

Liquid Nitrogen Energy Storage Units

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ABSTRACT

The energy storage units (ESU) described in this article are to be attached to the cold finger of a cryocooler with the objective of holding the low temperature environment constant while the cooler may be temporarily stopped to provide a totally vibration-free environment. Or, it may be used to damp out temperature fluctuations if a sudden cooling power increase is momentarily necessary.

The developed ESU consists of a nitrogen cell coupled to a GM cryocooler by a gas-gap heat switch, and connected to an expansion volume at room temperature to limit the pressure increase. It was designed to store ≈ 3600 J between ≈ 65 K and ≈ 80 K. After condensing the nitrogen into the liquid phase, the heat switch is used to decouple the cell from the cryocooler, and a constant heating power is applied. During the liquid evaporation, the temperature drift obtained is very slow.

In this paper, we present the tests performed using a 35 cm³ cell and an expansion volume of 6 litres or 24 litres. Applying 1 W to the ESU, about 4 kJ were stored with a slow drift from 76 K up to 80 K using the 24 litres expansion volume. Modelling of the experiment agrees within 5% with the experimental results. Software, written for sizing such an ESU, includes parameters for the ESU's stored energy, the cell and expansion volumes, and the cryogenic fluid used.

An ESU using the liquid-gas latent heat leads to a slow temperature drift, while a triple-point cell keeps the temperature strictly constant. However, such an ESU stores a thermal energy one order of magnitude larger than a triple-point one for the same low temperature cell volume.

Preliminary results for a gravity insensitive ESU are presented.

INTRODUCTION

New technologies allow construction of more and more sensitive sensors, the price we pay being that in many cases they must work at cryogenic temperatures. A great part of the investigation done on cryocoolers is to provide a stable low-temperature base consistent with a low power and mass budget. Moreover, a vibration-free platform also becomes more and more mandatory for such high precision sensors. This has resulted in modestly complex mechanical systems being proposed to significantly reduce the vibration level [1,2], but with associated cost and mass increase. A challenge for the cryogenists!

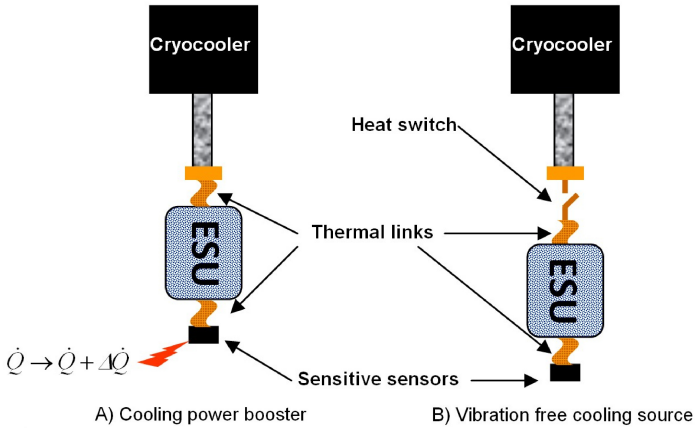


Figure 1. Two possible utilizations of an Energy Storage Unit:

A) In this configuration, the ESU is thermally coupled to the cold finger. In case of sudden heat burst of increase of dissipation sensors ($\Delta\dot{Q}$), the heat is adsorbed by the ESU without significant temperature change [3].

B) In this configuration, the ESU is firstly cooled down through the heat switch in its conducting state. After this phase, the switch is turned off (low conducting state). The cryocooler can be stopped (no vibration) and its natural warming does not heat the ESU. In this phase, the energy dissipated by the sensors is absorbed by the ESU [4, 5, 6].

One solution to solve or to reduce these issues is to use Energy Storage Units (ESU or Thermal Storage Units - TSU). These devices consist mainly of low temperature cell able to absorb energy without significant temperature change. To store thermal energy, they can use the thermodynamic properties of the triple point [3, 4]. In such a case, the energy input is absorbed thanks to the latent heat of solid to liquid (SL) transformation, and, at the triple point, the temperature remains strictly constant. ESUs can also use the high specific heat of some materials in order to reduce the temperature increase on heat input [5, 6]. In this article, we describe a cryogenic energy storage unit (ESU) working in the 65K - 80K temperature range that can be used alternatively (Figure 1):

- For reduction of the temperature drift in a case of sudden heat bursts;
- To reduce the temperature drift when more cooling power is temporarily needed;
- When a vibration free cold source is needed.

This system uses the latent heat of the liquid to gas (LG) transformation of nitrogen as energy absorber. In respect to a triple point ESU, such a system presents two main advantages:

- The LG latent heat ($\gg 200$ J/g) is significantly larger than the SL one ($\gg 26$ J/g) and then more energy can be stored for the same volume (or mass) at low temperature.
- One can choose the working temperature in a rather large temperature range.

The main disadvantage is that the temperature is not stable “by construction” as it occurs in the triple point systems. However, if some temperature drift can be admitted, such a system can find useful applications.

LIQUID-GAS ESU

Experimental Setup

Along the saturation curve, heat input leads to liquid evaporation. If the low temperature cell containing the cryogenic fluid is closed, this gas formation leads to a pressure increase. The temperature then rises quite rapidly as far as liquid and gas coexist. To reduce this temperature increase, our low temperature cell is connected by a capillary to an expansion volume at room

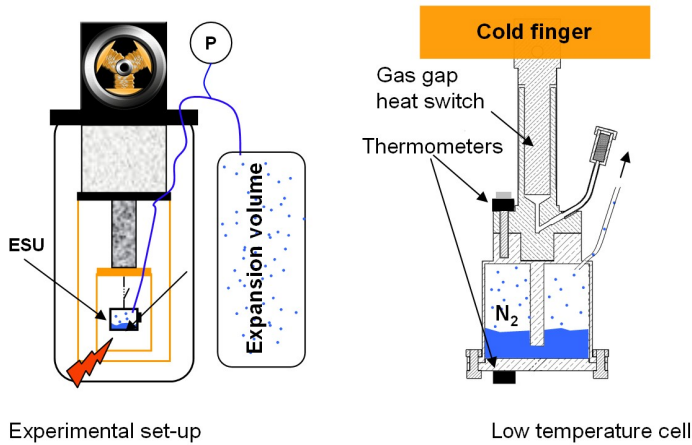


Figure 2. Scheme of the experimental set-up and of the low temperature experimental cell.

temperature in order to limit the augmentation of the pressure (Figure 2). In our system, an expansion volume of 6 litres and 24 litres were alternatively used. Let us point out that such an expansion volume has another advantage: it is also used as a storage volume when the whole system is at room temperature and then allows working with quite low gas charge pressure and thin cell walls. As a matter of fact, a low temperature closed cell filled with liquid at low temperature would lead to a huge pressure at room temperature: for instance, such a cell filled with N_2 at 77K (1 bar) would lead to pressure around 700 bar at 300 K. This advantage was recognized even in the case of triple point ESU where an expansion volume as large as 17 liters was used to store 3000 J at 63 K [3]. In our system, the use of an expansion volume allowed us to work with a charge pressure below 2 bar. Our low temperature cell (volume $\approx 35 \text{ cm}^3$) was made of copper with a brass cover. It was thermalized to the cold finger of a 4 K Gifford MacMahon cryocooler by a gas gap heat switch [7, 8] using nitrogen as the conducting gas and a small cryopump in order to toggle between the conducting (ON) and isolating (OFF) states.

In the OFF state (cryopump temperature below 100 K), its thermal conductance is around 1 mW/K at $\approx 70 \text{ K}$ and reaches 80 mW/K in the ON state (cryopump temperature above $\approx 130 \text{ K}$). This thermal switch in the OFF state leads to a good adiabaticity of the low temperature cell and then allows a reliable thermal characterization of the ESU. The cell temperature was measured by thermometers thermalized on the upper part (T_{up}) of the cell and on the brass cover (cell bottom, T_{bottom}). The pressure in the cell and in the expansion volume was measured at room temperature outside the cryostat. As long as liquid and gas coexist, this pressure can be transformed in temperature (T_{liq}) by the correspondence P - T on the saturation curve [9] and was used to determine the temperature inside the cell (T_{liq}). A heating resistor was thermalized on the top of the cell.

ESU Characteristics Determination

The expansion volume was filled at a determined charge pressure allowing the calculation of the total N_2 amount (typically $\approx 2 \text{ bar}$ in the 6 liters expansion volume, 1.5 bar in the 24 L volume, corresponding to $\approx 0.5 \text{ mole}$ and $\approx 1.5 \text{ mole}$ respectively) and opened to the cell. In the first phase, the cell is cooled down to T_{min} with the heat switch in the ON state. This T_{min} is an adjustable parameter mimicking the lowest temperature of a less powerful cryocooler than that used in our experiment. When the pressure and the temperature of the system correspond to a point on the vaporization curve, the gas begins to condense in the low temperature cell. Further cooling leads to an increase of the liquid amount in the cell and to a pressure decrease. During

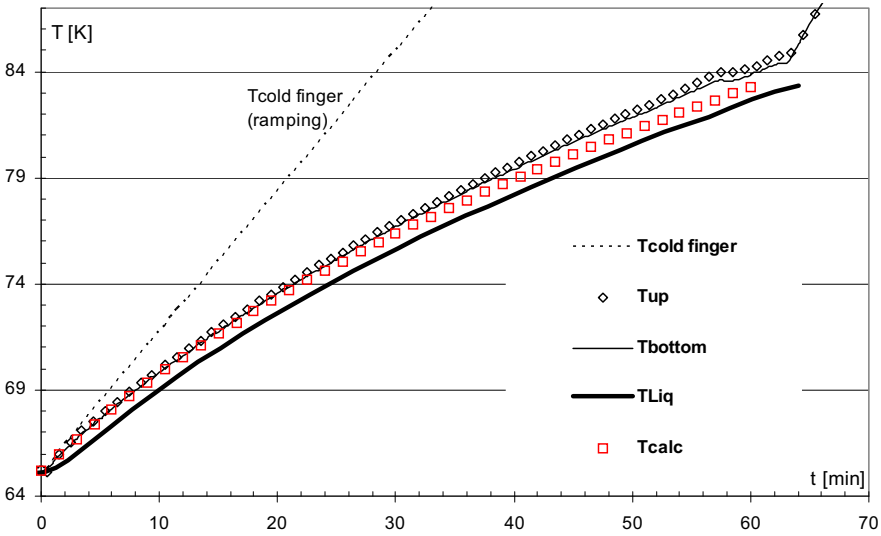


Figure 3. Temperature drifts while applying 1 W starting from $T_{min} = 65$ K (Charge pressure: 2 bar; expansion volume: 6 litres). The lines Tliq and Tcalc end when the liquid quantity vanishes.

this phase, the low temperature cell acts as a pump for the expansion volume, and T_{min} determines the minimum pressure reached by the system. The knowledge of the total N_2 amount, the pressure, the temperature, and the gas and liquid densities allow the determination of the liquid quantity in the cell (If $T_{min} \approx 65$ K, 39% of the cell volume is filled with liquid for an initial charge pressure of 2 bar in the 6 litres volume). When the temperature T_{min} was reached, the switch was toggled to the OFF state (2nd phase). Once this state is reached, a constant heating power started to be applied (3rd phase, ESU mode) and temperature and pressure were recorded up to total liquid evaporation. In most cases, the cryocooler cold finger temperature was ramped (0.3 K/min to 0.8 K/min) in order to mimic its natural warming after the cryocooler is stopped.

Figure 3 shows the temperature evolution of the cell with 1 W as the constant heating power applied at $t=0$. In this run, the charge pressure was 2 bar and the cell was cooled down to $T_{min} = 65$ K. At $t \approx 64$ min, the temperature drift increases drastically indicating that no more liquid exists in the cell and then the heating power is dissipated mainly by an increase of the copper housing temperature. The difference between the temperature measured by thermometers and by the gas pressure (≈ 1 K to 1.5 K) can be attributed to the thermal resistance between the liquid or the gas and the cell walls. Such thermal resistance may happen, since the cell was built without a special heat exchanger. This ESU mode time (≈ 64 min) corresponds to 3800 J stored by this ESU between 65 K and 84 K. Let us point out that to store this thermal energy between the same two temperatures without LN2 would require almost 1 kg of copper (or 500 g of aluminum), whereas the mass of our low temperature cell is around 150 g, and is yet to be minimized.

Experimental results were compared with what can be expected from nitrogen properties along the saturation curve. As already explained, the total amount of N_2 in the system as well as the initial percentage of liquid and gas can be calculated. Using the first law of thermodynamics for an open system (low temperature cell), the heat necessary to increase the temperature from T to $T+\Delta T$, $Q(T \rightarrow T+\Delta T)$, can be calculated as:

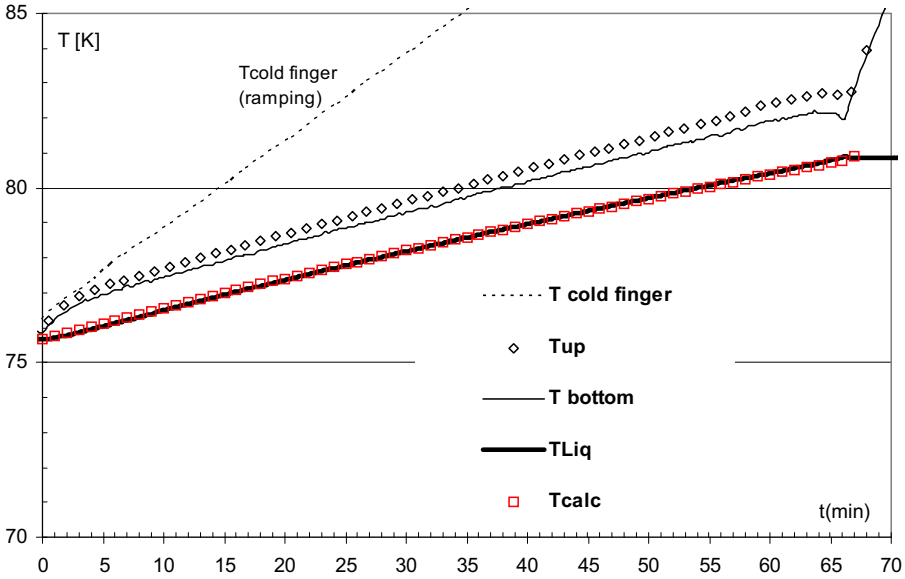


Figure 4. Temperature drifts while applying 1 W starting from $T_{min} = 76$ K (Charge pressure: 1.5 bar; expansion Volume: 24 liters). The lines T_{gas} and T_{calc} end when the liquid quantity reaches 0%.

$$Q(T \rightarrow T+\Delta T) = U_{cell}(T+\Delta T) - U_{cell}(T) - \Delta n h_{gas} + C \Delta T \quad (1)$$

In this expression, U_{cell} is the total internal energy of nitrogen (liquid and gas) existing in the cell, h_{gas} the molar enthalpy of the gas at temperature T , and Δn the amount of gas that flew out of the cell during this incremental small heating. C is the total heat capacity of the cell housing. Using the thermodynamic properties of nitrogen along the saturation curve (internal energies and densities of the liquid and gas phases, gas enthalpy), the temperature increase ΔT after each incremental small heat input can be calculated and the $T(t)$ drift entirely determined using the initial conditions as unique input parameters. These calculations by iteration were made using a programmed worksheet and the calculated temperature drift is plotted in Figure 3 (T_{calc}) for a charge pressure of 2 bar in the 6 liters expansion volume. The end of this line corresponds to the vanishment of liquid. Calculated and experimental results agree within 5 %. Let us note that a correction of about -4% on the expansion volume or on the heating power leads not only to a better agreement between the $T(t)$ curves, but also to a perfect prediction for the total evaporation time and then of the total energy absorbed.

In some cases a temperature drifting from 65 K to 84 K can be unacceptable: a solution to limit this drift is to increase the expansion volume. Similar experiments were performed using a 24 liter expansion volume, and the experimental results are displayed in Figure 4. In this experiment, the charge pressure was around 1.5 bar (1.5 mole) and the cell was cooled down to $T_{min} \approx 76$ K only. In such initial conditions, the cell is 64% filled ($\approx 22 \text{ cm}^3$) and the pressure in the expansion volume is a little less than 0.86 bar (saturation pressure at 76 K). Applying 1 W, the gas temperature drifts only ≈ 5 K (from ≈ 76 K up to ≈ 81 K) in ≈ 67 min while storing ≈ 4000 J. The iterative calculation previously explained succeeds to describe this temperature drift.

If such a system has to be used in space where gravity effects are very small, a special attention must be paid to avoid the pressure increase pushing the liquid outside of the cell. As a matter of fact, if this occurs, the heat storing material (liquid) becomes useless! This issue is well

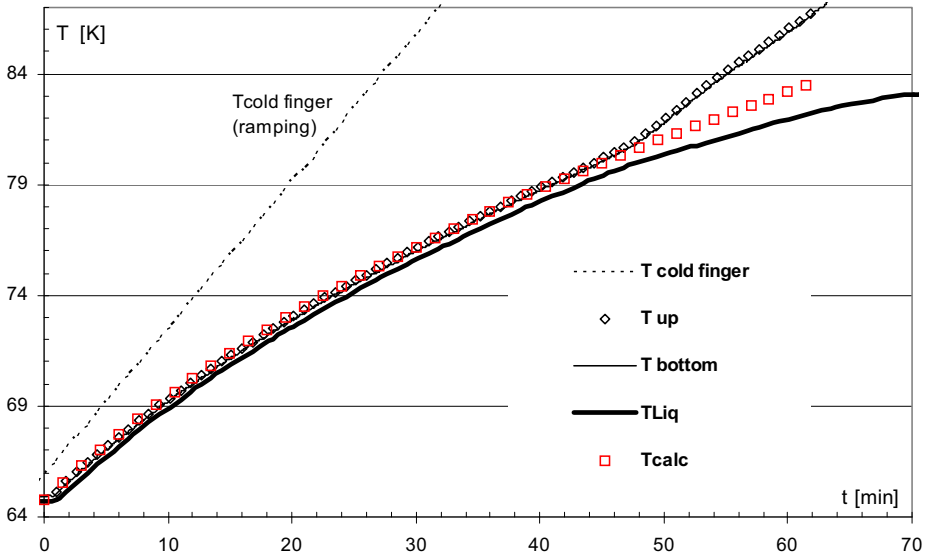


Figure 5. Low temperature cell filled with porous ceramics. Temperature drifts applying 1 W starting from $T_{min} = 65$ K (Charge pressure: 2 bar; Expansion Volume 6 liters). The line T_{calc} ends when the liquid quantity reaches 0%.

known and is usually solved using a spongy medium in which the liquid is retained by the capillarity effects [4, 10]. The cell described in Figure 2 was then filled with one piece of alumina ceramic ($\approx 90\%$ void, typical pore size $\approx 9 \mu\text{m}$) fitting the cell dimensions. Experiments similar to those previously described were performed to test the influence of this porous medium. The experimental results displayed in Figure 5 correspond to very close experimental conditions of those of Figure 3 (2 bar as charge pressure, $T_{min} \approx 65$ K), but the ceramic sponge inside the cell. The results of thermodynamic calculations are also plotted to compare with what can be expected. Two differences appear: The most evident occurs around $t \approx 48$ min ($T_{liq} \approx 80$ K). Before this time, the calculated result agrees quite well with the experimental one “as usual.” However, for $t > 48$ min, the temperature of the cell housing (measured by thermometers) starts to diverge clearly from the liquid temperature (measured by the pressure sensor) increasing faster, whereas the T_{liq} drift slows down. From this point on, the liquid quantity is below $\approx 10\%$, and this “critical” percentage appears in all the experiments done with this ceramic piece (different heating powers, expansion volume of 24 litres). The second difference appears by comparing the experimental results with (Figure 5) and without the ceramic (Figure 3). In Figure 3 the temperature difference between the copper housing and the liquid-gas mixture varies between 0.8 K and 1.5 K. With the porous ceramic (Figure 5), this ΔT is as small as ≈ 0.4 K (at $t \approx 10$ min) and remains systematically at least twice smaller than in the “no ceramic” case up to $t \approx 46$ min suggesting a better thermalization between cell walls and fluids. From $t \approx 46$ min on, this ΔT starts to increase very rapidly.

These two regimes (“small ΔT ” and “large ΔT ”) could be explained as follows: At the beginning, when the liquid percentage is relatively high, there is always some liquid N_2 near the cell walls due to capillarity effects (eventually only a liquid film fills the whole porous ceramic). Then, on heating these walls (the heater is located outside of the cell), the thermal energy is dissipated by evaporation of this liquid: a good thermal contact exists between the cell housing and the liquid. Below a certain “critical” liquid percentage (something to do with “below a percolation threshold”), no more liquid wets the walls, and the heat conduction becomes ensured

by the gas inside the ceramic or by the ceramic itself. This material, an electrical insulator, is a poor thermal conductor, and its highly porous structure leads to a very bad thermal conductance of the ceramic piece; moreover, it inhibits any gas convection. Then, below this “critical” percentage, a significant temperature gradient can exist through the cell. The cell walls are hot, whereas deep inside the ceramic the temperature is significantly colder. In our case, and in our geometry, this critical percentage would be about 10 %. Further investigations are in progress to confirm this explanation. If confirmed, a solution could be found by installing copper thermal links in the ceramic piece to improve the temperature homogeneity or by using a metallic foam.

CONCLUSION

The ESU prototype presented here is able to store up to 3800 J between 65 K and 84 K using a 6 litre expansion volume, or up to 4000 J between 76 K and 82 K using a 24 litres expansion volume. This somewhat large expansion volume at room temperature is the price one pays to store this thermal energy in a quite small volume at low temperature. The thermodynamic model agrees within 5% with the results, and software able to calculate the temperature drifts versus the various parameters is available in ref. [11].

For ground applications, in which gravity maintains the liquid in the bottom of the cell, and large expansion volumes are allowed, this type of liquid ESU can be a good solution to avoid large temperature drifts during heat bursts or to obtain a vibration free cold source after a cryocooler stop. A gravity insensitive ESU is under development.

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REFERENCES

1. Ikushima Y. et al., “Ultra-low-vibration pulse-tube cryocooler system – cooling capacity and vibration,” *Cryogenics* 48 (2008), pp. 406–412.
2. Veprik A, Nachman I., Pundak N., “Dynamic counterbalancing the single-piston linear compressor of a Stirling cryogenic cooler,” *Cryogenics* 49 (2009), pp 165–170.
3. Bugby D, Marland B., “Cryogenic Thermal Storage Units,” *Spacecraft Thermal Control Handbook, Volume II: Cryogenics*, Editor: M. Donabedian. The Aerospace Press (2003), pp 409-433.
4. Rijpmma AP *et al.* “A nitrogen triple-point thermal storage unit for cooling a SQUID magnetometer,” *Cryogenics* 45 (2005); pp 231–239.
5. Bonfait G. *et al.* “20 K Energy storage unit,” *Cryogenics* 49 (2009), pp 326–333.
6. Catarino I. *et al.*, “6 K Energy storage unit,” *Cryogenics* 50 (2010), pp 102-110.
7. Catarino I., Bonfait G. and Duband L., “Neon gas-gap heat switch,” *Cryogenics* 48 (2008), pp 17-25
8. D. Martins *et al.*, “Customizable gas gap heat switch,” *Adv. in Cryogenic Engineering*, Vol. 55, Amer. Institute of Physics, Melville, NY (2010), pp. 1652-1660.
9. Lemmon EW, Huber ML, McLinden MO. *NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties-REFPROP*, Version 8.0, National Institute of Standards and Technology, Standard Reference Data Program, Gaithersburg, (2007).
10. Castles S. H. and Schein M. E., “Development of a Space Qualified Surface Tension Confined Liquid Cryogen Cooler,” *Adv. in Cryogenic Engineering*, Vol. 33, Plenum Publishing Corp., New York (1988), pp. 819-826.
11. <http://www.activespacetech.com/esu/index.html>

