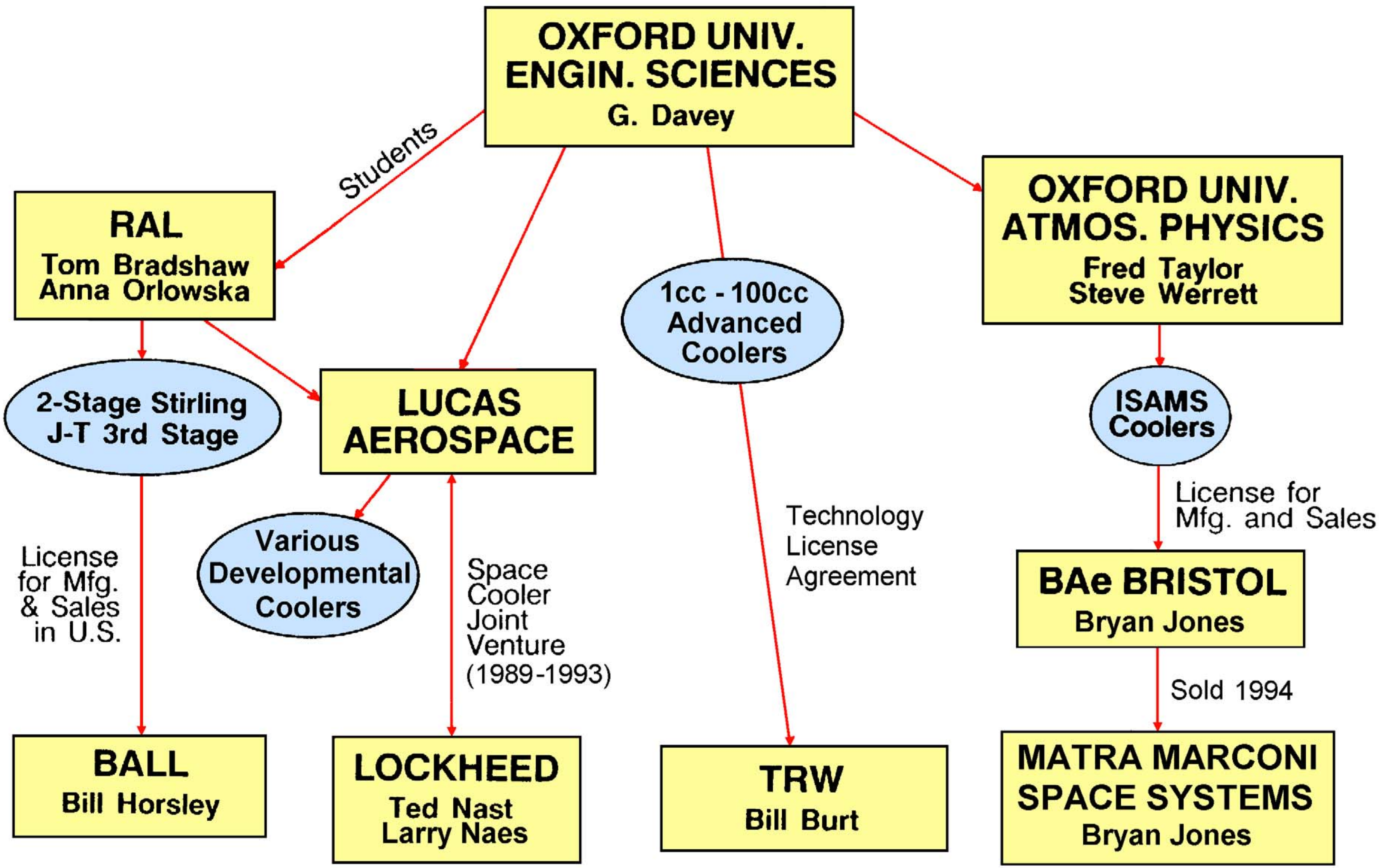
A Breakthrough Technology



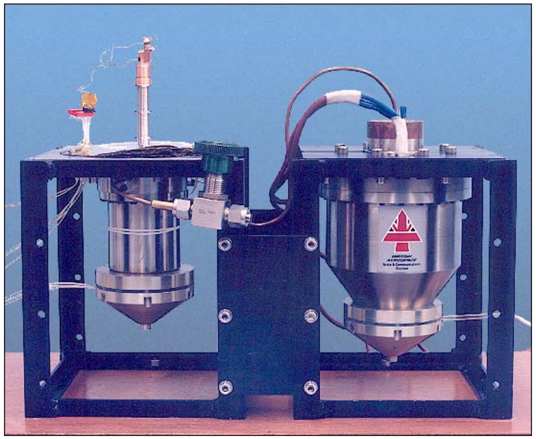
Flexure Spring



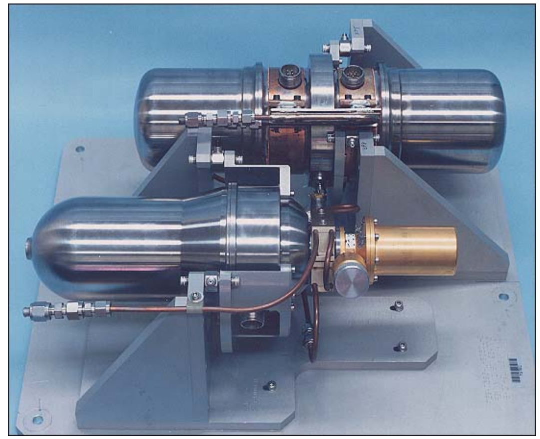
The Oxford Cooler Family Tree (1995)



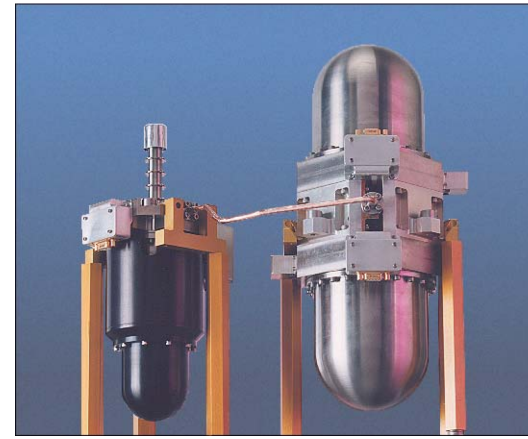
Oxford Heritage Stirling Cooler Developments (1985-1995)



BAe 50-80K

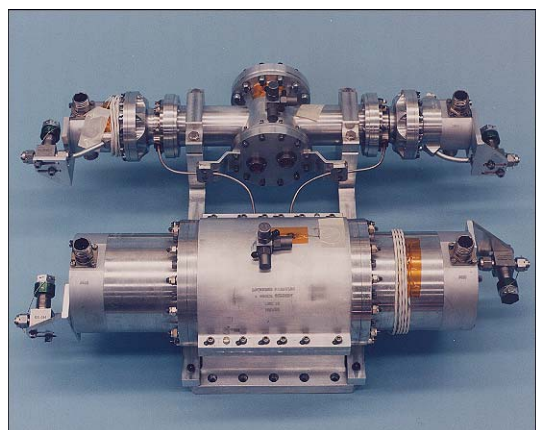


Hughes SSC 2W 60K

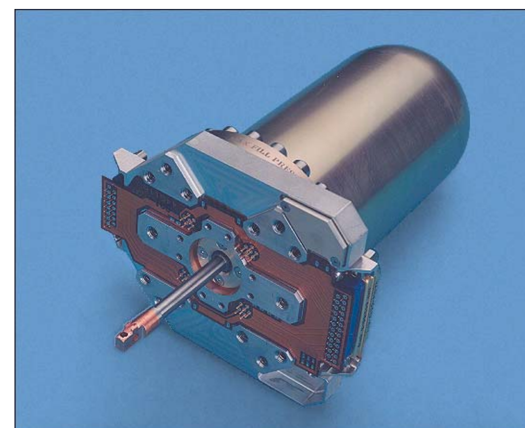


Ball 2W 60K

Lockheed



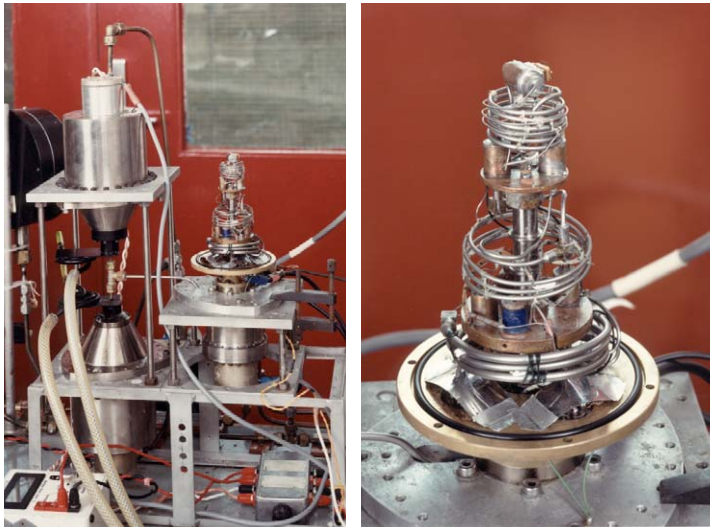
Lockheed SCRS



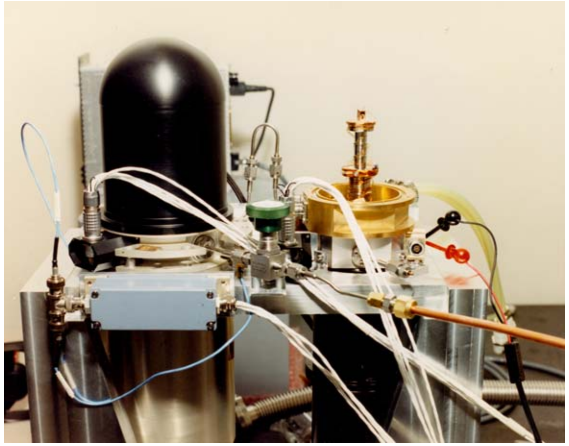
TRW

Multi-Stage Stirling Cooler Developments (1985-1995)

- **RAL 30 K 2-Stage Stirling**
  - EM level with lifetest unit
  - Transferred to BAe for production
- **RAL Hybrid Stirling/J-T for 4K cooling**
  - RAL 30 K 2-stage Stirling upper stage
  - Two-stage Oxford-compressor with reed valves for 4 K J-T bottom stage
  - EM level development with lifetest unit
- **Ball 30 K 2-Stage Stirling**
  - Re-engineered version of RAL unit
  - Targeted for EOS SAFIRE instrument

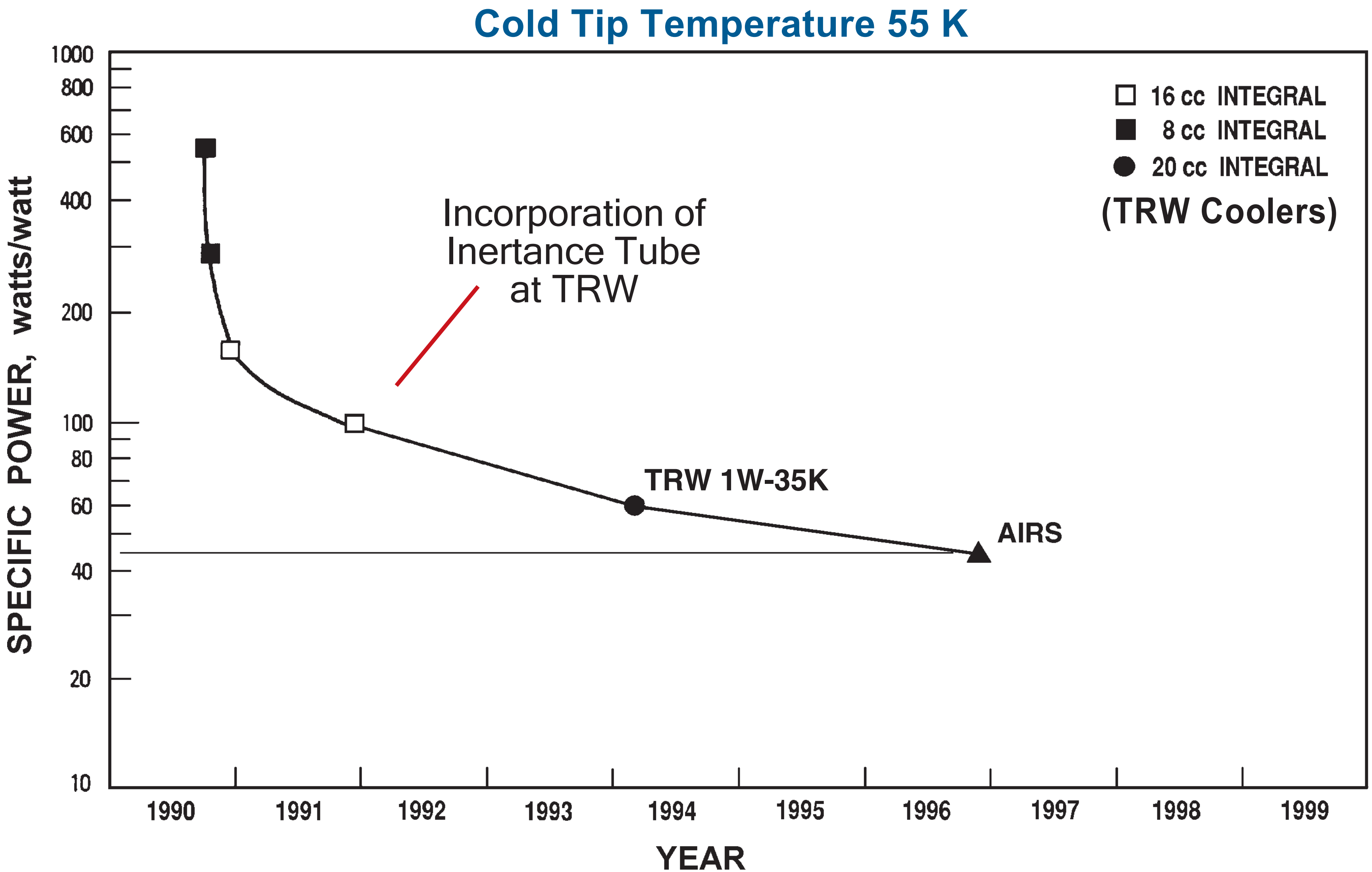


RAL 4K Brassboard Cooler

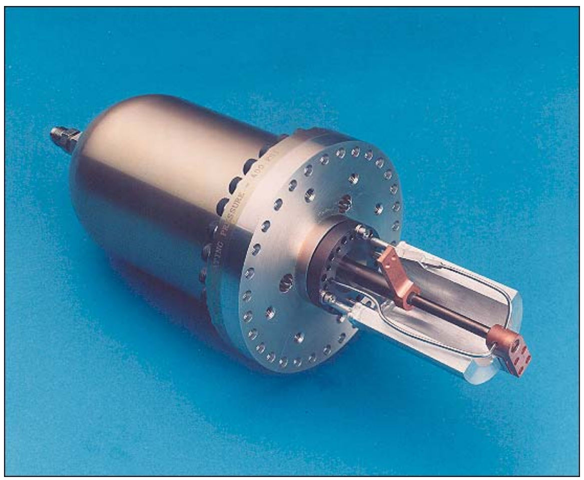


Ball 30K Cooler

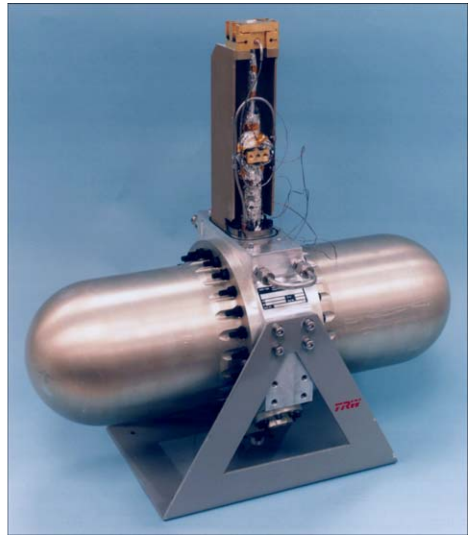
Rapid Development of the Pulse Tube Occurred in the 1991 Time



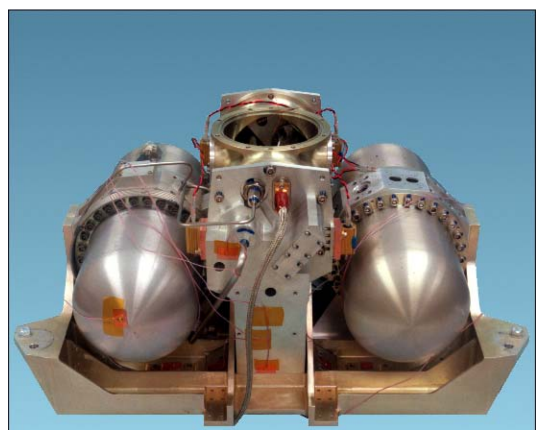
Oxford-Heritage Pulse Tube Cooler Developments (1985-1995)



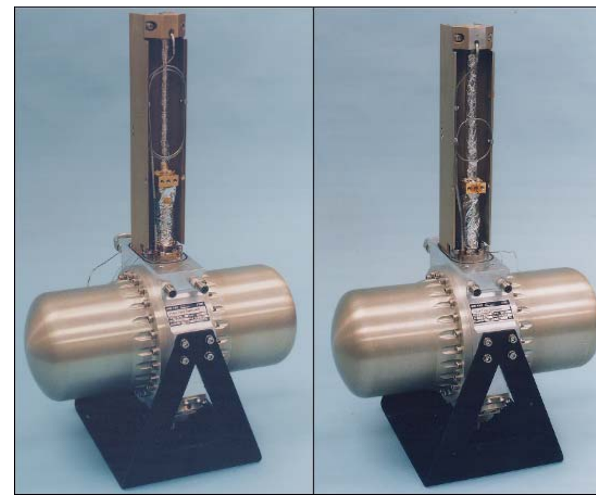
TRW Mini PT
1W at 80K



TRW 1W 35K

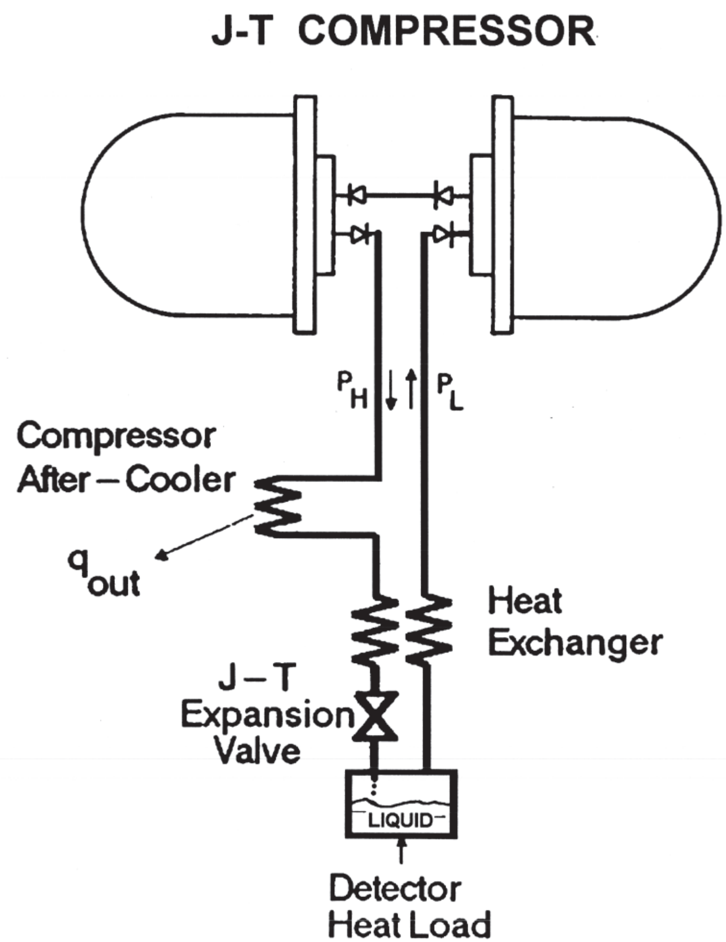


TRW AIRS



TRW 6020 and 3503
2W at 60K, 0.35W at 35K

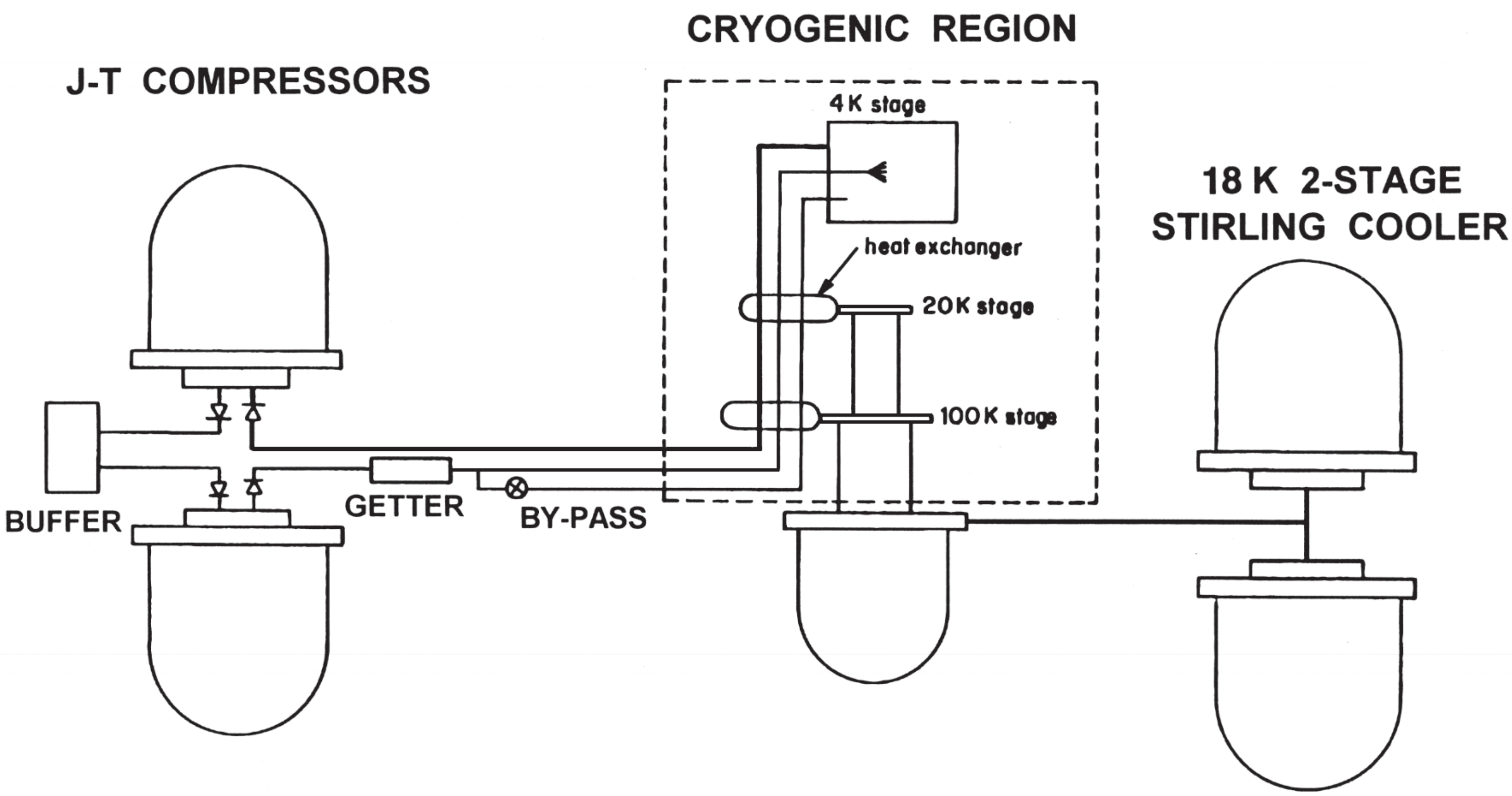
Closed-Cycle Joule-Thomson Cooler Schematic



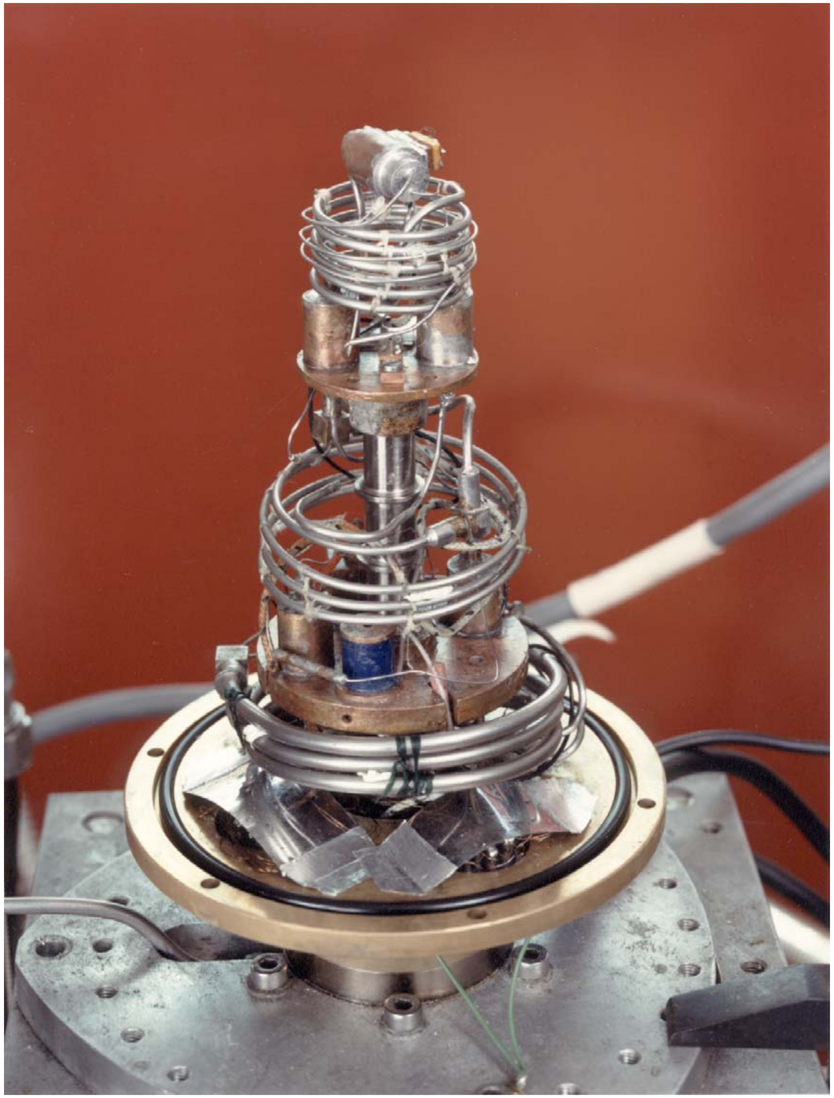
Closed-Cycle J-T Coolers for with Temperatures from 3 to 80 K

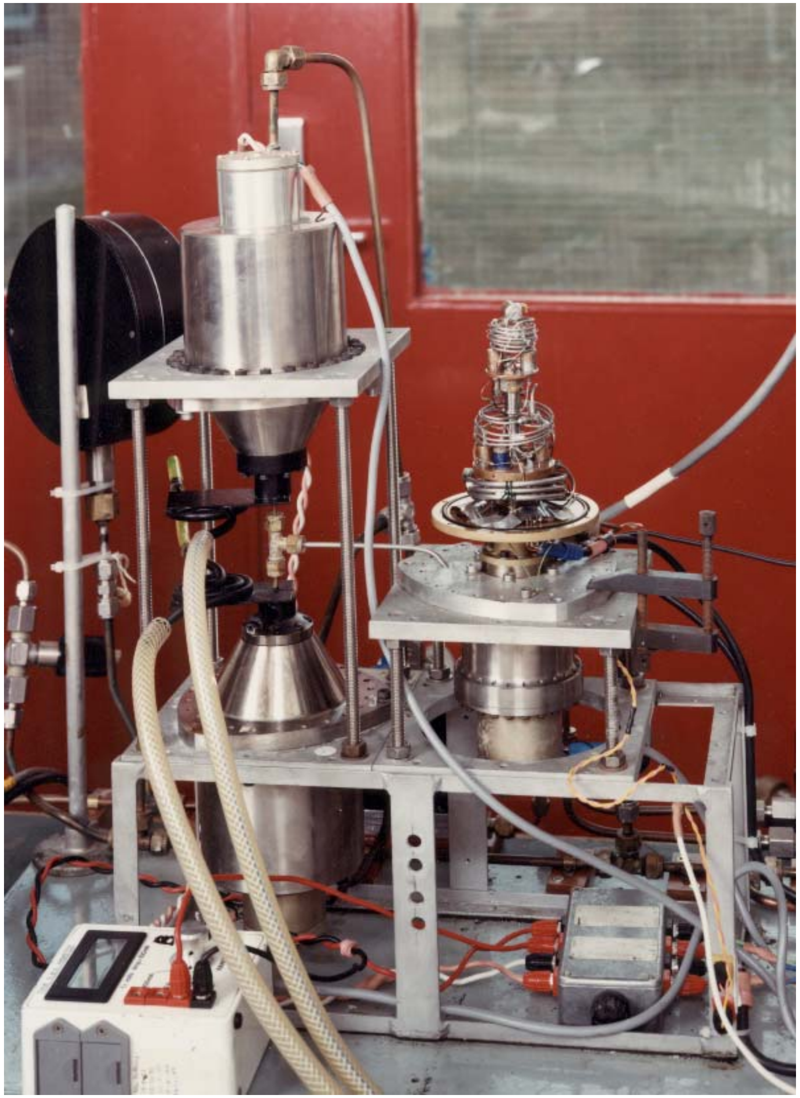
COLD-TIP TEMPERATURE	REFRIGERANT FLUID	COMPRESSOR TYPE
60 - 80 K	• Nitrogen & mixed gases	• Oil lubricated Pistons
18 - 30 K	• Hydrogen	• Sorption
10 - 14 K	• Solid Hydrogen	• Sorption
4 - 6 K	• Helium 4	• Oxford w/ Valves
3 - 4 K	• Helium 3	• Oxford w/ Valves

RAL 4K Closed-Cycle J-T Cryocooler

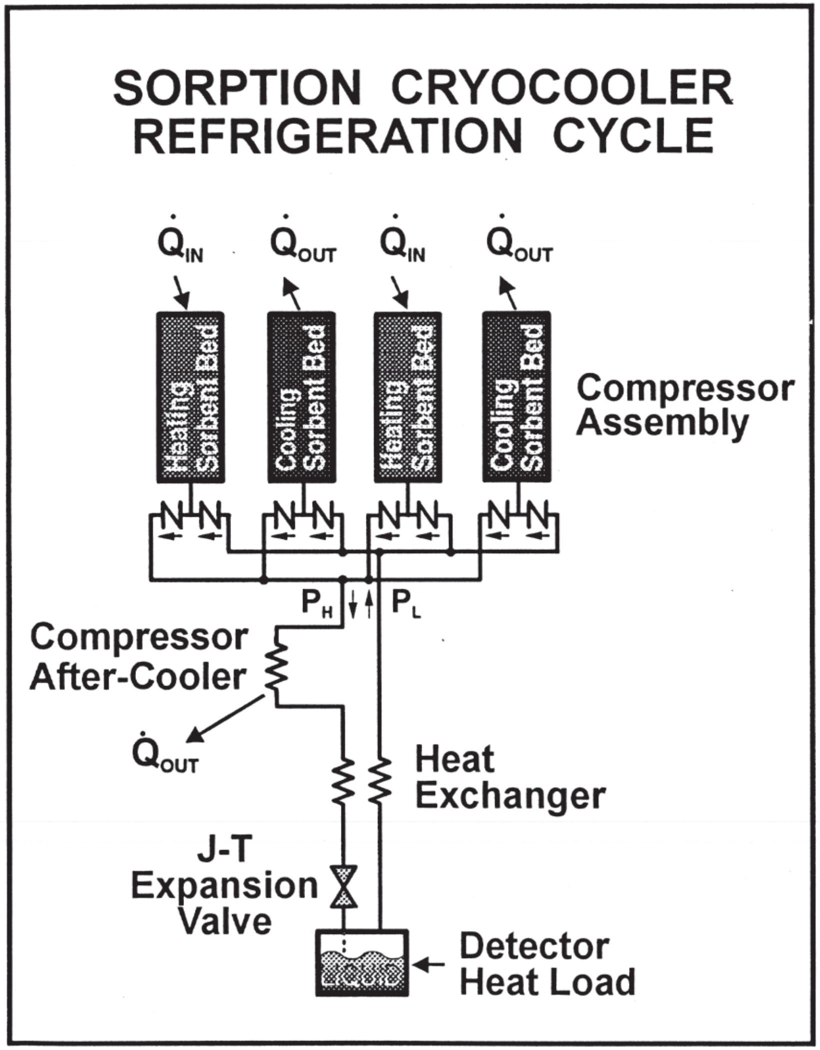


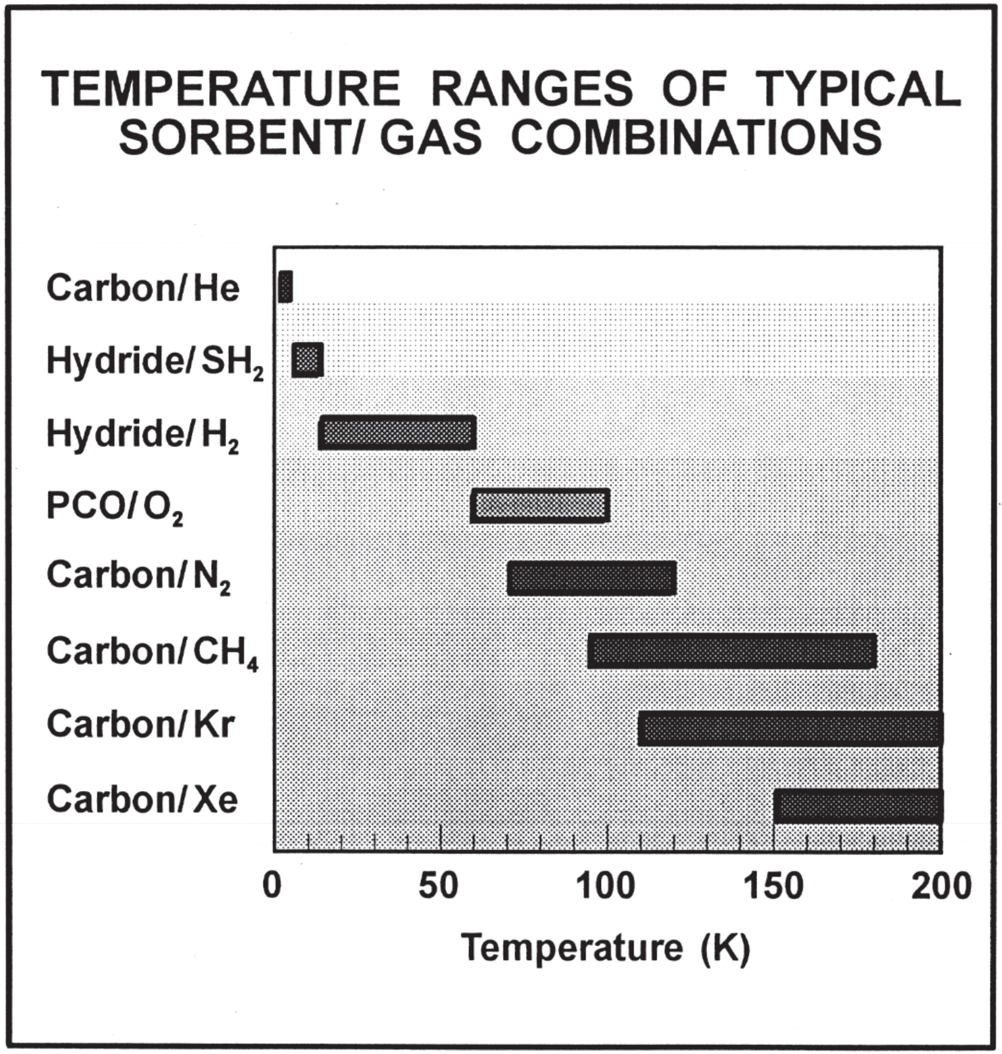
RAL 4K Breadboard J-T Cryocooler



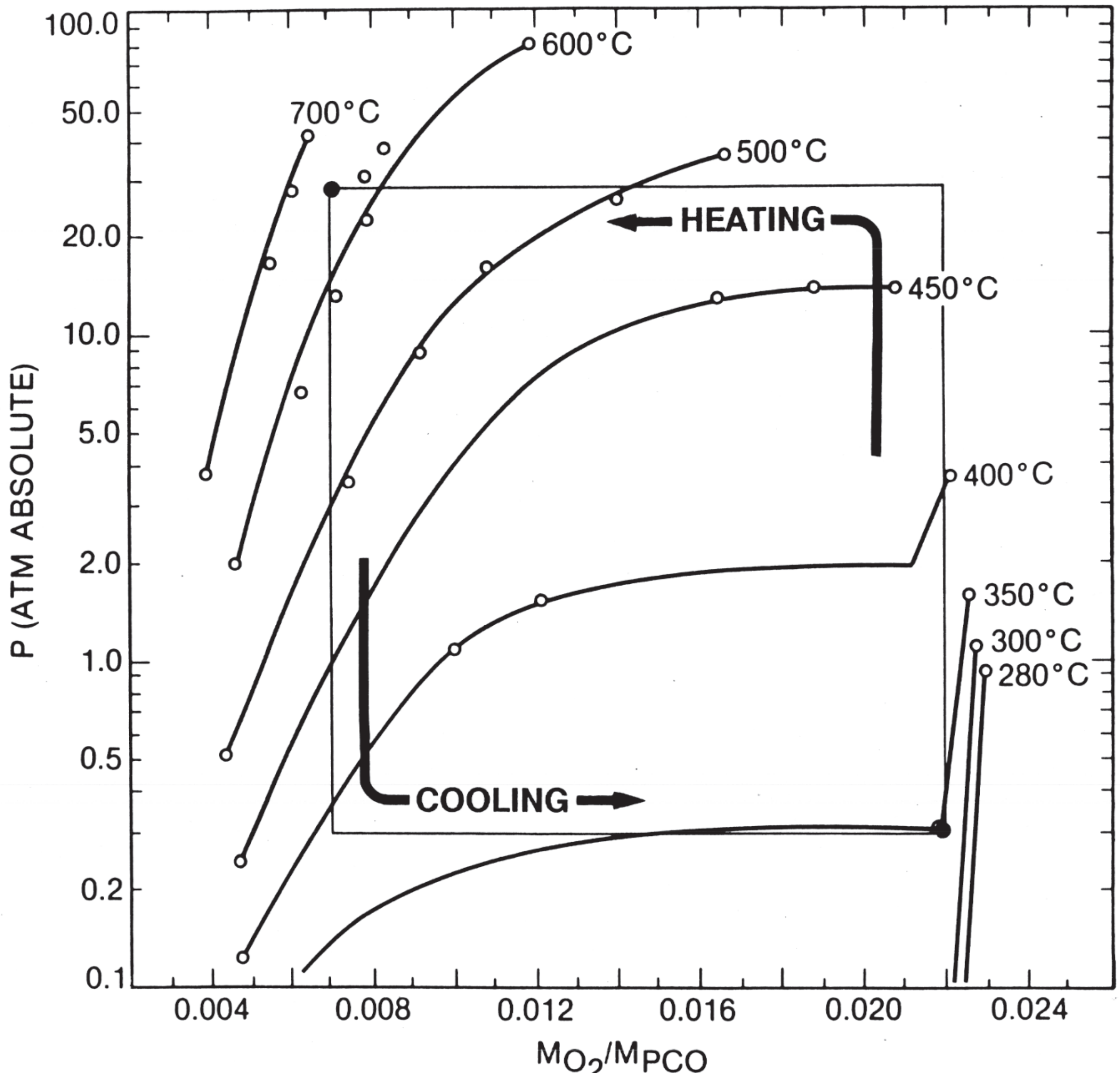


Sorption Cryocooler Operation





Typical Sorption Isotherms (Praseodymium-Cerium-Oxide/O_2)

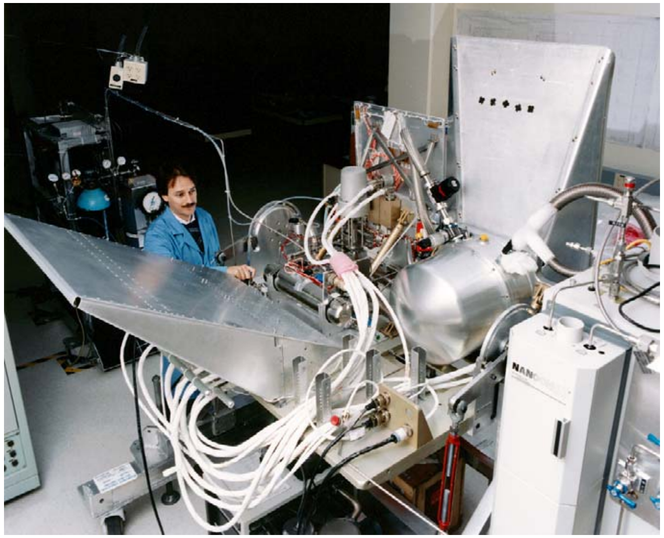


Sorption Cooler Developments (1985-1995)

- **HIMS 65K PCO Development cooler for Hubble IR Camera (1W at 70K)**
  - 70K Praseodymium Cerium Oxide lower stage
  - 130K Saran Charcoal upper stage
  - EM level development with lifetest unit

HIMS Sorption Cooler

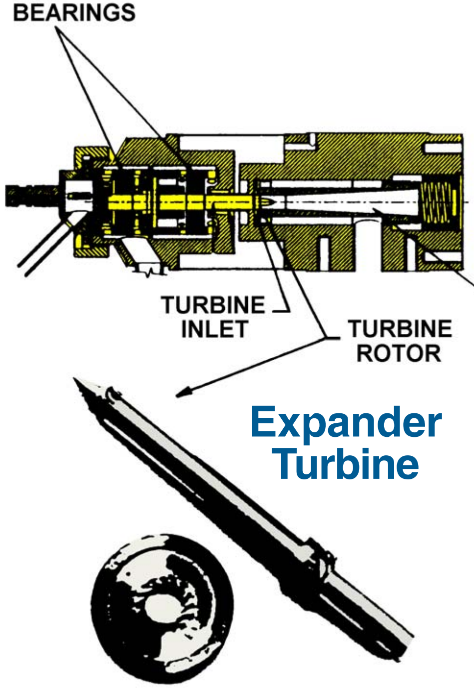
- **Brilliant Eyes 10K Sorption Cryocooler (BETSCE)** (150mW at 10K)
  - 10K Hydride lower stage
  - 80 K Stirling cooler upper stage
  - Test flight in space on shuttle STS-77 in 1996



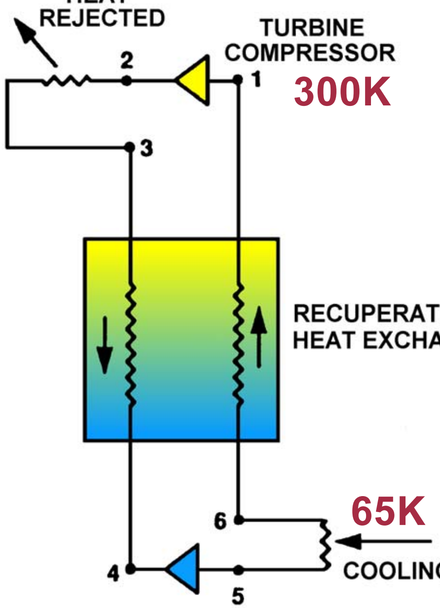
BETSCE 10K cooler

Turbo-Brayton Cooler Developments (1985-1995)

- **Creare Turbo-Brayton** (7W at 65K)
  - Joint funding from NASA GSFC and DoD
  - Engineering Model development with lifetest unit
  - Minimal vibration: 800,000 rpm



Expander Turbine



Creare Turbo Brayton

1995 to 2005

Long-life cryogenics achieves acceptance

Long-life cryocoolers achieve widespread acceptance

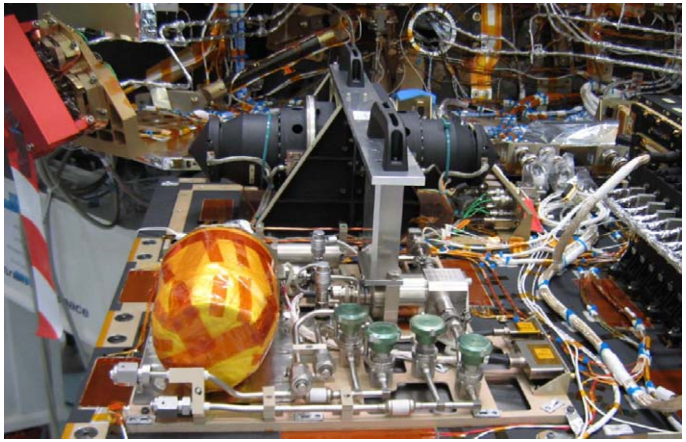
- Over 20 long-life Oxford-class coolers are in orbit by 2005 on a wide variety of US, ESA, and Japanese space missions
- The longest have been operating full-time for 7-10 years

- **Stored cryogen systems continue for applications below 10K**
  - 1996: MSX (Lockheed 10.5 K solid H_2 cryostat)
  - 1997: NICMOS (Ball 65 K solid N_2 cryostat)
  - 1999: WIRE (Lockheed 7 K solid H_2 cryostat)
  - 2003: SIRTF (Spitzer) (Ball SF He dewar)
  - 2003: GPB (Lockheed SF He dewar)
  - 2005: XRS (GSFC ADR cooled by SF He/solid Ne cryostats)

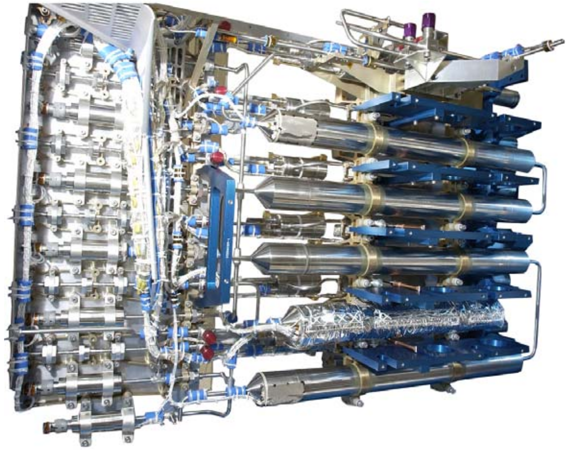
- **Development is shifted to cryocooler performance optimization**
  - Vibration and EMI reduction
  - Lower mass & size, increased efficiency
  - Expanded range of cooling capacities and temperatures
  - Hybrid coolers for 4-6 K cooling
  - Sub-Kelvin coolers for bolometer and x-ray detectors

JPL Planck 18 K Sorption and RAL 4 K JT Cooler (2009 Launch)

- Planck mission of the European Space Agency; Launched May 2009
  - Very high resolution mapping of temperature anisotropy in the CMB
- Two JPL hydrogen sorption cryocoolers
  - Cool the LFI detectors to 18 - 20 K
  - Precool RAL 4 K helium J-T for HFI
- RAL Oxford-style 4 K J-T cooler
  - Precool the HFI dilution cooler to 4.2 K



RAL Planck 4K J-T Cooler



JPL Planck Sorption Cooler

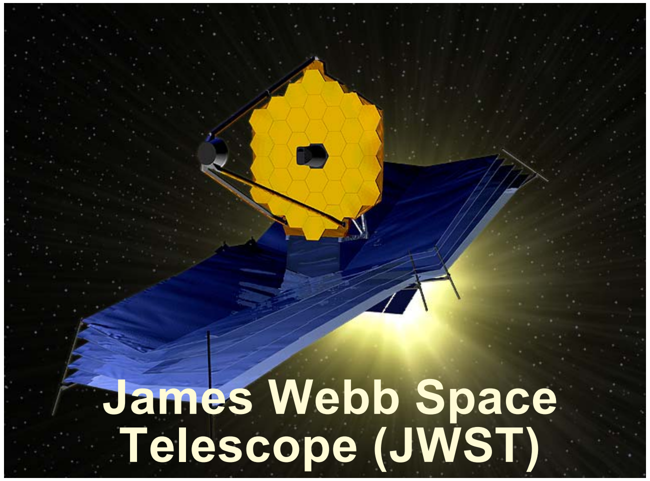
Recent Long-Life Space Cryocooler Flight Operating Experience (Oct. 2013)

Cooler / Mission	Hours/Unit	Comments
Air Liquide Turbo Brayton (ISS MELFI 190K)	63,000	Turn on 7/06, Ongoing, No degradation
Ball Aerospace Stirling		
HIRDLS (60K 1-stage Stirling)	80,000	Turn on 8/04, Ongoing, No degradation
TIRS cooler (35K two-stage Stirling)	7,000	Turn on 3/6/13, Ongoing, No degradation
Creare Turbo Brayton (77K NICMOS)	57,000	3/02 thru 10/09, Off, Coupling to Load failed
Fujitsu Stirling (ASTER 80K TIR system)	119,400	Turn on 3/00, Ongoing, No degradation
JPL Sorption (PLANCK 18K JT (Prime & Bkup))	27,500	FM1 (8/10-10/13 EOM); FM2 failed at 10,500 h
Mitsubishi Stirling (ASTER 77K SWIR system)	115,200	Turn on 3/00, Ongoing, Load off at 71,000 h
NGAS (TRW) Coolers		
CX (150K Mini PT (2 units))	139,000	Turn on 2/98, Ongoing, No degradation
HTSSE-2 (80K mini Stirling)	24,000	3/99 thru 3/02, Mission End, No degrad.
MTI (60K 6020 10cc PT)	119,000	Turn on 3/00, Ongoing, No degradation
Hyperion (110K Mini PT)	111,000	Turn on 12/00, Ongoing, No degradation
SABER (75K Mini PT)	107,000	Turn on 1/02, Ongoing, No degradation
AIRS (55K 10cc PT (2 units))	99,000	Turn on 6/02, Ongoing, No degradation
TES (60K 10cc PT (2 units))	80,000	Turn on 8/04, Ongoing, No degradation
JAMI (65K HEC PT (2 units))	72,000	Turn on 4/05, Ongoing, No degradation
GOSAT/IBUKI (60K HEC PT)	40,700	Turn on 2/09, Ongoing, No degradation
STSS (Mini PT (4 units))	30,200	Turn on 4/10, Ongoing, No degradation
Oxford/BAe/MMS/Astrium Stirling		
ISAMS (80 K Oxford)	15,800	10/91 thru 7/92, Instrument failed
HTSSE-2 (80K BAe)	24,000	3/99 thru 3/02, Mission End, No degrad.
MOPITT (50-80K BAe (2 units))	114,000	Turn on 3/00, lost one disp. at 10,300 h
ODIN (50-80K Astrium (1 unit))	110,000	Turn on 3/01, Ongoing, No degradation
AATSR on ERS-1 (50-80K Astrium (2 units))	88,200	3/02 to 4/12, No Degrad, Satellite failed
MIPAS on ERS-1 (50-80K Astrium (2 units))	88,200	3/02 to 4/12, No Degrad, Satellite failed
INTEGRAL (50-80K Astrium (4 units))	96,100	Turn on 10/02, Ongoing, No degradation
Helios 2A (50-80K Astrium (2 units))	74,000	Turn on 4/05, Ongoing, No degradation
Helios 2B (50-80K Astrium (2 units))	30,200	Turn on 4/10, Ongoing, No degradation
Raytheon ISSC Stirling (STSS (2 units))	30,200	Turn on 4/10, Ongoing, No degradation
Rutherford Appleton Lab (RAL)		
ATSR 1 on ERS-1 (80K Integral Stirling)	75,300	7/91 thru 3/00, Satellite failed
ATSR 2 on ERS-2 (80K Integral Stirling)	112,000	4/95 thru 2/08, Instrument failed
Planck (4K JT)	38,500	5/09 thru 10/13, Mission End, No Degrad.
Sumitomo Stirling Coolers		
Suzaku (100K 1-stg)	59,300	7/05 thru 4/12, Mission End, No degradation
Akari (20K 2-stg (2 units))	39,000	2/06 to 11/11 EOM, 1 Degr., 2nd failed at 13 kh
Kaguya GRS (70K 1-stg)	14,600	10/07- 6/09, Mission End, No degradation
JEM/SMILES on ISS (4.5K JT)	4,500	Turn on 10/09, Could not restart at 4,500 h
Sunpower Stirling (75K RHESSI)	102,000	Turn on 2/02, Ongoing, Modest degradation





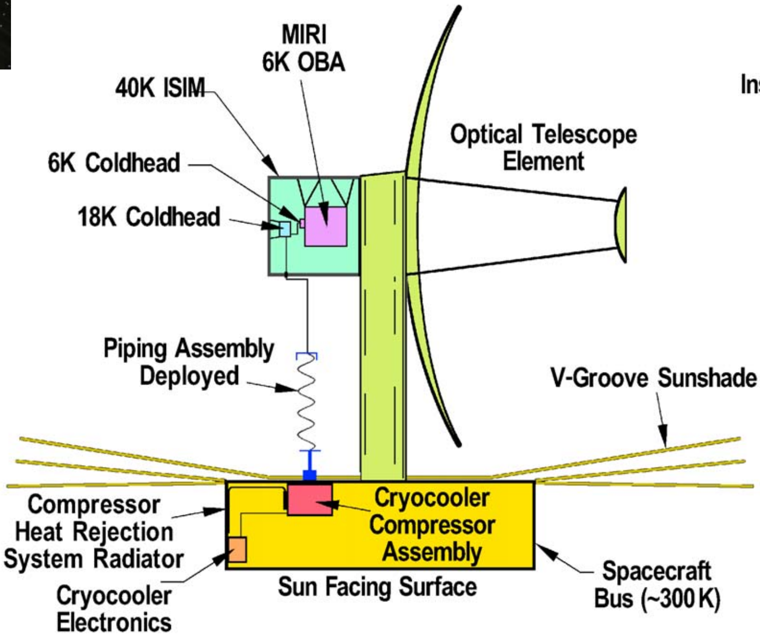

General Features of Next Generation Space Observatory Missions

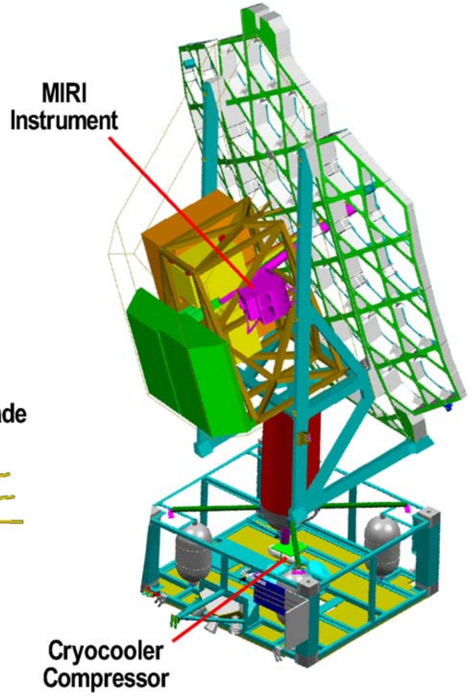


JWST—New infrared space telescope well beyond the capability of Hubble

- 6½ m telescope at 50 K
- IR imaging and spectrometry (0.6 - 28 μm)
- 6 K MIRI instrument (100 kg) is 12-m separation distance from S/C

MIRI in its MLI





Historical Overview and Application Summary

- **Cryogenics is an enabling technology for space missions viewing in the infrared, gamma-ray and x-ray spectrums**
  - **Earth science, Planetary science, Space Astronomy**
  - **Reconnaissance and missile defense**

- **Over the past 50-years enormous progress has been made in both developing the required cryogenic technologies, and in using them to further our understanding of Earth and the heavens**

- **Since 1991, over 50 long-life cryocoolers have been launched into space on cryogenic missions— over 30 of which are still operating in orbit on multi-year missions**

- **For the future, important new developments are focusing on the lower temperature range, from 6 to 20 K, in support of missions like JWST that study the origin of the Universe**