# A FRIDGE IN SPACE

## *A Case Study in Thermodynamics*

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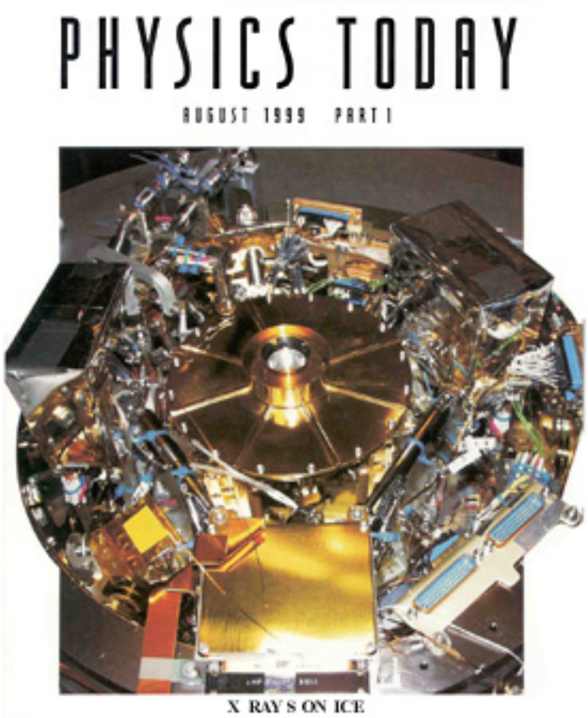
## Part I: The Case

"Houston, we have a problem!"

In early 2000, an X-Ray Spectrometer (XRS) calorimeter instrument is scheduled to be launched as part of the Japanese-US x-ray astronomy satellite Astro-E. The XRS is a detector for collecting and measuring the x-ray photons incident upon it. It is based upon the principle that the x-ray photons, when they are absorbed, give their energy to the detector, whose temperature increases.

The detector (an absorber) works best if it is at a very low temperature - around 50mK. However, a typical x-ray photon energy is 1keV (the XRS is designed to detect x-rays of energy 0.4-12keV). If the detector absorbs too many photons, there is a possibility that its temperature might go up substantially. In order to prevent this from happening, the XRS will be attached to a fridge unit to keep it "cool." To attain such a low temperature, the (adiabatic demagnetizing) refrigerator (ADR) makes use of the adiabatic demagnetization (or magnetocaloric) effect.



At a press conference, Dr. Peter Shirron at NASA described the fridge as follows: "... The fridge takes heat from the detector at 50mK and dumps it into a heat bath at 6K."

A physics student listening to the press conference is puzzled. "How can heat move from a colder region (50mK) to a hotter one (6K)?" he wonders.

***What do you think is going on here?***

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## Part II: Classroom Discussion of Thermodynamics

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| Question | • Why is a device (here the ADR) required in order to move energy from 50mK to 6K?<br>• State the relevant thermodynamic principle. |

Now that we have ascertained that a device is required to move energy "uphill," is there a generic name for such a device? Your favorite textbook does not talk about cooling detectors but has the following relevant discussion:

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| Textbook | A heat engine can move heat energy uphill at the expense of doing work. *Heat out* equals *heat in* plus *work done*. |

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| Question | • To say that a heat engine moves energy uphill by doing work is hiding one important fact: how does it really do it?!<br>• How does heat move into the heat engine? How does heat move out of the engine?<br>• In the process of transfering the heat from a colder to a warmer body, the engine temporarily stores the energy. Is there a constraint on how much energy can be stored?<br>• Is heat really traveling uphill? |

## Part III: Classroom Discussion of the ADR

In the previous section, we learned that saying that doing work moves energy uphill does not really explain how this is actually done. This is where the ADR comes in handy. We will dissect it in order to see how it performs its magic. In the software industry, this is known as reverse engineering. Here is what we will learn:

**Heat never flows uphill!**

In order to come to this conclusion, we need to know how an ADR does its thing. Your textbook has the following to say about the adiabatic demagnetization effect:

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| Textbook | The process of adiabatic demagnetization of a paramagnetic salt leads to cooling via the magnetocaloric effect. Applying a magnetic field at constant temperature leads to an inflow of heat into the salt lattice and an alignment of the spins. A subsequent removal of the magnetic field under adiabatic condition leads to heat flow from the lattice to the spin system, a randomization of the spins, and cooling of the lattice. |

Hence, the magnetocaloric effect is simply a mechanism for changing the temperature of a substance up and down by the use of an external magnetic field. How do we use this trick to move heat uphill?

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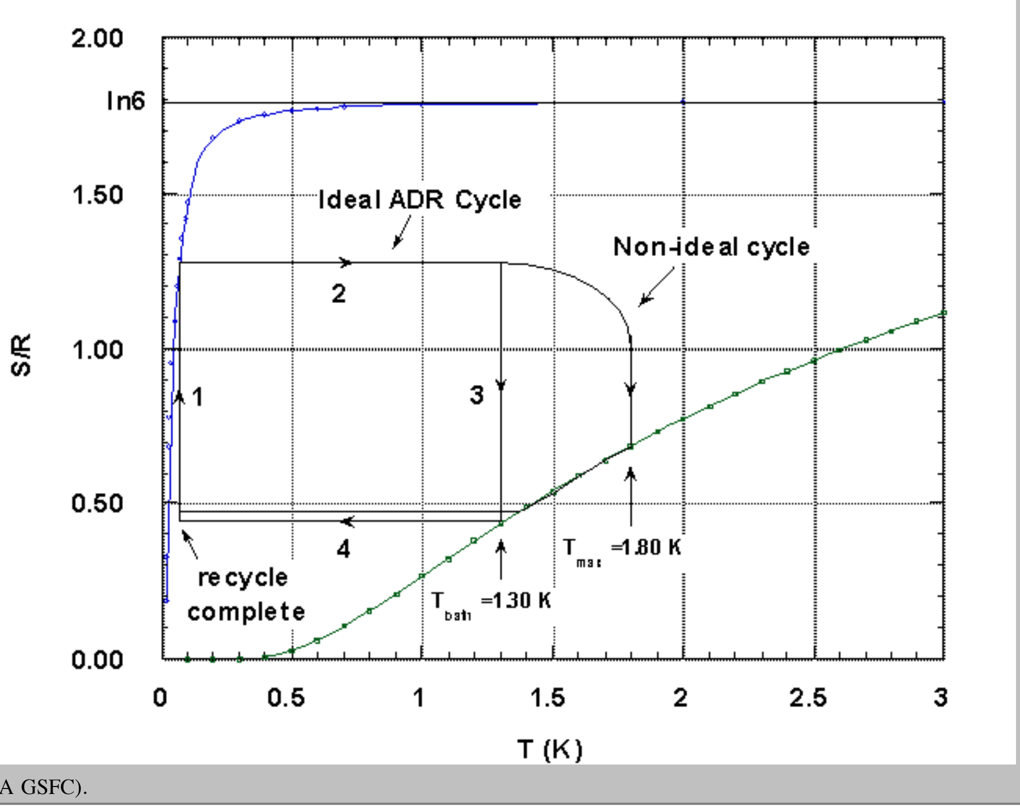
| | An example of an ADR cycle is shown in the figure below. The temperature regime shown corresponds to test parameters during the design of the fridge. Steps 1-4 form a closed cycle. Thus, the heat engine returns to its initial state. |

Textbook



Courtesy: Dr. Peter Shirron (NASA GSFC).

Question

1. Explain the terms adiabatic and isothermal.
2. Look at the ADR cycle. Does it correspond to a Carnot cycle? Explain.
3. The ADR is a physical realization of the abstract textbook heat engine.
    - On the S-T (entropy-temperature) indicator diagram, indicate where heat is being extracted from the detector and where it is being dumped from the fridge.
    - How can the *work done* be deduced from the indicator diagram?
    - Can you deduce why the two cycles labeled are respectively labeled *ideal* and *non-ideal*?
4. How does the heat dumped into the heat sink compare to the heat extracted from the detector?
5. How is the efficiency of a refrigerator defined?

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## Part IV: Summary

- The ADR manages to move heat from the cold detector to the warm heat bath by having its own temperature cycled. When its temperature is lower than that of the detector, heat flows into it from the detector; this is how heat is extracted from the detector.

- The energy is now stored in the paramagnetic salt of the ADR. Thus the amount and specific heat capacity of the salt (and its spin system) are important parameters.

- The temperature of the salt is then brought up to just above that of the heat sink (via the use of the external magnetic field), when the heat again conducts naturally to the cooler heat sink.

## Part V: Into the Future

The ADR described above is what will be flown in the upcoming NASA mission. Some of you might already be asking the following question: if the salt in the ADR stores the heat energy, what happens when it is "full"? This is, indeed, a concern since one would then have to shut down the detector while the ADR is being "emptied" into the heat sink. In fact, Dr. Shirron's group is currently working on solving this problem.

***Do you have any idea how to solve this problem?***

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## References

1. C. J. Adkins. *Equilibrium Thermodynamics*, 3rd edition, Cambridge University Press, 1983..
2. C. Stahle, D. McCammon, and K. Irwin. "Quantum calorimetry." *Physics Today* **52** (8), 32 (1999).

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