Energy Storage Unit
Summary Report

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CONTRACT REPORT

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Contents

1 Introduction

1.1 Scope

This document constitutes the Summary Report of the demonstration of feasibility and use of “Energy Storage Units for Cryocoolers”. The Energy Storage Unit is being developed by *Active Space Technologies* and *Universidade Nova de Lisboa* under the *European Space Agency’s* contract no. 20023/06/NL/PA.

The Energy Storage Unit, or ESU, provides a vibrationless environment to spaceborne instrumentation, while providing large observation windows at cryogenic temperatures.

1.2 Documents

1.2.1 Applicable Documents

[AD1] ESTEC Contract No 20023/06/NL/PA
[AD2] Low-temperature Energy Storage Unit (ESU), FCT-UNL, A00004001, 26/10/2005

1.2.2 Reference Documents

[RD1] http://cryogenics.nist.gov/MPropsMAY/material%20properties.htm.
[RD2] *Neon gas-gap heat switch*,Catarino, I., Bonfait, G. Duband, L, Cryogenics 48, 1-2, 2008
[RD3] *Vibration analysis of cryocoolers*, T. Tomaru et al., Cryogenics, 44 (2004) 309-317.
[RD4] *Heat capacities of potential regenerator materials at low temperature*, I.A. Tanaeva et al., proceedings of ICEC 19, Narosa Publishing house, 2002
[RD5] *A thermal switch for use at liquid helium temperature in spaceborne cryogenic systems*, Duband, L. 1995,Proceedings of the 8th International Cryocoolers Conference, Vail Colorado USA, Plenum Press 731-741
[RD6] *ESU Support Structure*, Active Space Technologies, January 2008.
[RD7] http://www.activespacetech.com/~webtest/

1.3 Acronyms and Abbreviations

A	Surface
AST	Active Space Technologies
BC	Boudary Condition
CB	Cold Block (of the GGHS)
CF	Cold Finger
Cp	Specific heat (constant pressure)
EM	Electromagnetical
ER	Enthalpy Reservoir
ESU	Energy Storage Unit
FCT-UNL	Faculdade de Ciências e Tecnologia – Universidade Nova de Lisboa
FE	Finite Element
FEA	Finite Element Analysis
FEM	Finite Element Method
FOS	Factor of safety
GGHS	Gas-Gap Heat Switch
GOS	Gd_2O_2S
H	Enthalpy
HB	Hot Block (of the GGHS)
HS	Heat Switch
L	Length
L/V	Launch Vehicle
MOS	Margin of safety
NIST	National Institute of Standards and Technology
P	Pressure
Q	Heat (Energy)
R	Thermal resistance
S	Entropy
Sorb	Sorbent = cryopump
SS316	Stainless Steel 316
SSSS	Stainless Steel Supporting Shell (of the GGHS)
T	Temperature
T	time
TRL	Technology Readiness Level
TS	Thermal Switch
VM	Von Mises
Δ	Gap width
κ	Conductivity

2 Objectives

The objective of this contract was to prove that no-vibrations-no-electromagnetic-noise environment below 20 K or below 6 K is possible using **Energy Storage Units** (ESU), allowing the use of very sensitive sensors in these temperature ranges. In such a device, an Enthalpy Reservoir (ER) is connected to the Cold Finger (CF) of a cryocooler by a Heat Switch (HS), sensors as thermometer or detectors being thermalized to this ER. To use this ESU, the ER is cooled down to the cryocooler lowest temperature, the HS being in the ON state (high thermal conduction state), in the first step. This cooling down is very efficient but leads to a rather noisy environment due to the pressure oscillations and electromagnetic noise produced by the motor driving the cryocooler. In the second step, the HS is turned OFF (very low thermal conductance state). The third step starts by turning OFF the cryocooler: the CF temperature begins to drift naturally (and rapidly) to high temperature. Due to the HS OFF state, the ER is almost thermally isolated and its temperature increases mainly because of the power dissipated on this ER by the sensors. Thanks to the high enthalpy of the ER, this temperature drift can be very slow: measurements can be done in a totally quiet environment during a long time, allowing high precision measurements with highly sensitive sensors.

In order to facilitate ESU optimizations, a database on high specific heat materials and heat switches were built (Section II). A Gas Gap Heat Switch (GGHS), loaded with Hydrogen or Helium, was experimentally characterized in the OFF and ON state. These results for conductivity were compared with theoretical semi-analytical results and with Finite Elements (FE) method. To easily obtain the thermal characteristics of such switches, the software "SwitchWare" was developed [RD7]. All these results are described in section III. Enthalpy reservoirs using lead (Pb) and Gd2O2S (GOS) to keep temperature below 20K and 6 K respectively were studied and built (section IV). In the section V, we focus on the experimental results obtain with these ER coupled by the GGHS to the CF of a cryocooler. These results are compared with calculated predictions obtained by the software "ESUware" that simulates these ESU. In conclusion, some aspects needed to be clarified in order to obtain a fully functional ESU are discussed.

3 Databases: Switches and High Enthalpy Materials

The Enthalpy Reservoir (ER) holding time, i.e., the time that the ER can stay below a determined temperature with a given dissipated power, increases with the enthalpy difference between the final and the initial temperatures of the materials used:

$$\Delta H = H(Tf) - H(Ti) = \int_{Ti}^{Tf} CpdT \qquad HoldingTime = \Delta H / power$$

In order to increase ΔH without drastic ER volume/mass increase, materials with high specific heat at low temperature were searched in the literature. The NIST [RD1] provides the specific heat of many such materials. Most of them are lanthanide compounds in which a specific heat peak occurs due to a magnetic transition. Other data were collected for interesting materials for the 2K-50K range (mainly in ICC proceedings [RD5]), as well as for "construction materials" used for the ESU housing (copper, aluminium, stycast, etc). The specific heat of 47 materials was provided in an Excel file. As far as possible, the long-term stability and safety aspects were investigated: the worst material for health issue is the lead, the lanthanide compounds being relatively safe if manipulated with "normal" precautions.

The holding time also depends on the heat power arriving on the ER from the CF through the HS even in the OFF state. As higher is the thermal resistance in the OFF state, lower is this power, longer is the holding time. An extensive bibliographic research has been made, covering the last 25 years, in a trial of building a trade-off about heat switches. The gas gap heat switches [RD2] in which the gas management is obtained by a small adsorption pump appeared to be a good solution by its simplicity and by its nonexistence of moving pieces. This solution was adopted for this contract - as specified in the original proposal- and is described in the next section.

4 Heat Switch

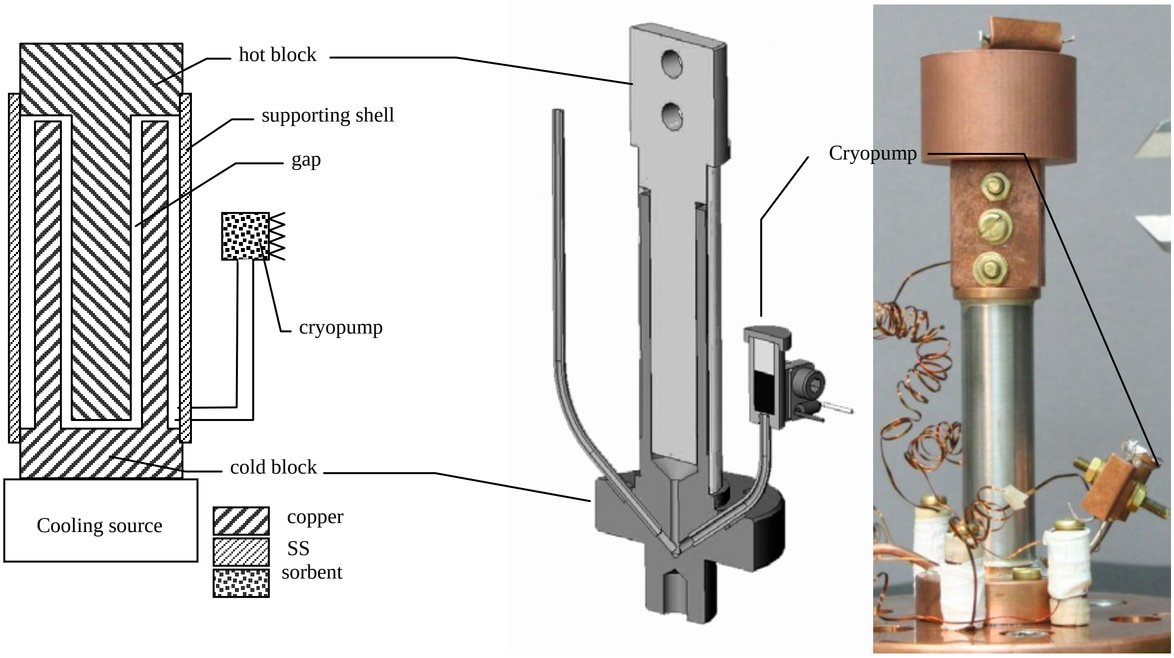

Figure 1: Gas-Gap Heat Switch [RD2]. Left and middle: The legend Hot and Cold Blocks refer to the switch use for the "ESU-Pb". As explained later in the text, for the ESU-GOS, the switch was inverted. Right: ESU Pb#2 coupled to the GGHS.

The heat switch used in this contract is displayed in figure 1 and was previously fully described and tested with Neon as an exchange gas [RD1]. In the OFF state, the cryopump is cooled down in order to adsorb completely the exchange gas: in this case, the only thermal path between the two switch ends (Cold and Hot Block) is the Stainless Steel Supporting Shell (SSSS). Its thermal resistance defines the maximum OFF state resistance and can be calculated using its geometrical characteristics and the stainless steel thermal conductivity. On heating up the cryopump, the adsorbed gas is released to the space between the two copper blocks, triggering a high conductance between these blocks thanks to the heat conduction through the gas. A more quantitative description of this switch and the thermal model used to analyse the results can be found in reference [RD2]. In order to easily calculate the ON and OFF thermal conductance, the software "SwitchWare" was written using the simple thermal model developed in this reference. The geometrical characteristics, the metals used for the different parts (supporting shell, hot and cold blocks), the base and maximum temperature at which the switch is planned to be used and the exchange gas are the input parameters. The software provides a table (power vs temperature) for these two states, using semi-analytical calculation.

Figure 2 displays some experimental results for the ON and OFF states (with H_2 as exchange gas) and are compared to the analytical ones and with those obtained via FEA: quite good agreements are obtained. The $\approx$10% discrepancy between the experimental and analytical results in the ON state is quite close to that found with Neon [RD2] at $\approx$ 20K and with ^{4}He at $\approx$ 5K (in this work). Such a systematic error shows that it could be due to 10% discrepancy between the actual and nominal geometrical dimensions. However, the very good matching between the experimental and FEA results in this ON state could indicate that the simple analytical model used has to be refined. The matching between FEA results and experimental results for the OFF state is less satisfying as it yields an error of 30% at 10 K that nevertheless converges to as little as 4% at around 90 K.

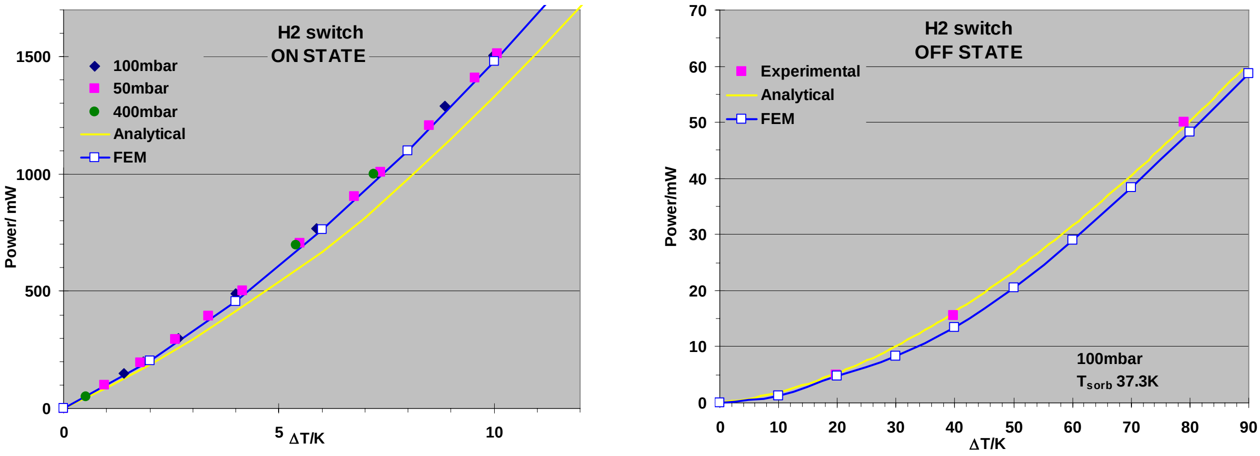

Figure 2: ON and OFF states switch conductance (H2). The cold block temperature was controlled at 11K and the power was applied to the hot block.

Very similar results were obtained for this switch filled with ^{4}He gas.

The cryopump temperatures needed to toggle the switch between the ON and OFF states are strongly dependent on the gas used. Figure 3 shows typical ON-OFF transition versus the cryopump temperature with Neon [RD2], H_2 and ^{4}He gases. As described in reference [RD2], the ON-OFF transition can be slightly tuned by changing the amount of gas introduced in the switch. For instance, with H_2 as exchange gas, with our switch geometrical characteristics, our results (not shown) indicated that this ON to OFF temperature can range roughly from 45 K up to 65 K.

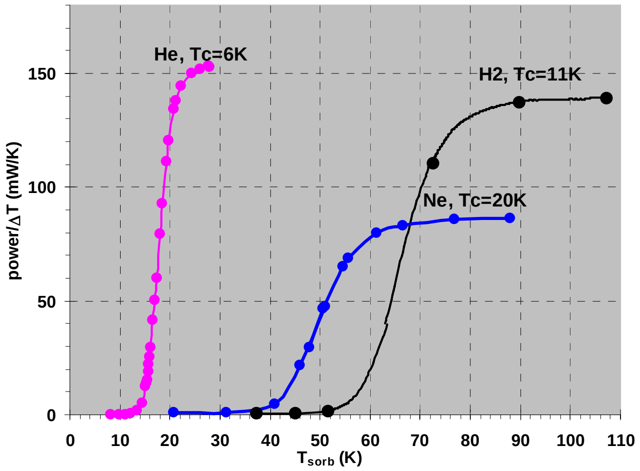

Figure 3: ON and OFF state transition with ^{4}He, H_2 and Ne. Tc denotes the temperature (fixed) of the cold block.

5 Enthalpy Reservoir

As mentioned in the proposal of this contract, ESUs were studied to maintain temperature below 20 K and 6 K[1], starting from 11K and 3 K, respectively. Three ER were designed and their main features are displayed on table 1.

	Initial Temperature	*Final temperature*	*heat load*	*holding time*	*Enthalpy*	*High-Cp material*	*volume calculated*	*Tested*
ER-Pb#1	11 K	20 K	10mW	7 h	252 J	Lead	70 cm^3	NO
ER-Pb#2	11 K	20 K	10mW	1 h	36 J	Lead	10 cm^3	YES
ER-GOS	3 K	6 K	10mW 1mW	1h 10h	36 J	Gd_2O_2S	24.6 cm^3	YES

Table 1: ER description

The ER volumes were calculated using a database providing the specific heat data of high specific heat materials between 1K and 50 K. The software "EnthalpyWare" was designed in order to easily dimension the ER and to take into account the copper housing of the high specific heat material. The starting and final temperatures, the total heat power applied, the material and the volume of the different parts of the ER are the input parameters, the outputs being the ER temperature drift and "holding time", i.e. the time during which the ER remains below the final temperature.

These ER were also studied by FE method in order to validate this technique in the case of more complicated geometries. As an example, the temperature profile was determined for the three ER applying a heat load power in different spots. The results showed that for ER-Pb the thermal diffusion time is much shorter that the temperature drifts: the temperature in the lead is nearly homogeneous. Once again, the validation of such a technique will be useful for the case where materials with lower diffusivity or with more complicated geometries are used.

6 ESU: tests and results

Two ESU were tested. The first one (ESU-Pb) used the ER-Pb#2 (Cf table 1) coupled to the cold finger of a 4K cryocooler by the switch previously described with H_2 gas. The amount of gas used in these tests corresponds to a ON transition for a cryopump temperature Tsorb≈ 65 K and Tsorb≈ 45 K for the OFF state. The ER was cooled with the switch in the ON state. When the ER temperature reached the cryocooler cold finger temperatures TCF, the cryopump was cooled down and the switch reached the OFF state, decoupling the ER from the cold finger. At this time, the cryocooler was stopped (t=0). The temperature drifts of the various components of the ESU are displayed in Figure 4: in the experimental results showed in this figure, the starting temperature was 11 K and 5 mW was applied to the ER to simulate a sensor dissipation. Due to the cryocooler intrinsic characteristics, the CF temperature increases relatively rapidly (red line), reaching about 50 K within 1 hour; the cryopump being loosely coupled to the cold finger, its temperature increases more slowly (t= 1 hour, Tsorb≈ 45 K).

In the same time, thanks to the thermal decoupling and to the high enthalpy reservoir, the ER temperature (green line) drifts very slowly reaching only 20 K 1 hour after the cryocooler stop: our ESU provided indeed a cold source with T< 20 K in a vibration and EM noise free environment. The upturn of T_{ER} vs. time about t≈ 70 mn indicates that the cryopump reaches a temperature (≈ 47 K) corresponding to the beginning of the H_2 desorption. This point forward, the gas pressure slowly increases in the switch and it toggles gradually into the ON state, the full ON state being reached at t≈ 130 mn when TCF≈ 75 K.

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[1] Actually, the proposal mentioned 5K with GAP - Cp peak at 3.5 K. Since the cryocooler minimum nominal temperature is 3 K, it was decided that it would be more prudent to use GOS - Cp peak at 5.2 K- in order to store more enthalpy and, therefore, to built a more efficient ESU.

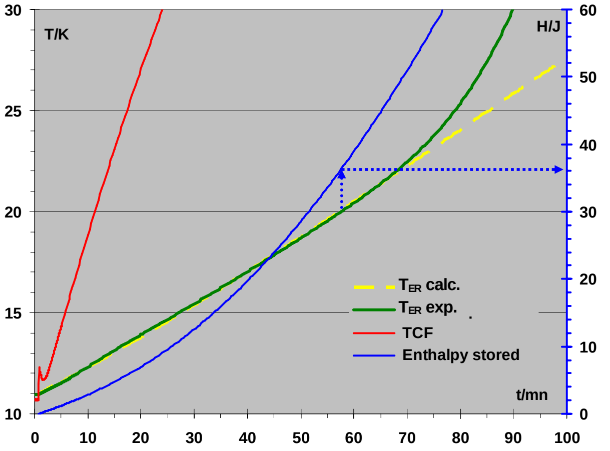

Figure 4: ESU-Pb, Temperature drifts after cryocooler stop (5 mW)

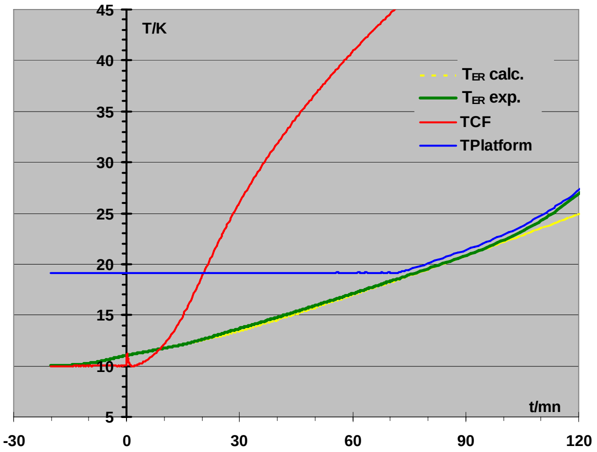

Figure 5: 19 K stabilized during 50 mn without vibrations

In order to compare the slow ER temperature drift with that expected for this ESU-Pb, we simulated it in a worksheet: the unique inputs are the cryocooler temperature drift (i.e TCF(t) on figure 4), the initial ER temperature (11 K), the stainless steel thermal conductivity and the copper and lead specific heat data as well as the S/L SSSS ratio. The ER temperature T(t) at time t+dt is calculated by an iterative way using the following equations:

$$T(t+dt)=T(t)+\frac{\Delta Q}{C(T(t))} \qquad with \qquad \Delta Q=\Delta t\,.\left(\frac{S}{L}\int_{T(t)}^{TCF(t+dt)}\kappa(T)\,dT+\dot{Q}_{ext}\right)$$

In these equations, C(T(t)) is the total ER heat capacity at T and is calculated from the volume of its different parts (Pb and Copper housing), ΔQ is the heat amount arriving on ER due to the heat flux through the switch and to the heat power applied externally $\dot{Q}_{ext}$ (measurements were performed at 0mW, 5 mW-Fig- 4- and 10 mW) . The result of this calculation corresponds to the yellow dashed-line line of figure 4: a very good agreement is obtained taking into account that there is no adjustable parameter in this simulation and that the errors on T_{ER} are accumulated through the calculation. In order to make easier a ESU simulation, the software "ESUware" was developed. Its input parameters (user's data) are the cryocooler temperature drift, the initial ER and CF temperatures, the final ER temperature, the external input power, the volume and the material of the different ESU parts, the material and the geometrical characteristics of the supporting shell. The ESUware calculation is based on the last equations and provides the ER temperature drift as well as the holding time (i.e the time period between the initial temperature and the final one).

Another test was performed, simulating the use of an ESU in a method probably very close to the wishes of the potential ESU users (figure 5): in this test, a small copper platform, loosely coupled to the ER, is stabilized at 19 K during all the experiment. During the first step, 19 K is maintained with the cryocooler working (vibrating and noisy environment), the switch is in the ON state and the ER is cooled down to the cold finger temperature (10 K in the case of results displayed on figure 5). The cryopump is then cooled down and the switch becomes OFF. At this time (t=0), the cryocooler is turned OFF, obtaining a no-vibrations-no EM noise environment: the temperature platform is completely stable at 19 K whereas that ER temperature slowly increases. This test was performed with the Pb-ER#2 and 19 K was maintained during more than 1 hour. Such a process can be useful when the sensors need to work at constant temperature and with minimum temperature variations.

The second tested ESU was designed to keep the temperature below 6K (^{4}He GGHS+ ER-GOS). Being very difficult to adsorb He for T> 15 K and the CF reaching this temperature rather quickly after its stop (more or less 25 mn), the cryopump was thermalized to ER (actually, the switch position was "simply" inverted in respect to the former position in which the cryopump is thermalized to the CF). Therefore, if not heated, the cryopump temperature remains close to the ER temperature, and the OFF state is kept up to ER temperature about 11 K. The material used for this ER, small GOS spheres (~250 μm), was located in an indium sealed copper recipient. Probably due a discrepancy between the nominal density (7.6 g/cm^3) used for the cell volume determination and the actual one (<7 g/cm^3) less GOS material was introduced in the recipient, and the quantity actually introduced corresponded to 30 J of enthalpy stored between 6 K and 3 K, i.e. 10 mW during 50 mn instead of 60 mn initially expected. The free volume is filled with one bar of ^{4}He at room temperature to allow a good spheres thermalization at low temperature. Beside these technical modifications, the experimental process to test this ESU is basically identical to that used for lead ESU (cooling down to lowest temperature with switch in ON state, turning the switch OFF, stopping the cryocooler).

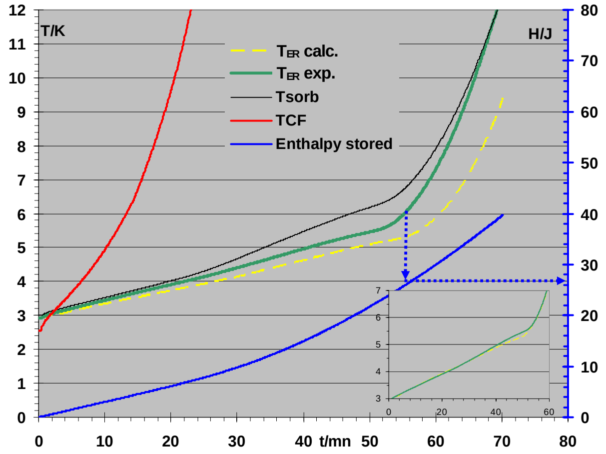

Figure 6: 6K stabilized during 50 mn without vibrations. Inset: T_{ER} experimental and calculated with 1.4 mW parasitical heat load.

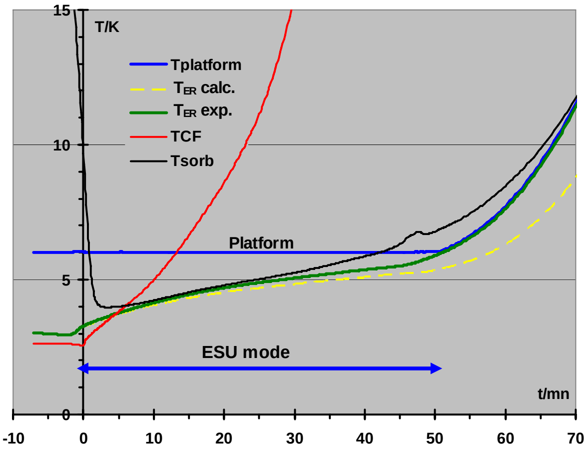

Figure 7: ESU-GOS, Temperature drifts after cryocooler stop (5 mW)

One typical experiment (5 mW applied on the ER) is shown on figure 6. The 6 K temperature is reached 55 mn after the cryocooler stop whereas the CF attained more than 35 K. Our calculations for the heat accumulated versus time calculated from the T_{ER} experimental data and from specific heat of GOS showed (blue line on figure 6, right axis) that between 3 K and 6 K, 27 J were stored, value rather close of the 30 J expected. This ≈10% discrepancy also appeared comparing the T_{ER} experimental drift (green line) and the T_{ER} calculated (yellow dashed line) as previously explained. Other experiments performed (0 mW and 10 mW applied on the ER) showed that this 10% discrepancy is systematic. Several reasons could explain this small discrepancy. A poor thermal coupling between the GOS spheres and the copper recipient, or GOS specific heat somewhat 10% lower than the nominal values or parasitical leak around 2 mW could explain fairly well this small discrepancy.

Similarly to the ESU-Pb, a small platform loosely coupled to the ER was regulated to 6 K whereas the ER was cooled down to 3K. After turning the switch to the OFF state, the cryocooler was stopped at t=0: the platform remained at constant 6 K temperature during 50 mn (See Figure 7) in a no-vibrations-no EM noise environment showing as useful can be an ESU. Again, the heat accumulated calculation showed the same 10% discrepancy.

7 Conclusion

The ESU concept was validated by this work up to TRL 3: a completely quiet cold source for temperature below 20K and below 6 K were built and obtained during one hour or more, for a low mass penalty, using a standard cryocooler. With the GGHS type used and tested in our experiments and with the specific heat data available in the literature, complete characteristics of an ESU can be trustingly determined "on-the-paper": the temperature drift experimentally obtained agreed almost perfectly with the calculated one for the Pb-ESU, whereas a discrepancy of less than 10 % was obtained for the GOS-ESU. Let us now discuss the main issues that should be more studied in order to obtain a fully functional ESU, adapted for space applications.

| Mass increase considerations

The lead used in ER-Pb is not the better choice from the point of view of system mass: Some materials can store more enthalpy by mass unit in a similar temperature range. For instance, between 10 and 20 K, for the same enthalpy stored, an ER using $ErCu_{0.95}Ga_{0.05}$ would be twice lighter than one made of lead.

The mass of a cryogenic system equipped with an ESU increases for three reasons: i) the ER+switch mass, ii) because the cryocooler must cool the ER (far) below the temperature limit (for example, for the ESU-Pb, 20 K it is considered as the temperature limit, whereas the ESU was cooled down to 11 K), and, closely related to the previous one, iii) because there is an input power increase, needed to cool the ER in a reasonable time interval down to the lowest temperature.

To minimize the mass increase of the total system, a not totally obvious optimization must be done. For instance, for the same enthalpy stored below 20K, it can be - or not - more advantageous to cool down the ER down to 15 K only (**lighter** cryocooler but **heavier** ER) than down to 11 K with less ER material (**heavier** cryocooler but **lighter** ER). To perform this optimization, data on minimum temperature *versus* cryocooler mass should be available. With such data, a high specific heat material must be chosen in order to optimize, for a given temperature range, the enthalpy stored between the starting temperature and the temperature limit. For instance, in the case of a temperature limit of 20 K and a cryocooler with a minimum temperature of 15 K, the $Er\text{-}Ag_{0.9}\text{-}Al_{0.1}$ compound (Cp peak at ≈ 17 K) is a good solution ($H(20\ K)-H(15\ K)=3.8\ J/cm^3$) whereas the $ErCu_{0.95}Ga_{0.05}$ (broad Cp anomaly between 13 K and 18 K; $H(20\ K)-H(10\ K) \approx 5.85\ J/cm^3$) can be the best choice if a cryocooler reaching 12 K is "not much" heavier. A Cp database - delivered in this project-, and one on cryocooler mass *vs.* lowest temperature and cooling power are needed to achieve a full optimization. More pragmatically, ESU performances can be calculated using the existing space qualified cryocoolers.

| Power increase considerations

As already mentioned, to cool down the ER in a reasonable time, the cooling power, and then the input power, must increase. As an example, we can compute (roughly) the power input needed to cool down a copper cold finger (10 cm3) from 20 K to 11 K. Using *Cooling power [mW] = 40* (T coldfinger - 10K) * Input power [W] / 150W* and the copper specific heat, the CF is cooled down below 11 K in 20 s with an input power of 100 W. With an ESU-Pb designed for 252 J (10 mW during 7 hours, 68 cm^3, 750 g)), with the same input power, 32 hours are needed; with an input power of 500 W, less than 7 minutes is needed, a quite reasonable time regarding if such an ESU could maintain a temperature below 20 K during 7 hours.

| Integration, mechanical support

The objective of this contract being to prove the ESU concept, no especial efforts was made in order to build a compact ESU. Many solutions for a compact ESU can be envisaged. A mechanical support - not trivial because the relatively high ER mass involved- has been proposed without adding significant heat leaks.

| Low vibration Cryocooler vs zero-vibration-ESU

Many solutions to reduce the vibrations in cryocoolers have been proposed. The ESU proposes a new one: stop the cryocooler! Its advantage is to reduce at zero the vibrations coming from the cold source, the problem is that this solution cannot work steadily as the low vibration cryocoolers. We already discussed the added mass and the additional power in the case of the ESU. These values can be compared to these necessary to put a low vibration Cryocooler working.

A problem that has not been discussed here is that the heat load on the ESU is highly dependent of the natural CF temperature increase after stopping. Obviously, the heat leak through the switch increases - dramatically- as the CF becomes hotter: for instance, with our cryocooler, 1 h after stopping, this temperature reaches about 40 K, injecting ≈10 mW to the ER! Actually, this heat load for TCF> 40 K is the main limitation to maintain the ESU at low temperature during longer times. One solution to overcome this effect is to increase the thermal inertia of the cold finger, adding directly on it some high enthalpy material. Lighter solutions could exist.