Tips for Success When Using an ADR Cryostat

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In the Fall 2013 issue of ***Cold Facts***, we discussed when an Adiabatic Demagnetization Refrigerator (ADR) cryostat is the right tool for the job. Here we will discuss how to effectively use an ADR.

Review of entropy and the principle of adiabatic demagnetization

Entropy is often explained as the measure of disorder in a thermodynamic system. ADRs employ materials that have two relevant sources of entropy, thermal and magnetic. In a simple sense, an ADR works by transfering entropy between the material's thermal and magnetic entropy components.

ADR cryostats produce cooling by cycling the magnetic field applied to a paramagnetic refrigerant material (commonly referred to as a "salt pill" since many of the materials are paramagnetic salts). When the salt pill is subjected to a magnetic field, its magnetic regions (spins) will align, becoming orderly, with a corresponding decrease in magnetic entropy. During this process, the lost magnetic entropy is converted to thermal entropy, resulting in an increase in temperature. If this process happens with the salt pill heat-sunk to a cooling source, this heat is conducted away, and the temperature is held constant during the magnetization process. This step is called isothermal magnetization, and is shown in Figure 1 as the path between points A and B. Typically the cooling source is either liquid helium (at 4.2K) or a cryocooler (at ~3K). The adiabatic cooling process occurs when, after thermal equilibration is complete, the salt pill is disconnected from the cooling source (by opening a heat switch; refer to Figure 2) and the magnetic field is reduced, shown as the line going from points B to C in Figure 1. When the salt pill is thermally isolated, reducing the magnetic field causes the temperature of the paramagnetic material to fall toward its "ordering" temperature. One common ADR salt material, ferric ammonium alum (FAA), has an an ordering temperature near 26mK.

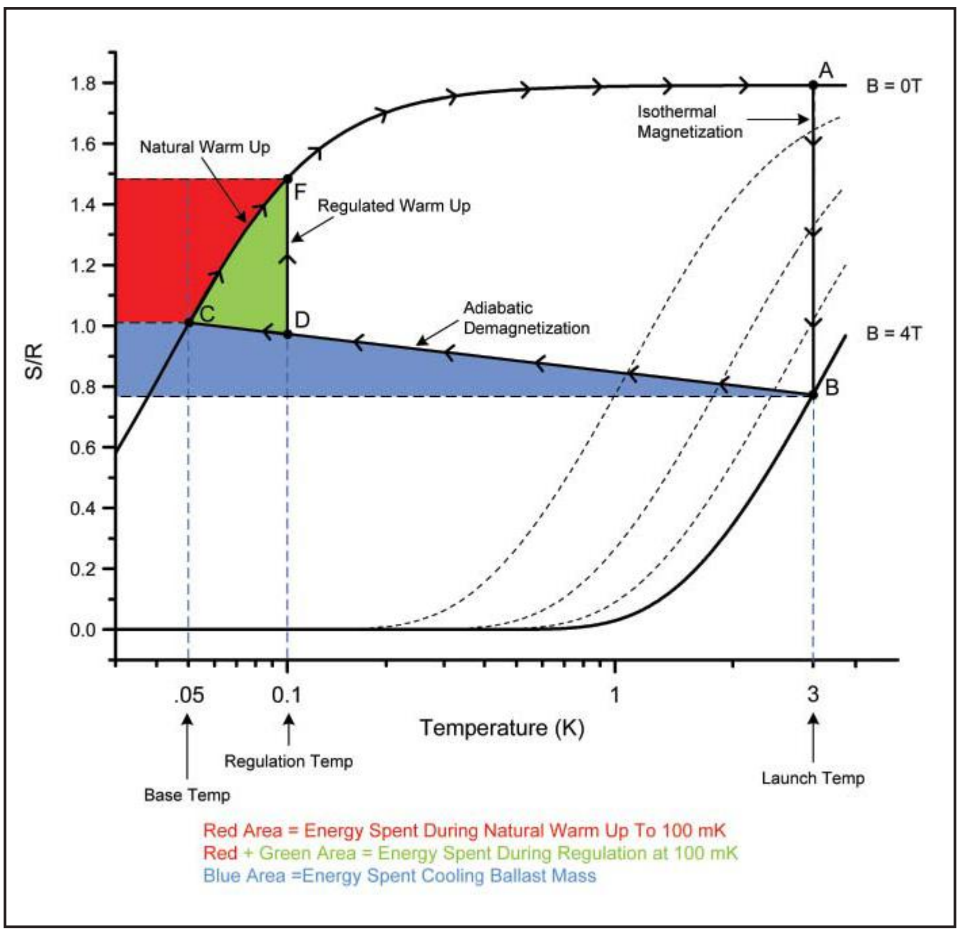

Figure 1: Entropy as a function of temperature and magnetic field

"Single-shot" cooling

Most ADRs offer a "single-shot" cooling approach. This means that once the pill's entropy has increased to the point where it can no longer maintain the desired temperature and the magnetic field has decreased to zero, the system then needs to be recycled. Depending upon heat load, common ADRs can offer cooling durations anywhere from a few minutes to on the order of a week. Most of the discussion here concerns single-shot ADRs.

Continuous Adiabatic Demagnetization Refrigerators (CADRs)

ADR systems can be devised by using multiple magnets, salt pills and heat switches to provide continuous cooling. CADRs are significantly more complex than single-shot ADRs, but offer the great advantage of being able to maintain their regulation temperature indefinitely.

What variables affect salt pill base temperature and hold time?

The base temperature that can be achieved for a given refrigerant is determined by three things: the ballast mass of the experimental setup, the "launch" temperature of the system and the initial magnetic field strength.

The amount of time that the system can be kept at a given temperature (the "hold time") is a function of the size of the salt pill and the rate of steady-state heat flowing into the paramagnetic material. The contributors to this heat load are, typically, support system conduction, conduction through the experimental wiring, blackbody radiation from warmer surfaces and energy dissipated by the experiment.

Optimizing the magnet cycle

Users can obtain better performance from the system by following a few simple techniques.

1) **Achieve a good soak.** In order to maximize the cooling energy, the salt material must fully cool to the heat sink temperature. The user can help ensure this by allowing adequate time for equilibration to occur when the magnet is at full field.

2) **Demagnetize the system slowly.** Slowly demagnetizing the system allows the heat from the experimental load to flow into the paramagnetic material while it is at a higher temperature, where, thermodynamically, it has more cooling capacity. Additionally, decreasing the magnetic field slowly reduces the amount of eddy currents that develop in metallic parts.

3) **Reduce the launch temperature.** Although sometimes the launch temperature of an ADR system is relatively fixed, oftentimes it can be improved by paying attention to the system setup, such as reducing conduction loads or radiation loading coming from your intermediate cooling stage.

4) **Subsequent magnet cycles.** In practice, the experimental setup, and other items that contribute to ballast mass, are imperfectly attached to the refrigerant material. This means that their thermal equilibration may be delayed by several minutes, or even hours. As a result, improvements in performance are often realized between the first and subsequent demagnetization cycles.

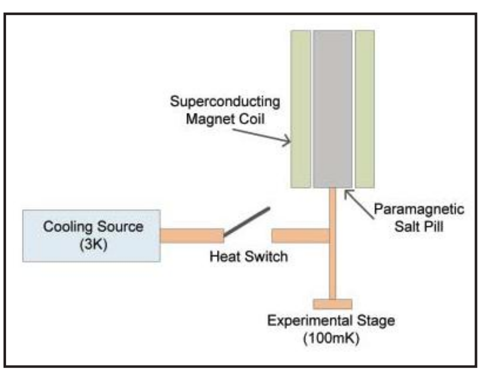

Figure 2: Schematic of components of an ADR cryostat, including superconducting magnet, paramagnetic salt pill, heat switch, experimental stage and cooling source

The benefit of regulating base temperature

If the user is conducting an experiment that must occur below a certain temperature, there is an advantage to isothermally demagnetizing the system (using the magnetic field to control the temperature), as opposed to reducing the magnet current to zero and then allowing the salt pill to warm up. Because entropy is a function of temperature, if the pill's temperature is intentionally kept higher there will be more cooling energy available than otherwise.

Let's consider two scenarios and compare the available cooling in each. In both situations we will assume that the ADR will be recycled when it no longer can provide cooling below 0.1K.

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In the first scenario, the ADR is allowed to cool until the magnet current has reached zero, and then the ADR provides cooling until the salt pill has naturally warmed to 0.1K. The available cooling energy is represented by the area in red in the graph of Figure 1. In the second scenario, the user lowers the magnetic field until the salt material reaches 0.1K and then regulates the magnet current so as to maintain 0.1K, until the magnet current has been depleted. This second method is called isothermal demagnetization. The additional cooling in the second scenario is shown in the green area of Figure 1.

Tradeoffs of hold time versus regulation temperature

As we saw above, the amount of cooling energy is dependent upon the temperature of the salt pill during the regulation period. This means that a user can apply a thermal economy mindset to experimenting, knowing that longer hold times are possible if a higher regulation temperature is used.

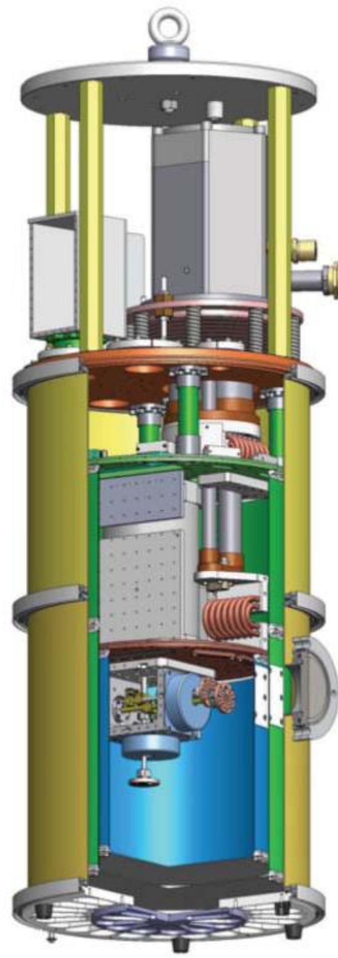
Methods to extend experimental time

Assuming that the experimental temperature is fixed and thus the available cooling energy of the paramagnetic material is constant, there are several things that can be addressed in the experimental setup that will serve to optimize the hold time.

The parasitic heat leak from the experimental wiring can be minimized by choosing conductors with poor thermal conductivities. Phosphor bronze and constantin are popular choices, along with NbTi.

It's important to include generous lengths of the conductors as they travel between the different temperature stage plates.

The user should make sure that all conductors are thermally attached in a manner that ensures their thermal equilibration at the various stages.



Section view of HPD's Model 103 ADR Cryostat. The Model 103 is one of a family of commercially available ADR cryostats.

What is a quench?

ADRs typically employ a superconducting magnet to generate the polarizing magnetic field. If at any time during the magnetic cycle any portion of the superconducting circuit ceases to be superconducting (i.e. goes "normal"), Joule heating in the non-superconducting portion of the circuit quickly causes the neighboring portions of the circuit to go normal. Once this process begins, the phenomena of the material going normal cascades through the system and the whole circuit is quickly driven normal and a quench has occurred. During a quench, the energy stored in the magnet is nearly instantaneously converted to heat. If possible, quenches should be avoided. At a minimum, this event interrupts the experiment and, more seriously, it can result in damage to the cryostat.

How to avoid a quench

Superconducting materials have a critical current. This is the current density below which they remain superconducting. This critical current value is temperature dependent, increasing as the temperature of the material is reduced below the critical temperature.

In an ADR, quenches are typically caused by one of three things: an increase in the magnet current above the critical current of one of the superconducting materials, an increase in the temperature of the system (or, more specifically, the superconducting circuit material) above the critical temperature for that given current level, and exceeding the threshold voltage of the protection diodes.

Accordingly, one of the best ways to avoid a quench is by knowing the maximum-rated current of the system at its operating temperature and then staying below that current level by a safe margin.

Since a magnet is an inductor, changing its current results in an opposing electromotive potential (i.e. back EMF voltage). Avoiding a quench caused by exceeding the diode threshold voltage requires two things of the operator: knowing the relationship, for the subject magnet, of the current ramp rate and the resultant back EMF voltage and knowing the threshold voltage of the diode. From those two things the operator can easily define ramp rates whose back EMF values are well below the diode threshold voltage, thereby avoiding a magnet quench.

Knowing your cryostat's behavior

Becoming familiar with the different phenomena in an ADR cryostat can help one become familiar with the system's limitations. This familiarity will help the user operate the system safely and effectively. Hopefully these tips support that mission.