Cryogenic Systems

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NASA Technology Roadmap Study
Washington, DC
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Education and Employment

- Education
  - PhD, Low Temperature Physics, Purdue 1966
  - NBS/NRC Postdoctoral Fellow, 1966-1968
- Professional Employment
  - Physicist and project leader, NBS/NIST, 1968-2009
  - Leader, Cryogenic Technologies Group, 1995-2009
  - Appointed NIST Fellow, 2008
  - Retired from NIST in 2009
  - Working for NIST half time under contract

Personal Research Areas

- Millikelvin Refrigeration (10 mK to 200 mK)
  - ^3He-^4He dilution refrigerator, modeling & experiments
  - Kapitza thermal boundary resistance
  - Johnson noise thermometry
- Cryocoolers
  - Stirling and pulse tube cryocoolers (4 K to 150 K)
  - Joule Thomson cryocoolers (4 K to 200 K)
  - Microcryocoolers (77 K to 200 K)
- Cryogenic Material Properties
  - Thermal conductivity, specific heat, thermal contact
  - NIST database (www.cryogenics.nist.gov)

Outputs

- Publications
  - >160 papers in open, refereed literature
  - 8 invited book chapters on cryocoolers
- Short courses (~30)
  - UCLA: 5-day course on cryocoolers (1981-1998)
  - NATO Advanced Study Institute: 1990, 2002, 2004
  - NASA, Air Force, KAIST, KIMM, Georgia Tech
  - Cryogenic Society of America (1/year since 1997)
- CRADAs with private industry funding
  - About 2-3 per year
  - Medical, gas liquefaction, sensor cooling, energy

Awards and Recognition

- Plenary lectures at international conferences
  - 10 (3 with > 1000 attendees)
- 1987, 1999, and 2001, Best Paper Award at Cryog. Eng. Conf.
- 1990 R&D 100 Award for 1st cryocooler with no moving parts
- 1995: DOC Silver Medal for advanced refrigeration systems
- 1999: J&E Hall Gold Medal, Institute of Refrigeration for pioneering work on pulse tube cryocoolers
- 2003: DOC Gold Medal for technology transfer in advanced cryocoolers
- 2009: Samuel Collins Award from the Cryogenic Engineering Conference for contributions to cryogenics

Benefits of Cryogenic Temperatures
(Applications)

- Preservation of biological material and food
- Densification (liquefaction & separation)
- Quantum effects (fluids and superconductivity)
  - Low dissipation (superconductivity)
  - High-precision metrology (atomic parameters)
  - Action over a distance (fast response)
- Low thermal noise
  - Electromagnetic
  - Electronic
- Low vapor pressures (cryopumping)
- Property changes (permanent and temporary)
- Tissue ablation (cryosurgery)

Enabling Cryogenic Applications for NASA

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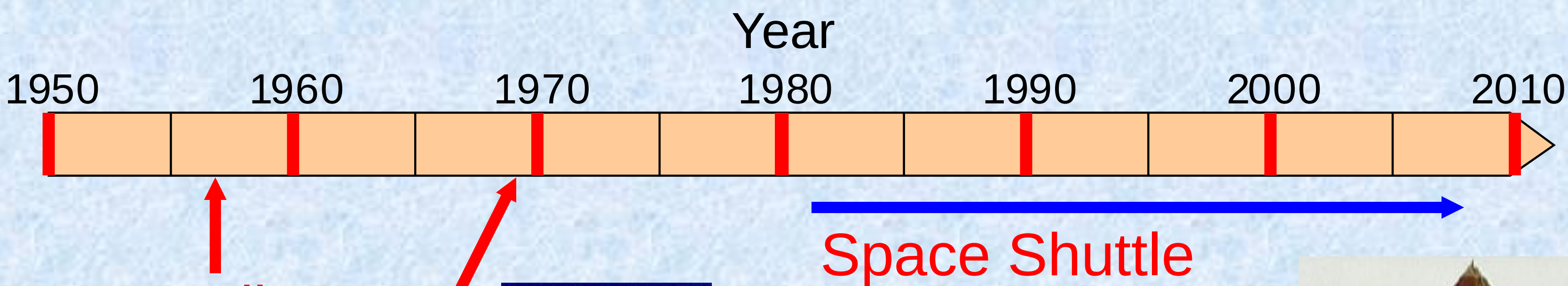
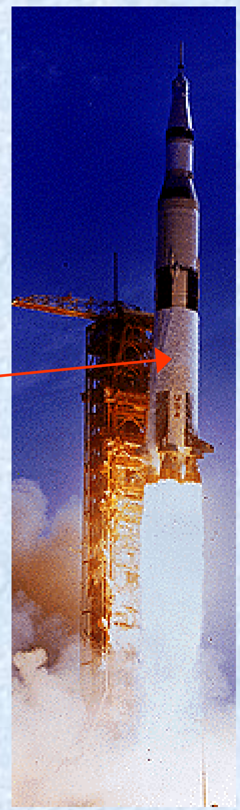
Densification
Liquid Hydrogen and Oxygen Rockets



Sputnik I

Apollo 11 moon landing

Saturn-V



H_2 and O_2

- 1.8×10^6 kg LOX
- 5.0×10^4 kg LH_2

- Properties:
- H_2:

$\rho_{liq} = 0.071$ g/cm^3

$\rho_{liq}/\rho_{vap} = 866$

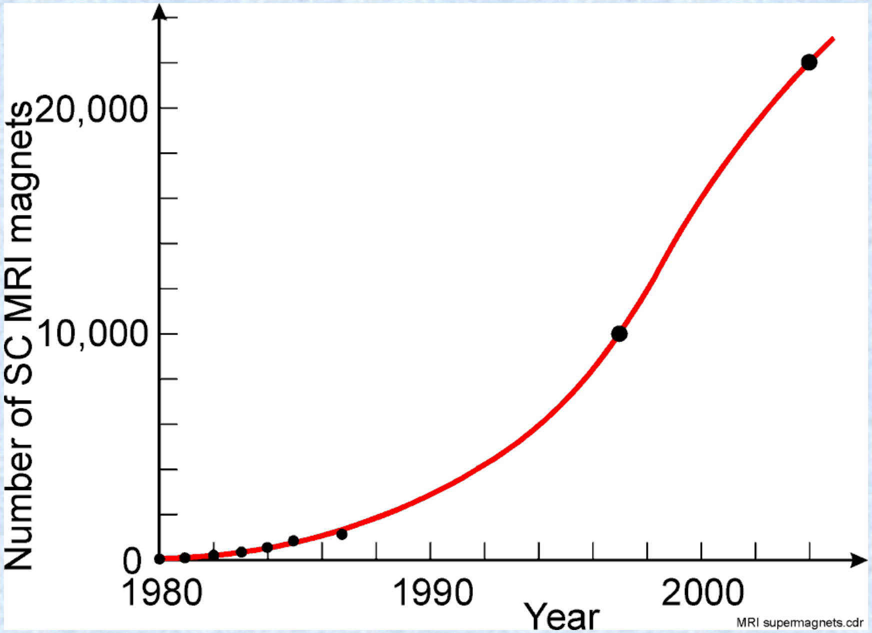
- O_2:

$\rho_{liq} = 1.14$ g/cm^3

$\rho_{liq}/\rho_{vap} = 877$

Advantage of cryogenics

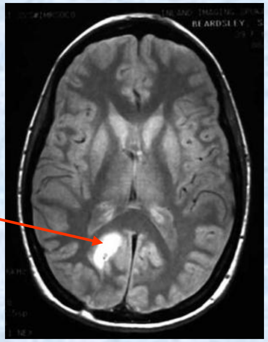
Superconductivity
Magnetic Resonance Imaging (MRI)



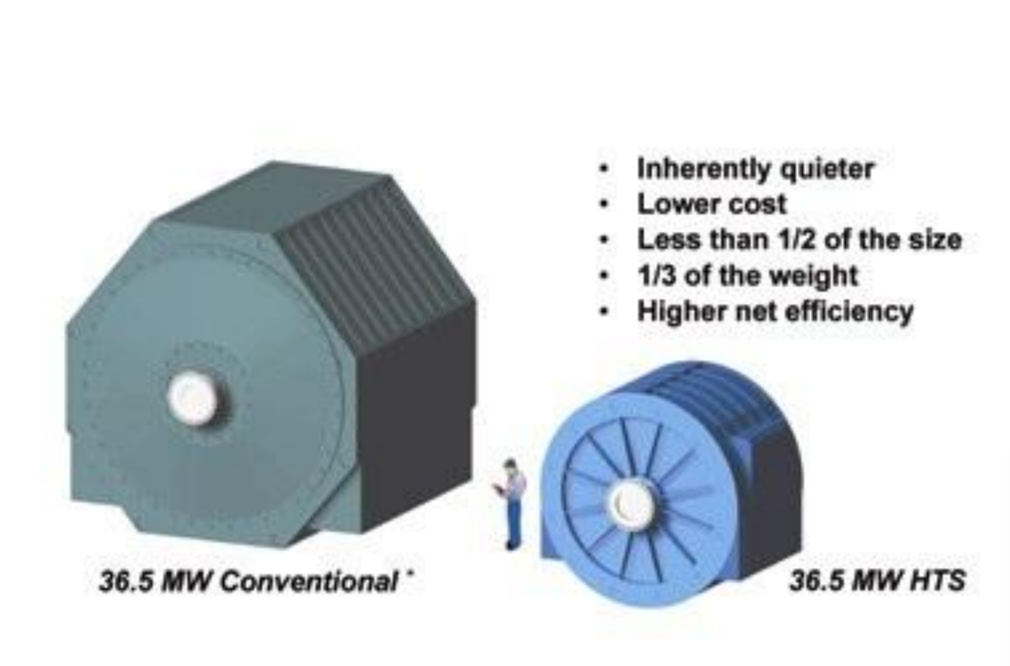
Cumulative number of MRI superconducting magnets sold

- 1.5 T Superconducting magnets
- 1 W at 4 K
- Non-magnetic regenerators
- >7000 4 K cryocoolers since 1995

Tumor

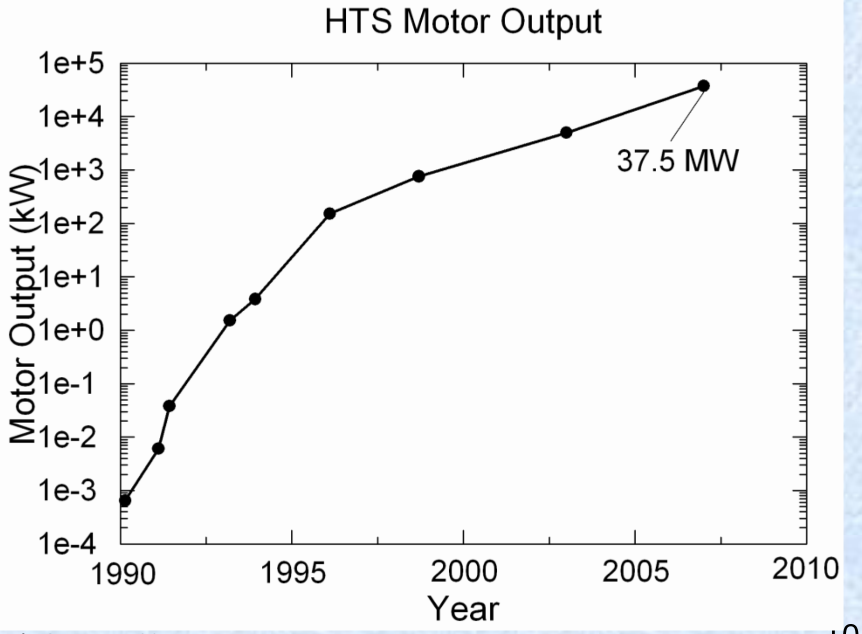


HTS Superconducting Motors



Drawing courtesy: American Superconductor Corporation

35 K to 50 K

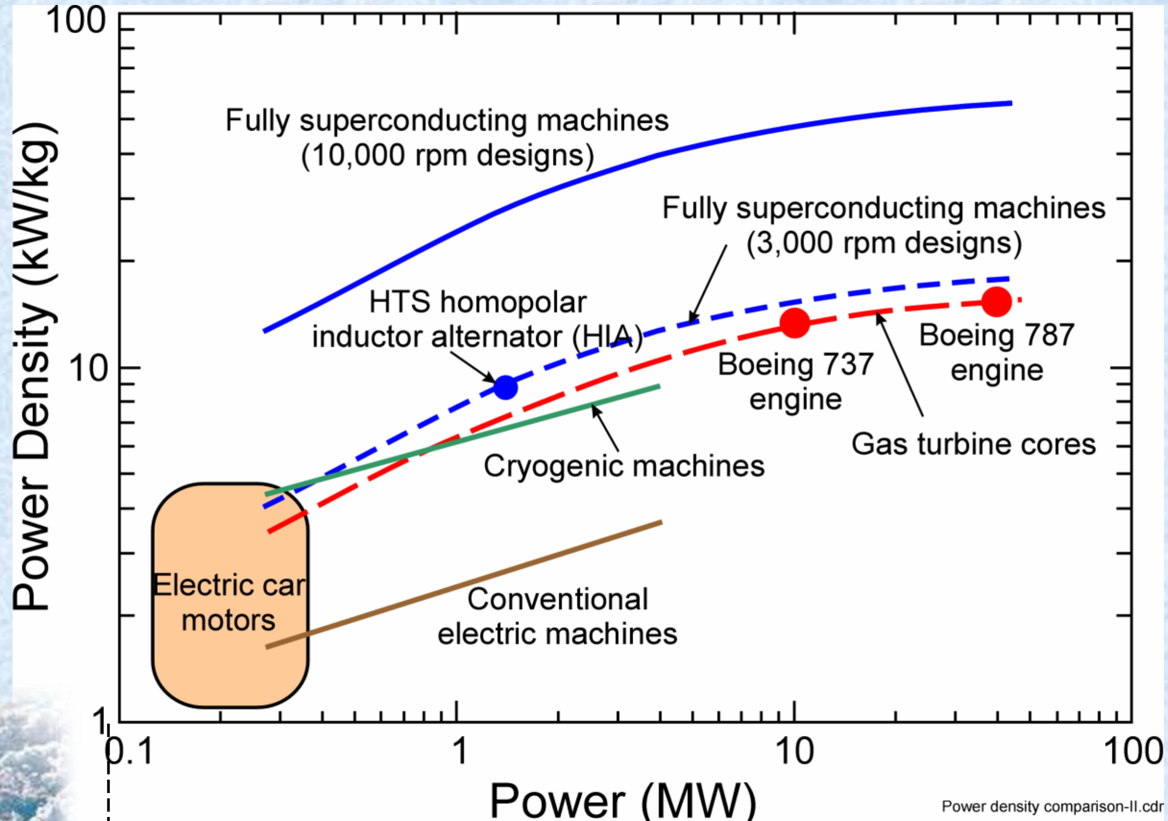


Superconducting Machines for Aircraft

NASA plans for 2035

10,000 rpm gas turbine and HTS generator

Artist drawing courtesy of NASA/Glenn



Cryocoolers (desired)

3000 rpm HTS motors and fans

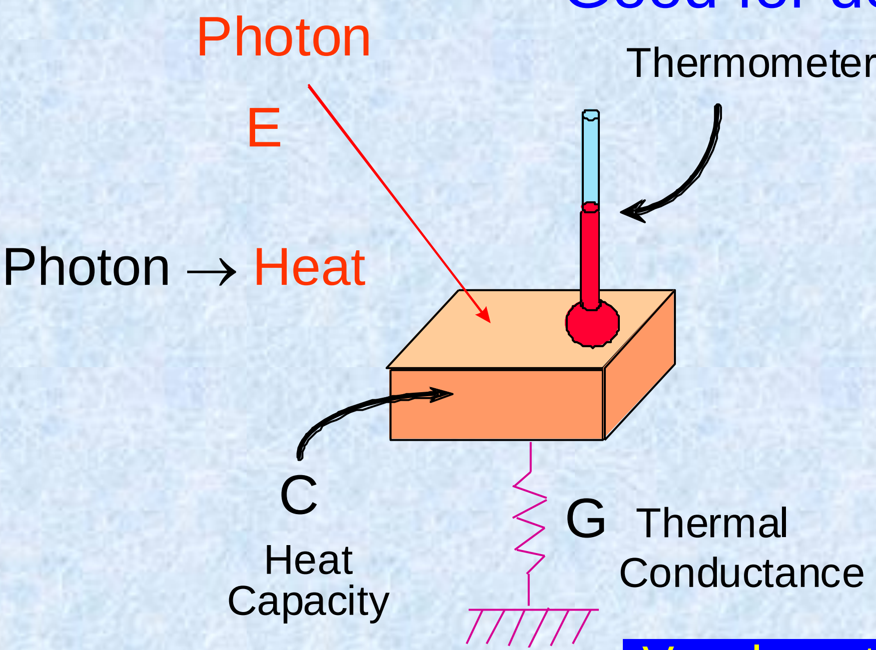
Cryocoolers required:

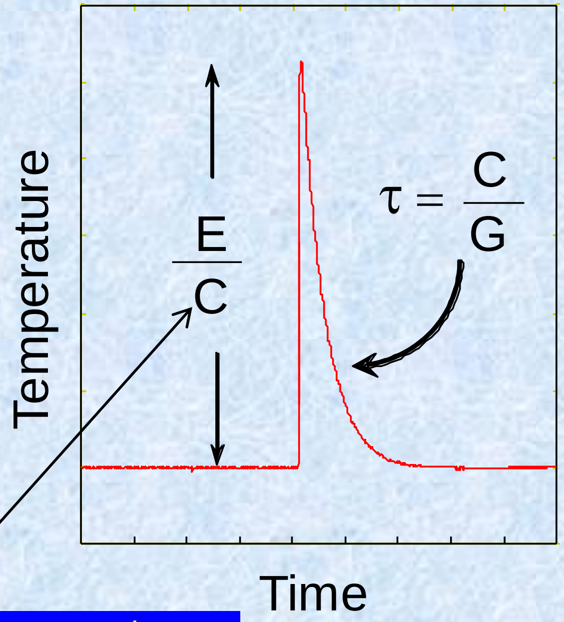
- 3-10 kW at 50-60 K
- 30% of Carnot
- 3 kg/kW input

Low Thermal Noise

Microcalorimeters (Bolometers)

Good for detecting X-rays





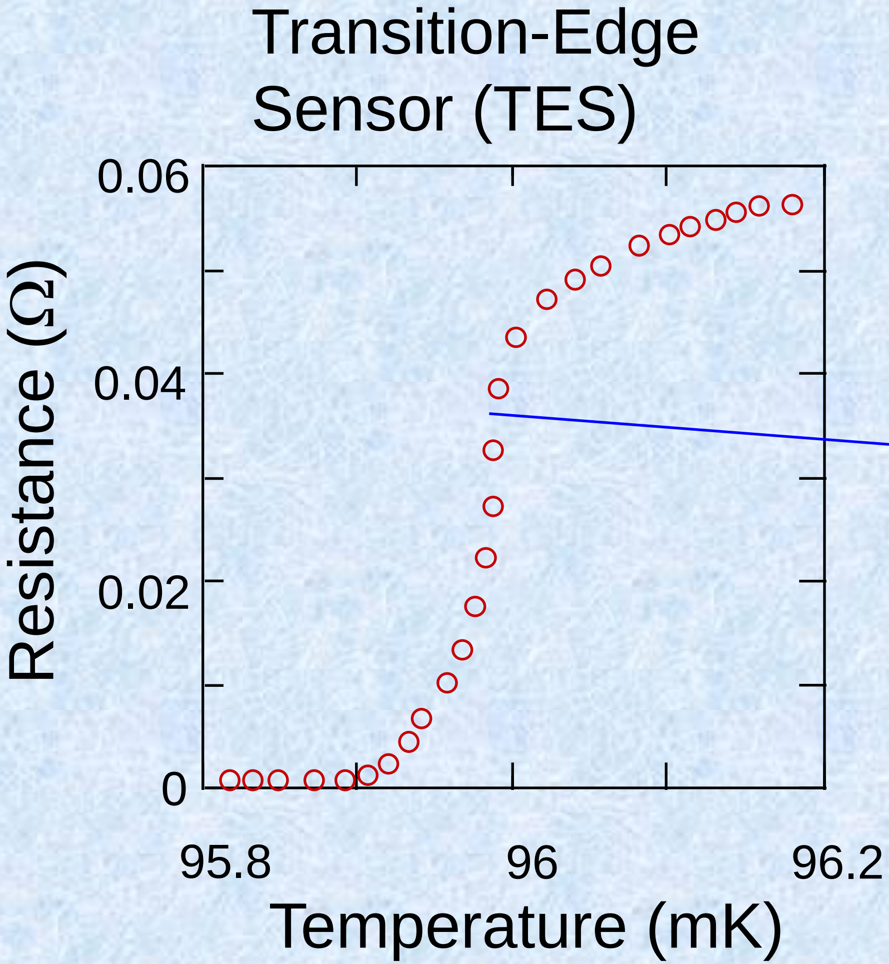
Very low at low temperatures

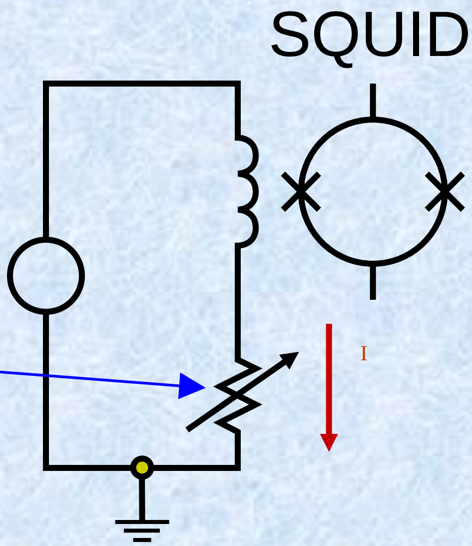
- Root-mean-square energy fluctuations ~ $(k_b T^2 C)^{1/2}$
- For T = 0.1 K, C = 10 pJ/K, ΔE ~ 10 eV
- Need to integrate a thermometer into C

  several possibilities, such as transition-edge sensors

Courtesy: J. Ullom, NIST

Superconducting Transition-Edge Sensor





Resolution:
15 eV out of 1.5 keV
130 eV conventional

Photon → Heat → Resistance → Current

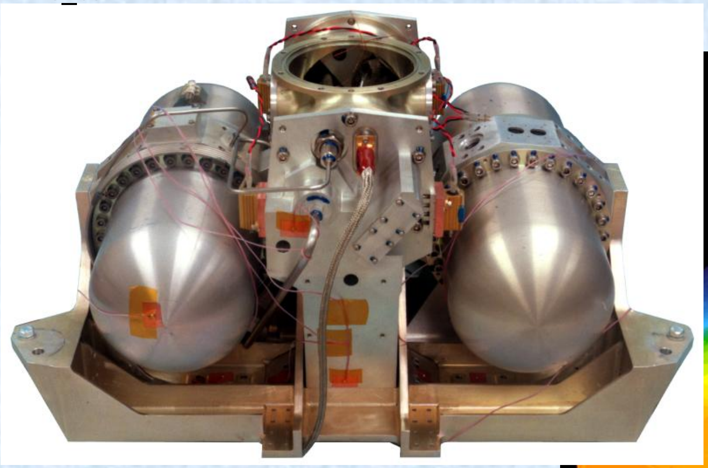
Courtesy:R. Harris, NIST

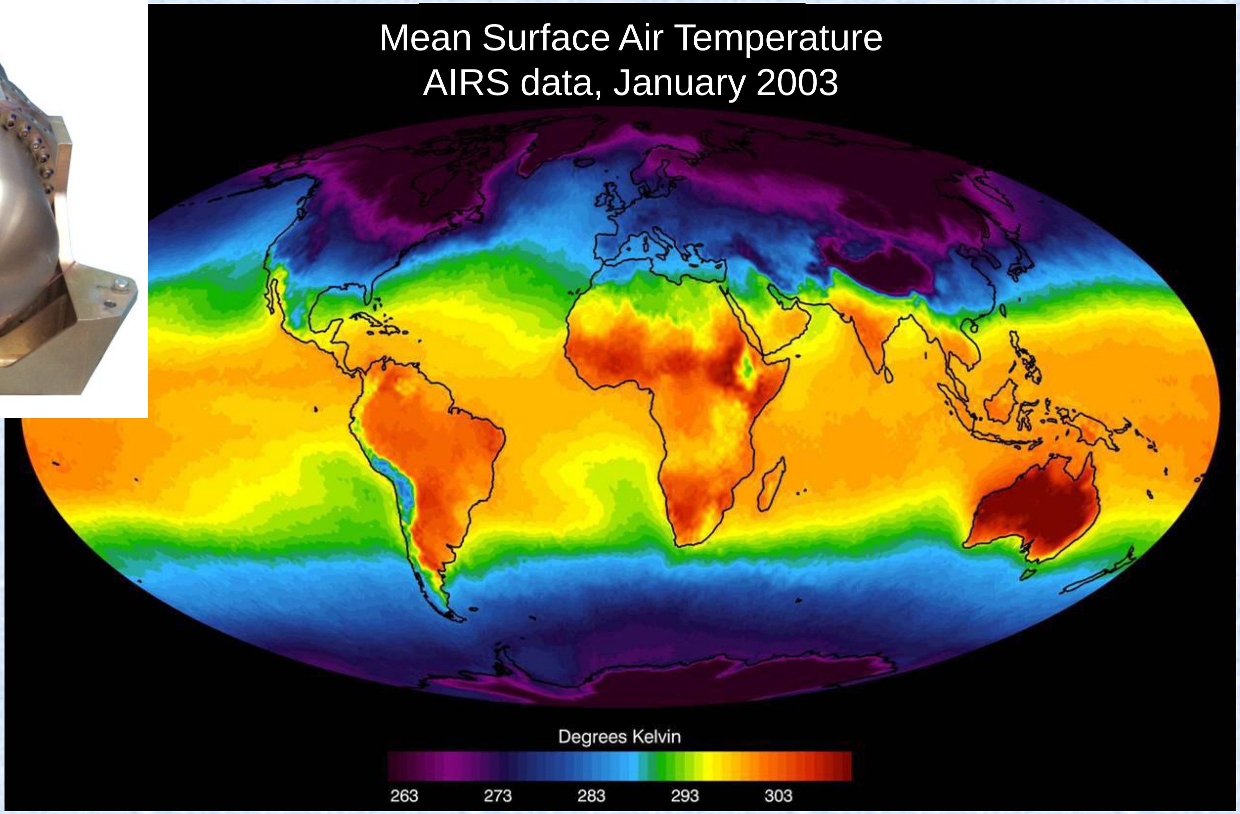
Atmospheric Infrared Imaging

Low thermal noise leads to low dark current in IR sensors

Earth Observing System (EOS)

Airs_cut.tif



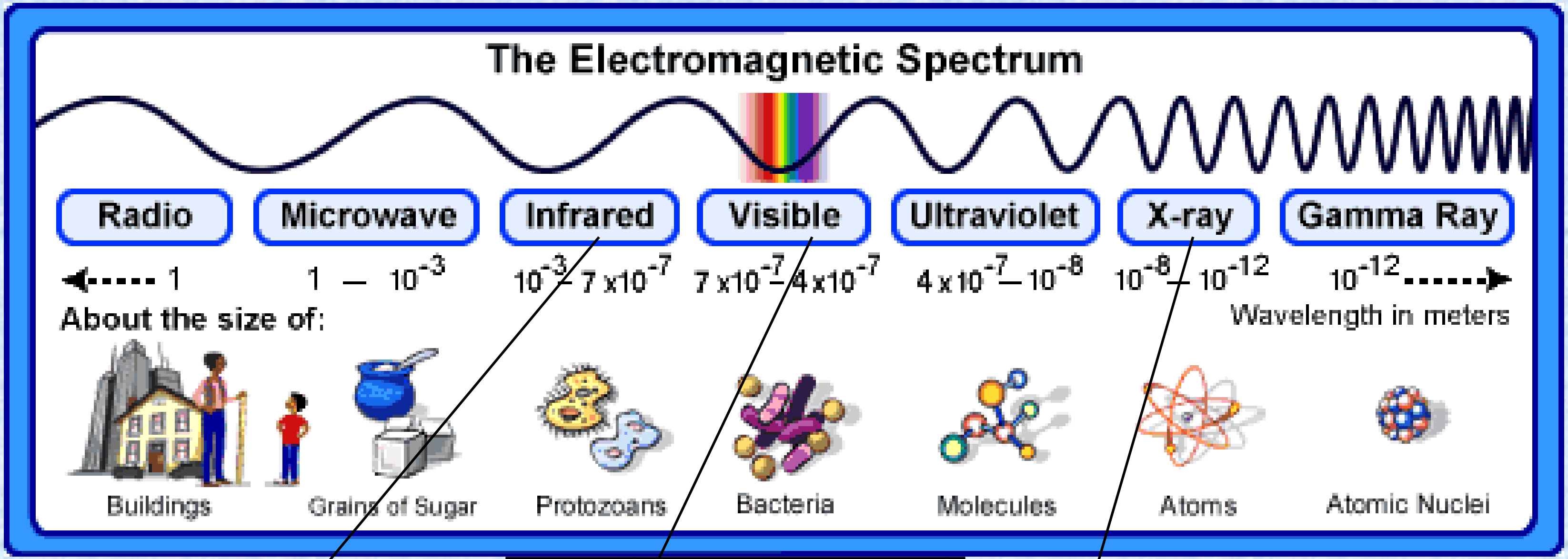


AIRS Pulse Tube Cryocoolers (2)

- 1.2 W @ 55 K
- 60 W input
- TRW
- May 2002 Launch

airs_surface_temp1_full Jan03.jpg

Infrared and X-Ray Space Telescope Missions



Only 4% of universe mass seen as visible

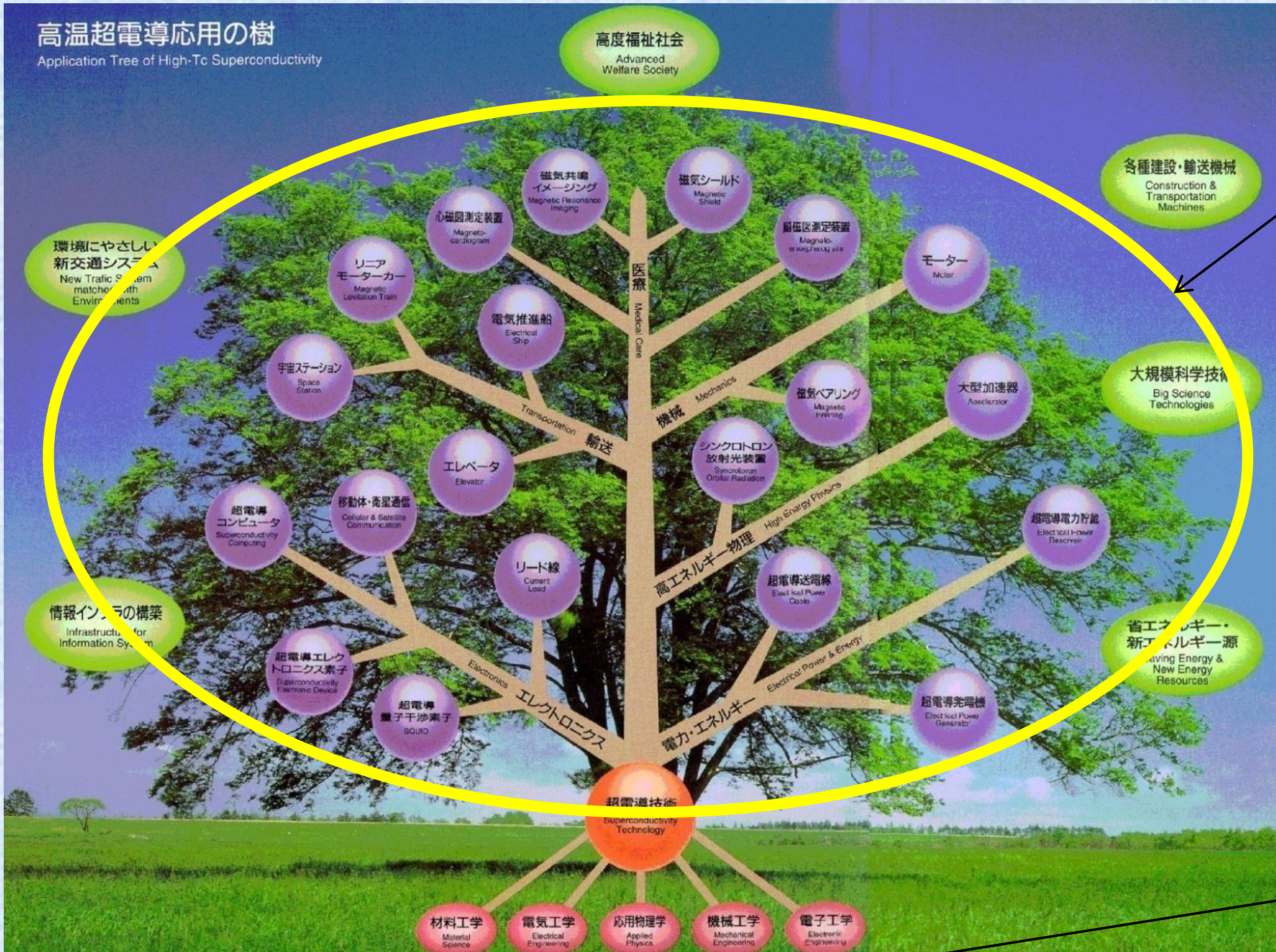
Why infrared?

- Cold universe
- Obscured regions
- Dust emissions
- Molecular spectral lines
- Highly redshifted universe

Why X-Ray?

- Detect dark matter
- Test gravitational theory
- X-rays around black holes
- Elements in universe

Cryogenics – An Enabling Technology



Source: ISTEC, Tokyo, Japan

Cryogenics

Supercondtree.jpg

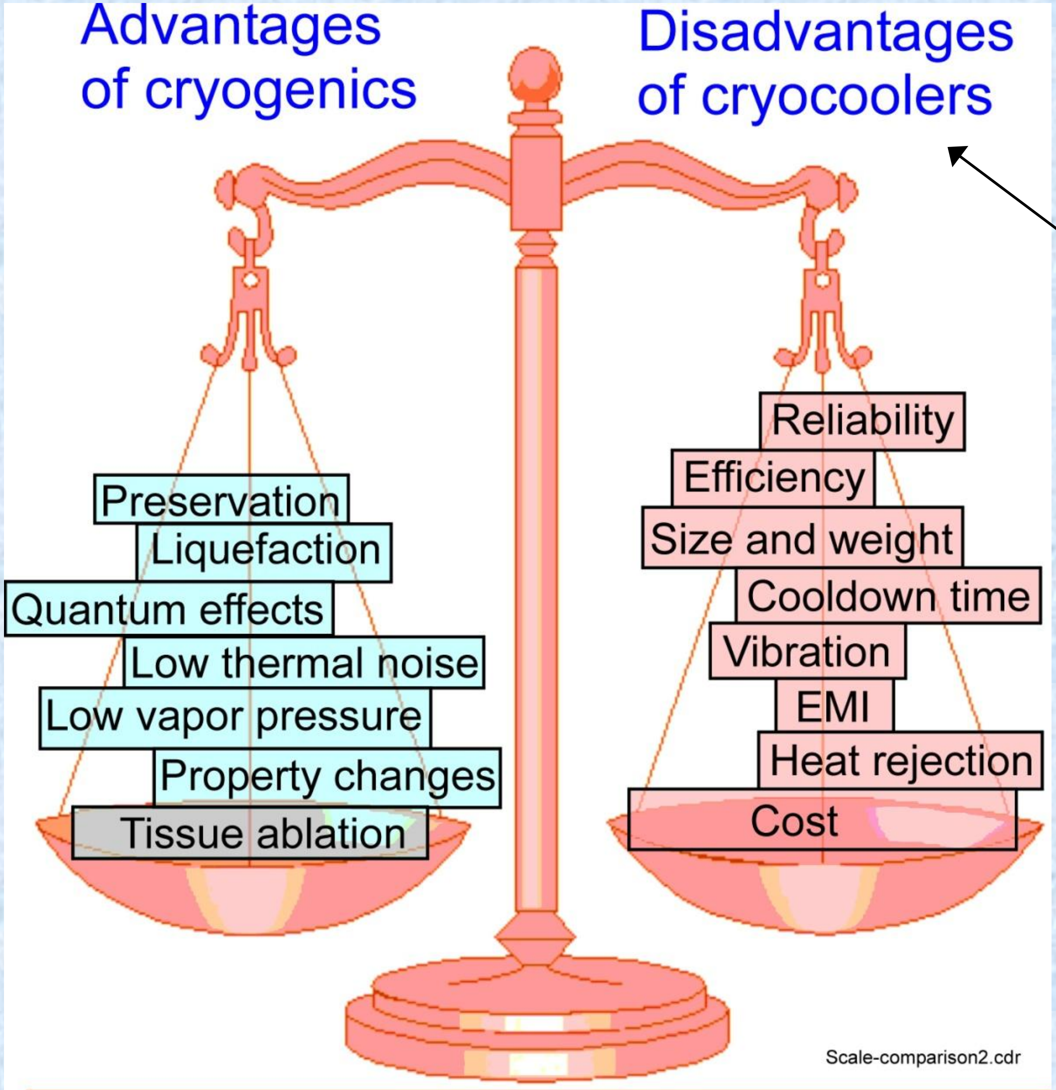
Spectacular applications

Spectacular =

- high resolution
- high precision
- high sensitivity
- high power density
- low power
- low noise

Enabling technology

Balancing Act



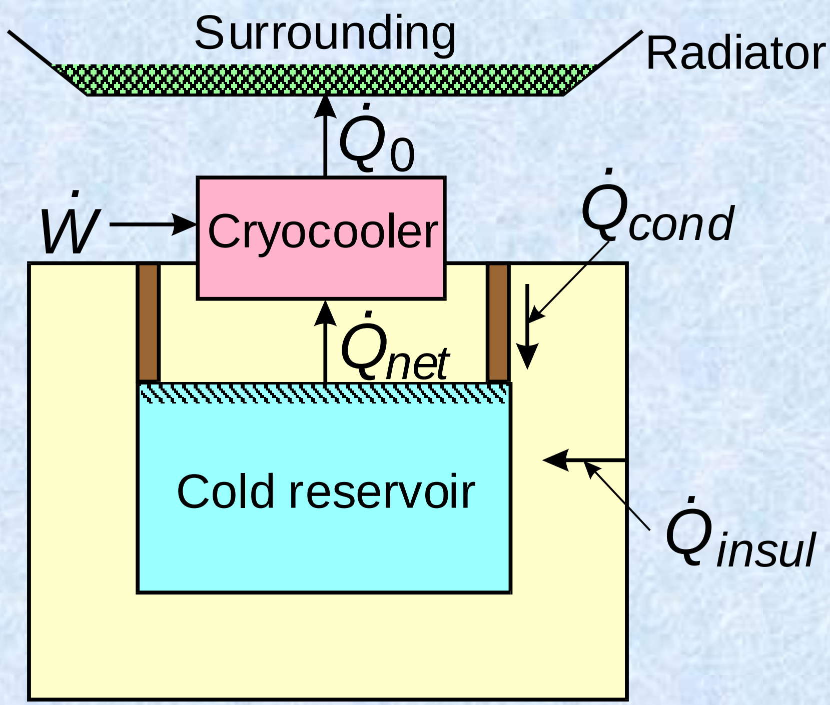
Cryocooler Research

Goal

Reduce disadvantages

(Cryocooler invisible to user)

Cryogenic Systems



Reservoir: $\dot{Q}_{net} = \dot{Q}_{cond} + \dot{Q}_{insul}$

Cryocooler: $\dot{W} = p_s \dot{Q}_{net}$ p_s = cryocooler specific power

Radiator: $\dot{Q}_0 = \dot{W} + \dot{Q}_{net}$

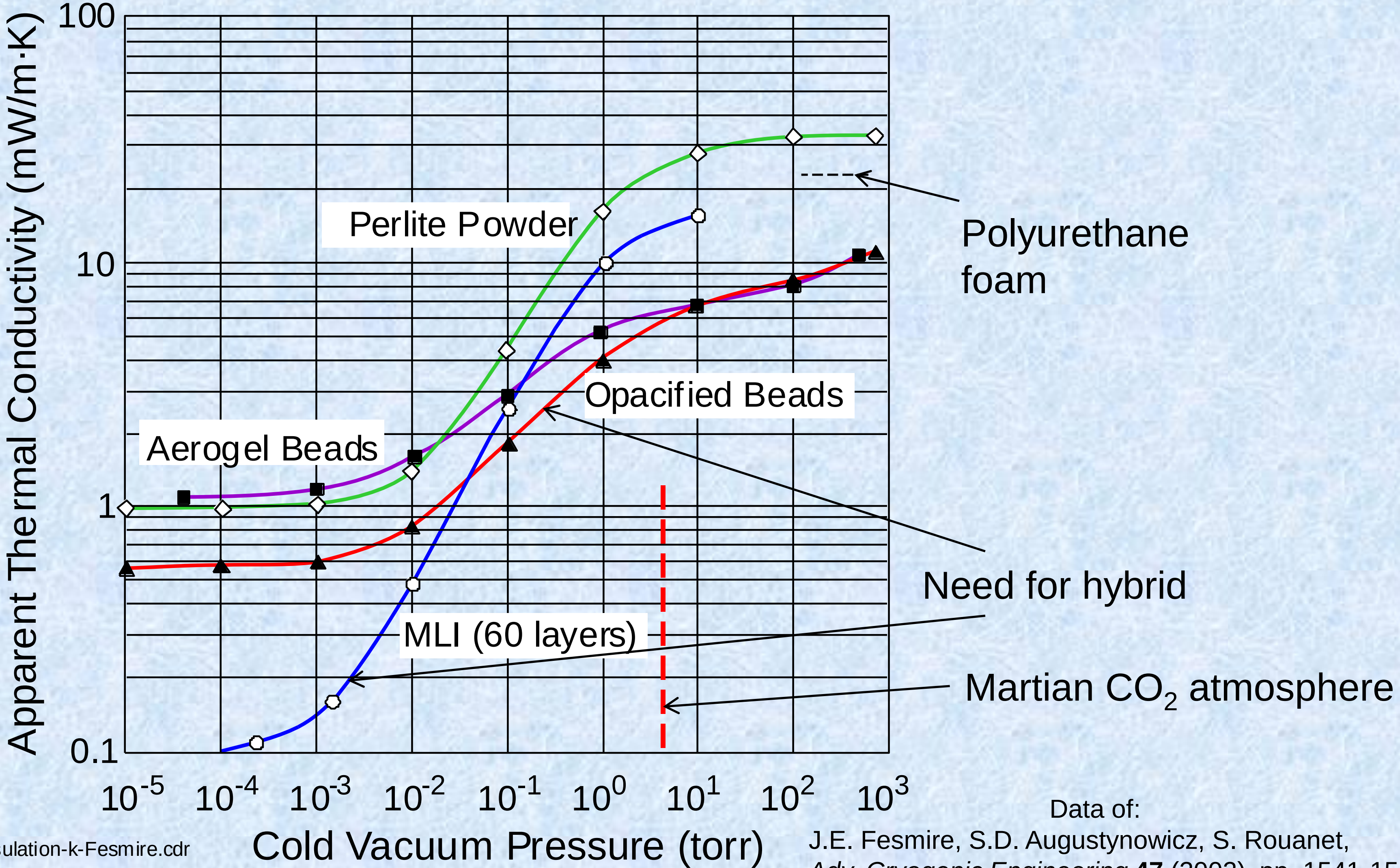
Refrig17c.cdr

Roadmap Topics

Passive Thermal Control

- Insulations
  - Multi-Layer Insulation (MLI)
  - Foams and aerogels
  - In situ insulations (lunar or Martian regolith)
  - Structural supports (composites)
- Low Temperature Radiators
  - Flexible and deployable
  - 50 K state of the art; 20 K desired in 8-10 yrs.

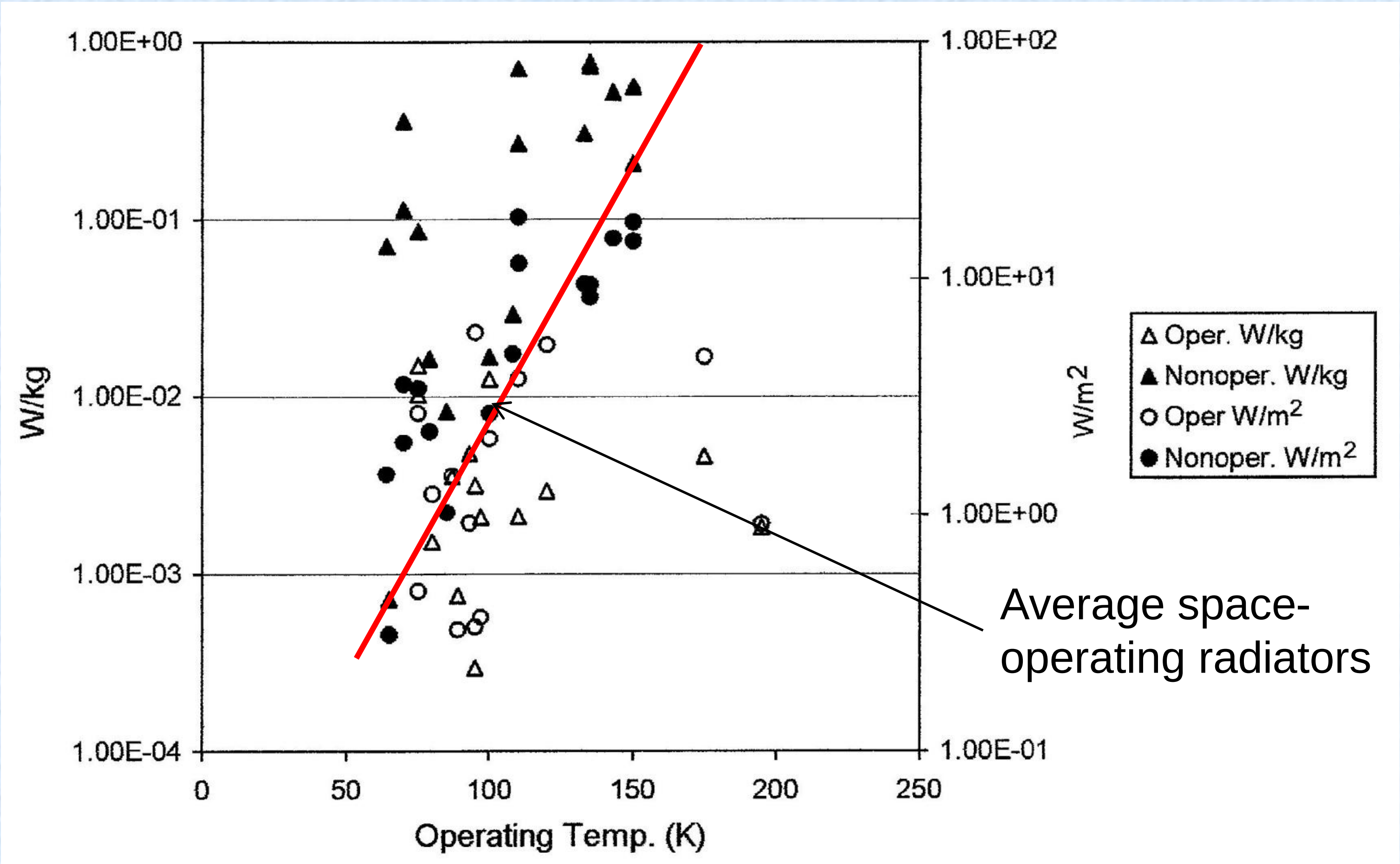
Insulations



Insulation-k-Fesmire.cdr

Data of:
J.E. Fesmire, S.D. Augustynowicz, S. Rouanet, *Adv. Cryogenic Engineering* **47** (2002), pp. 1541-1548

Cryogenic Radiators



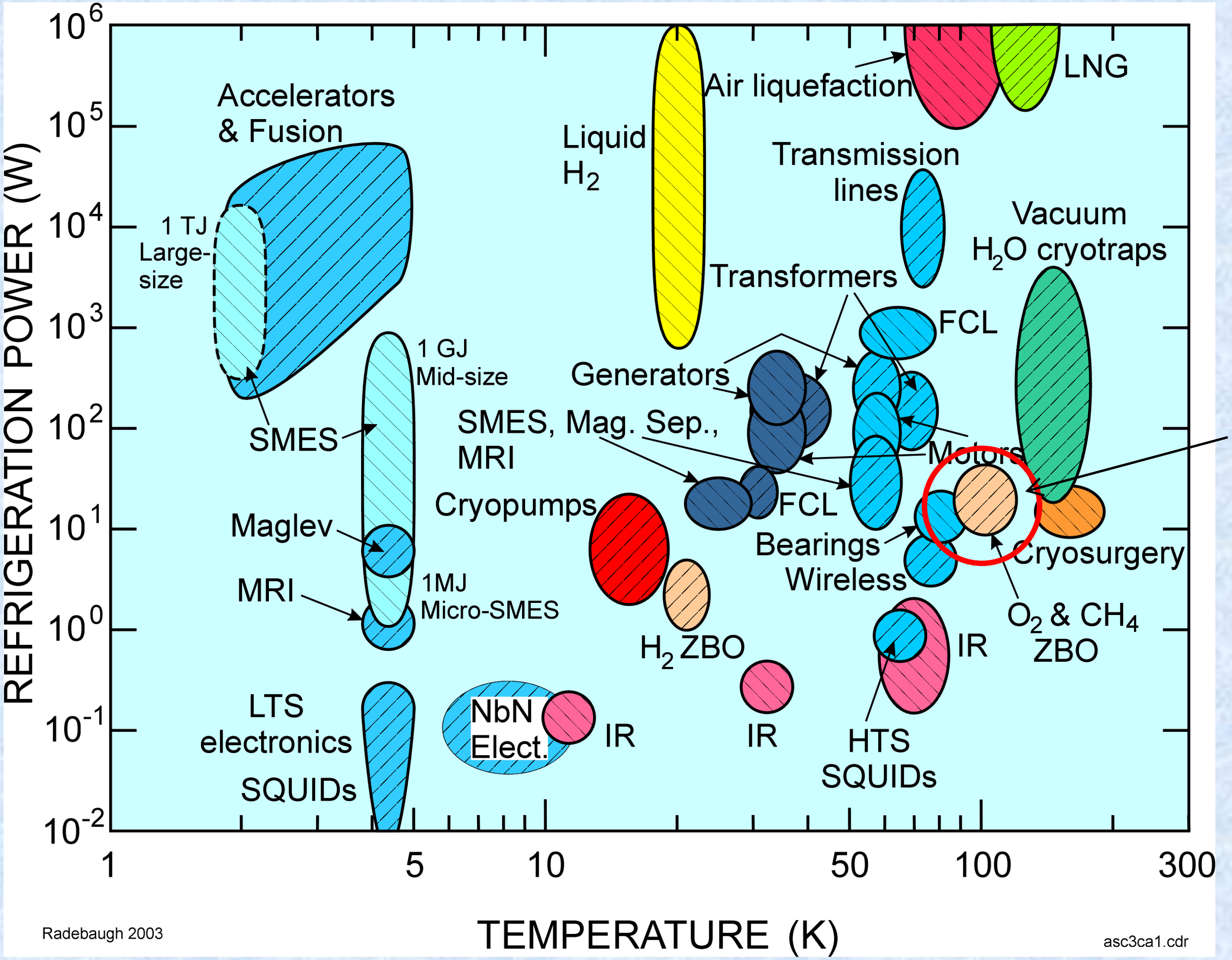
From: F. Roush and T. Roberts, *Cryocoolers 14*, (2007), pp. 11-20

Roadmap Topics

Active Thermal Control

- Small 20 K Cryocoolers for Liquid Hydrogen
  - 5 – 20 W at 20 K for long term ZBO storage
  - Reduce specific power, mass, and vibration
  - Pulse tube cryocoolers
    - Improved regenerator materials
    - Low temperature flow rectification for DC flow
    - Reduce flow nonuniformities in larger systems
  - Turbo-Brayton cryocoolers
    - Higher effectiveness and lower mass recuperators
    - Low leakage and bypass rates with hydrogen or helium

Cryocooler Applications



Not addressed In draft report

Cryocoolers in Space

2010 Data

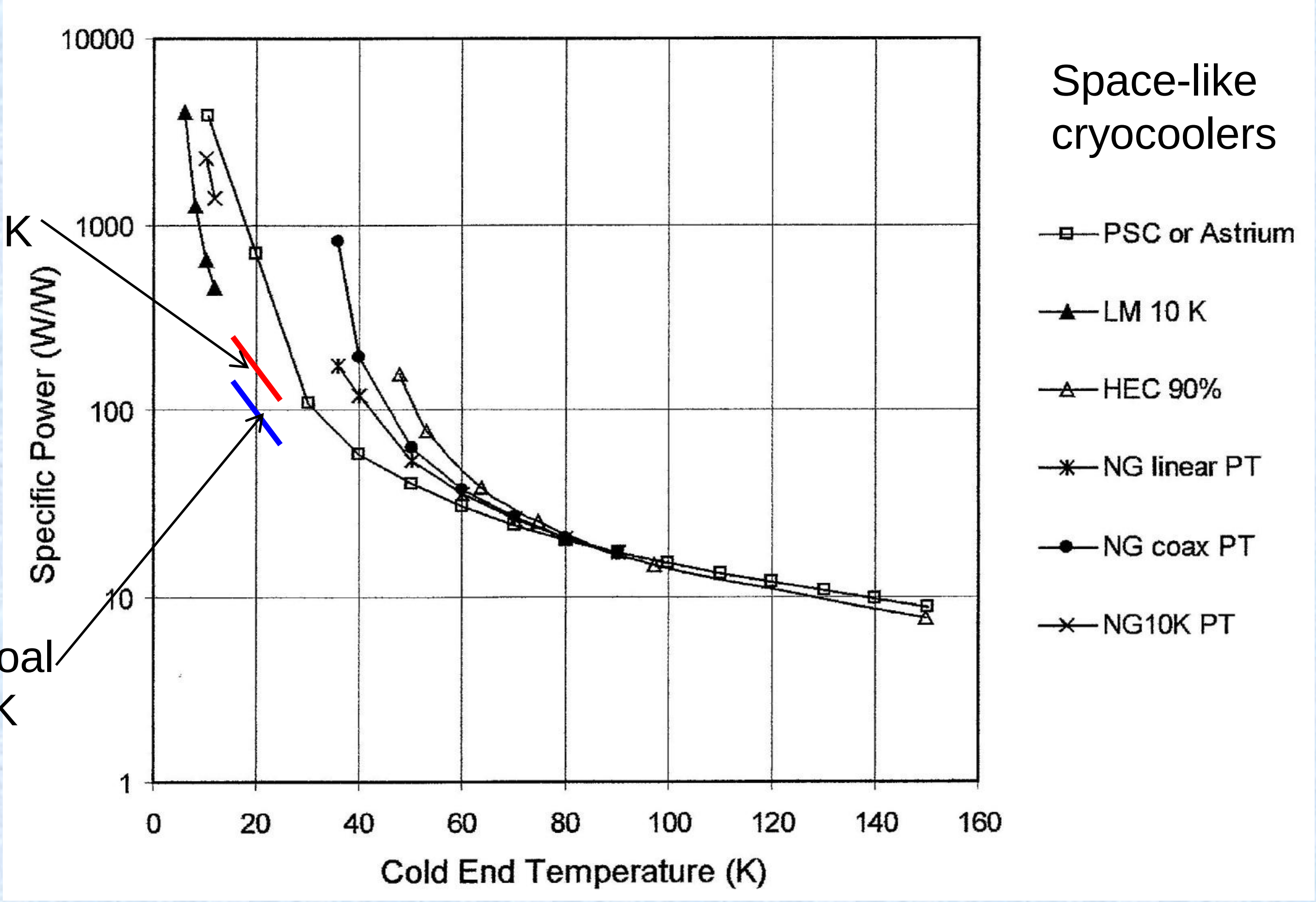
All at *T* > 60 K except JT

Data from Ron Ross, JPL

Cryocooler type	Bearings	Quantity	Run time (hours)	Failures
Turbo-Brayton	Gas	1	59,000	0
Stirling	Flexure + 1 gas	25	16,000-112,000	2
Pulse tube	Flexure	12	9,000-107,000	0
Joule-Thomson	None (sorption comp.)	2	6,000	0

Cryocooler Specific Power
(Watts input per watt of net refrigeration power)

Current SOA
Draft Roadmap
180 W/W @ 20 K
7.8 % of Carnot



Draft roadmap goal
100 W/W @ 20 K
14 % of Carnot

From: F. Roush and T. Roberts, *Cryocoolers 14*, (2007), pp. 11-20

Roadmap Topics

Active Thermal Control, p. 2

Not addressed in draft

- High Power Liquefiers
  - From gas produced by ISRU (H_2, O_2, and CH_4)
  - Low temperature radiators for gas precooling
  - High pressure electrolysis system for compressor
  - Need for transition from industrial to space
- Cryocoolers for Science Instruments
  - 20 mK adiabatic demagnetization refrig. (ADR)
    - For cooling TES detectors for X-ray astronomy
    - Need for improved paramagnetic materials (for higher T_h)
  - 2 K cryocoolers for precooling ADR
  - 6 - 10 K for As:Si IR detectors; 35 K for HgCdTe

Roadmap Topics

Active Thermal Control, p. 3

Not addressed in draft

- Component Development
  - Cold compressors, pumps, and valves, bearings
  - Need for thermal expansion matching over wide *T*
    - Initial testing at 300 K, but final operation at 100 K or less
  - Subcooling technology for longer hold times
  - Subcooling for densified propellants

Roadmap Topics

System Integration

- Shields
  - Passive and active
  - Flexible materials
- Heat Transport
  - Heat rejection from cryocooler compressors
  - Heat pipes and loop heat pipes
  - Heat switches (for T < 10 K) for ADR systems
- Staging
- Superconductors (low and high T)
  - Motors, magnets, and science missions

Summary (Gaps and Challenges)

- Technology gaps
  - Cryogenics for ZBO and liquefaction of O_2 and CH_4
  - Technology path for cold compressors
    - Must operate over wide temperature range (100 K – 300 K)
    - Cryogenic materials properties (thermal expansion matching)
- Top Technical Challenges (Priorities)
  - Reducing mass of cryocoolers
    - Compressor mass for pulse tube cryocoolers
    - Recuperative heat exchanger for Brayton cryocoolers
  - Increasing cryocooler efficiency
  - Lightweight insulations in a wide range of atmospheres
  - Flexible radiators
  - Heat transport over long distance (heat pipes, fluid pumping)

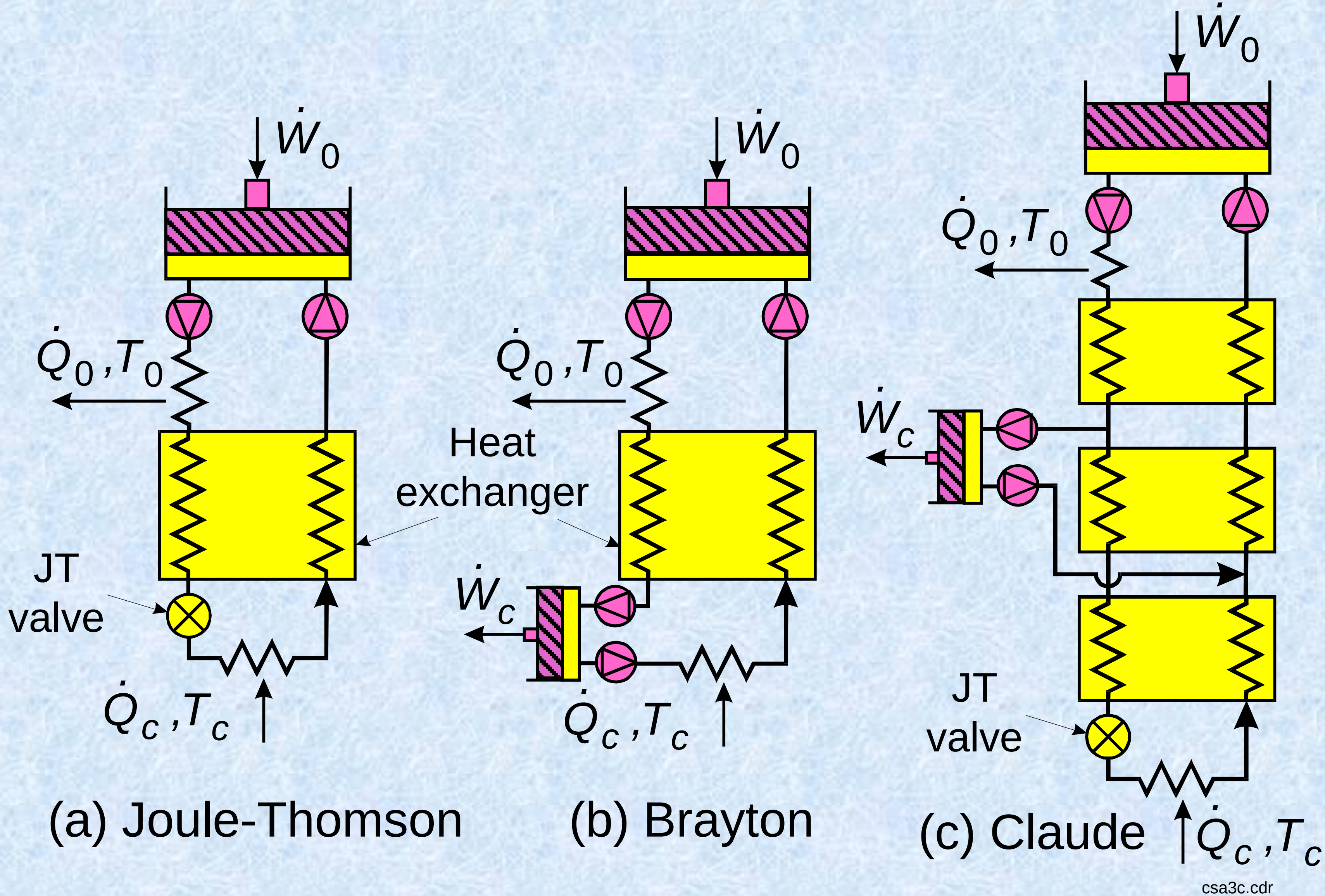
Summary (Expertise and Capabilities)

- NASA expertise and capabilities
  - Overall system studies
    - Provide component requirements
  - Insulations (Kennedy)
  - Adiabatic demagnetization refrigerators (Goddard)
  - Cryocoolers (JPL, Ames, Goddard)
  - Radiators
- Utilize expertise at other institutes
  - Air Force (IR sensor cooling, cryocooler testing)
  - NIST (cryocooler modeling, concepts, component testing, material properties)
  - Private industry (expertise in flight hardware)

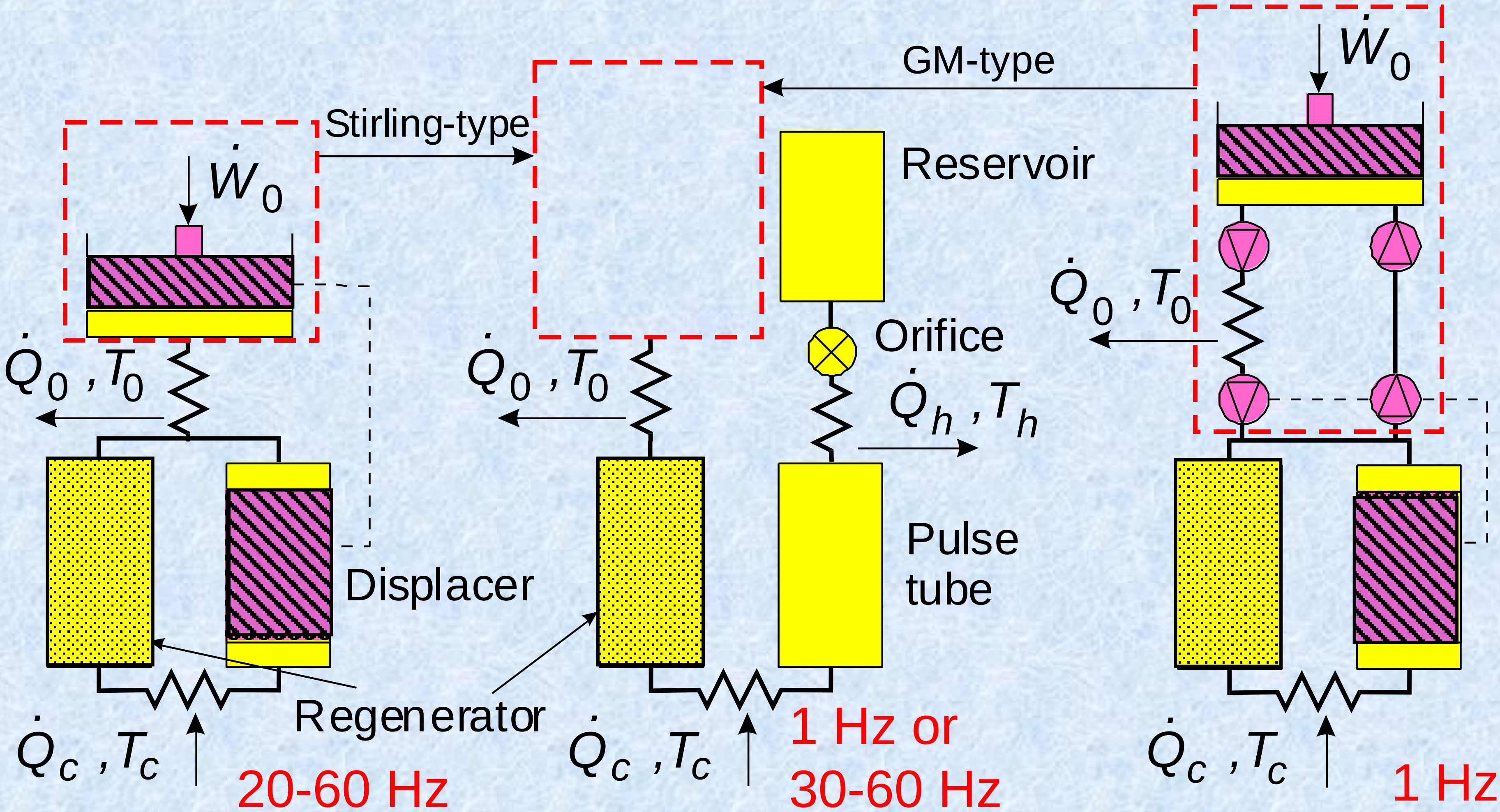
Questions?

Thank you

Recuperative Cryocoolers
(Steady Flow)



Regenerative Cryocoolers
(Oscillating Flow)



(a) Stirling

(b) Pulse Tube
Stirling- or GM-type

(c) Gifford-McMahon
(GM)

csa4ca.cdr