P.Gorbunov (Univ. of Toronto) 24 February – 16 March 2004
Final version

Heat flow measurements during the ATLAS End-Cup-A cold test

1. The set-up

In total, 63 PT100 temperature probes were installed: 20 in the cryostat, 8 on the FCAL cold tube, 18 on the FCAL warm tube and 17 on the cryostat outer surface. Fig. 1 shows, schematically, the positions of the probes relevant for our measurement. See Tables 1 and 2 for more details. The probes on the front and back walls (111-131, 141 and 143) were installed by Alice Thiebault on my request (Figures 2 and 3). The PT100 read-out controller (Fig. 4) was connected to a standalone laptop PC running a commercial DAQ application under Windows 98. The temperatures were recorded every 2 minutes.

The DAQ could also monitor the status of the warm tube kapton heaters, by sampling the TTL status level delivered by presetable window comparators controlling the power relays of the heaters. The sampling rate during the measurements was 1 Hz[1]. The comparators, connected to temperature sensors of the heaters[2], defined the upper temperature at which the corresponding heater was turned off. The lower limit, at which the heater was turned back on, had been hardwired to be 4°K less than the upper limit. For example, if the comparator setting was 16°C, then the temperature of the heater was oscillating between 16°C and 12°C. Each of the two heaters could be configured individually. The heaters having the resistance of about 16Ω were powered by AC from a transformer connected to 230 VAC mains. The output voltage could be selected between 50 and 25 VAC . I chose the lower voltage, to have a better power sampling accuracy (due to a longer ramp-up duration: 110-120 s).

Since the DAQ did not measure the heater currents, I added digital ampermeters (3-digit KONTRONs) in series with the heaters. The voltage on the heaters could be measured manually with a multimeter. It proved to be stable within ±1.5%. The status signal (later, the direct heater voltage level) was also monitored by a standalone chart recorder with 12 cm/h resolution. The power supply and the power measurement setup are shown in Figures 6 and 7.

The data was saved in ASCII form, in a native format which could be converted into Excel format by a standalone utility. Alice was changing the output data files once per day and transferring copies of the raw data to me, via a USB flash disk. I converted raw files into N-tuples usable with PAW. Each record in the PT100 N-tuple corresponds to one read-out cycle; it contains a time-stamp and all the temperatures read in that cycle. In the heater N-tuple, records correspond to complete heating cycles, each record containing the time-stamp, the heater number, the cycle duration and the heating ramp-up duration. [3]

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[1] This was the best granularity which Alice's PC could afford without overflowing the hard disk.
[2] These probes are not monitored by the DAQ.
[3] The PT100 N-tuple is ~3 times and the heater N-tuple ─ about 3000 times smaller than the raw data.

2. The measurements

The cryostat cooling started on Monday, February 16th. The monitoring started on February 17th, after installation of all external probes and closing the warm tube of the cryostat with plugs (see Appendix A). The initial heater setting was lower/upper=14/18°C, as we hoped to keep the average temperature of the warm tube at ~16°C (the hall temperature at that moment). On Thursday (19-Feb) we decided to decrease the warm tube temperature to 6/10°C. The arguments were: a) to see whether cooling could be speed up; b) to start the heat leak measurement from a low point and then "scan" the entire range of temperatures (10-20°C) which could be referred to as "ambient". On Friday morning we discovered that the temperature in the warm tube cavity was approaching 0°C and decided to increase the heater temperature to 10/14°C , first in the heater 2 alone and, later, in both heaters.

By Monday morning (23-Feb) the cooling was finished and I started increasing gradually the heater temperatures: 12/16°C at 10h14, 14/18°C at 16h10 and, finally, 17-21°C at 20h34. My plan was to set 20/24°C at ~2 am and continue till 9h, then stop the heaters and monitor the temperatures evolution throughout the day. Unfortunately, this plan was compromised by a power cut which occurred at ~23h, due to a failure of one of the vacuum pumps. Both DAQ and the heater power supply stayed down till the morning. No time remained for slow heating and stabilization, so we decided to make 2-3 quick steps up, then stop the heaters and monitor the temperature drop in the FCAL tubes (without opening the plugs) till Wednesday morning, till the scheduled end of the cold test.

The idea of the new plan was to measure the heaters power at temperatures way above the room temperature, in order to set an upper limit on the heat leak from the warm tube. The dynamics of cooling down with the heaters off should also give some information on the heat flow in that region.

The plots [Ref. 4, my_probes.ps] show the trends of temperatures and the average heater power over the entire test period. [Ref.4, temp2.ps] shows the temperature distributions in the cold and warm tubes recorded when the system was in the most stable condition, with the preset heaters temperature of 14-18°C.

[Ref.4, temp1.ps] represents an attempt to estimate the "asymptotic" temperature distribution over the warm tube without heating[4].

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[4] The graphs in this file show the temperature trends during the last phase of the test (24-25 February), when we warmed the heater-2 up to 60C (in steps: 21, 40, 60C), then turned the heaters off and let the system cool down. If we could let it stabilize, at least for one more day, then we had a true temperature map on the inner tubes (with the inner volume isolated) reflecting heat flows in that region. Unfortunately, we had to stop on Wednesday morning and start preparation for warming-up. So I made a "quick & dirty" attempt to estimate the asymptotic temperatures of the warm tube probes, by fitting the trends with a generic exponential-based function (without any model in mind). Actually, I tried several different functions, but this one

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DOUBLE PRECISION PAR(24),FITFUN;  FITFUN=PAR(1) + EXP(par(2)*(1-PAR(3)*x**PAR(4))
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The details of temperature settings used during the tests are given in Appendix A.

3. The situation after warming-up

Warming-up was completed by Tuesday, March 9. The end-cup cover was opened, after cutting off the soldered edge of the warm tube. The interior of the area near the cold bellow was inspected to see if the sensors 61 and 69, which were suspected to fall off, are in place. Fig. 8 shows Alice cutting the Axon sections of the PT100 signal cables. No visual evidence for detaching of those two sensors from the inner wall of the cold tube was found. I use the term "evidence" because the sensors themselves could hardly be seen (personally, I could not – but Aboud claimed that he saw that the aluminium scotch tape fixing the sensors was intact).

I was amazed by the amount material (cables, Panduit strips, Al scotch) present in the vacuum gap near the cold bellow (Figures 10 and 11). As far as I could judge, the cables stuffing the narrow gap between the bi-metal joints of the warm and cold tubes could create heat leakage channels in the area inside the cold bellow (see Fig. 11 for reference).

On Wednesday, March 10, the warm tube was removed and we could inspect the interior of the cold tube directly (Figures 12 and 13). Indeed, the sensors 61 and 69 seemed to be properly glued. Alice said she did not see any anomaly in the way they were attached..

Finally, Figures 14 and 15 show the narrow end of the warm tube. Another personal observation I made concerned the spacer. As Fig. 15 shows, the points where the spacer touches the cold tube are half-filled with steel bolts. I thought that isolating bolts would be more appropriate here.

4. Summary

This preliminary summary results from our e-mail discussions with G.Oakham. I largely used his wording to compile the text below.

- *Heat leak is below a critical value for the FCAL.*
  The heat generated by the heaters was around 8 watts when the warm tube was kept at a temperature between 17 and 20°C. If we consider that this flows over 0.6 sq. meters[5], heat flow is 13 w/m^2. By prorating the measurements to the real temperature differential of 200°K with a crude linear model [Ref. 6] we get values ranging from 8-12 W/ m^2 with a high value of 19 W/ m^2 closer to the bellows.

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gave the best results and it was easy to find a good first approximation for its parameters. The parameter #1 is the asymptotic value to which the temperature seems to be converging. The systematical uncertainty is ~0.2-0.3C in all the cases (evaluated by playing with the fitting function). The histograms are available from [Ref.5].

[5] The area of the narrow part of the warm tube is ~0.6 m^2 (the diameter ~10 cm and the length is ~190 cm.

This is less than the 75 W/m^2 limit we set, so we can probably say that there doesn't appear to be a problem in the FCAL region.

- *The leak is mainly in the region of the bellows in the rear part of the cryostat.* The temperature of the cold tube increases dramatically towards the vicinity of the bellows. This may be due to heat transfer at the bellows or simply because the super-insulation only goes about 10 cm from the spacer in the direction of the bellows. This could well allow an easy path for heat to travel around the insulation and across the spacer. There can also be a localized heat leak "channel" around the warm tube probe 43, which was always colder by 6° than the probes 33 and 45 located nearby.
- *The forward (wide) part of the warm tube is difficult to keep well above 0°C with existing heaters.* This matter was discussed with P.Fassnacht and A.Falou and they admitted that this is a serious issue. Proposals like adding an extra heater to that region (and re-distributing more evenly the heating power) or blowing a dry nitrogen through the warm tube during the beam operation were expressed.

References

1. G,Oakham , Notes on heat flow measurement in FCAL region, 10th February 2004
   http://cern.ch/atlas-fcaltb/Memos/Hardware/Heatleak%20test/Heatleaktest.doc

2. G.Oakham, J.Rutherfoord, P.Gorbunov: e-mail exchange before the tests.
   http://cern.ch/atlas-fcaltb/Memos/Hardware/Heatleak%20test/History.doc

3. Photographs of the cold and warm tubes, during the assembly
   http://www.physics.carleton.ca/research/atlas/Construction/fcal3c/fcal3_files/Board_files/warm_cold_tube_photos.htm

4. Summary plots (Postscript)
   http://cern.ch/atlas-fcaltb/Memos/Hardware/Heatleak%20test/my_probes.ps , temp1.ps and temp2.ps

5. PAW N-tuples (ASCII): probes, heaters. Kumac-files:
   /afs/cern.ch/user/p/petr/public/ECA_Cold_Test
   To produce all the plots, copy this directory to a local PC, run PAW and execute `my_probes.kumac, temp1.kumac and temp2.kumac.` File `temp1.rz` contains the histograms with temperature trends recorded when the system was cooling down without heating.

6. V.Strickland, An estimate of the heat flow through the end-cup warm tube with the cryostat at the LAr temperature (EXCEL spreadsheet).
   http://atlas-fcaltb.web.cern.ch/atlas-fcaltb/Memos/Hardware/Heatleak%20test/Vance_Cold-Test-Analysis.xls

Tables

Table 1: PT100 probes inside the cryostat

Name	Number	Z-distance,cm	Y-position,cm	Comment
TF1	61	≈197	6.7	Z-distances are given with
TF2	63	≈148	6.7	respect to the warm cavity
TF4	65	≈47	6.7	wall
TF6	67	≈6	16	
TF12	75	≈6	-16	
TF10	73	≈47	-6.7	
TF8	71	≈159	-6.7	
TF7	69	≈197	-6.7	
TC8	47	9	0	
TC6	43	9	5.4	
TC8	59	9	-5.4	
TC5	41	9+30=39	5.4	
TC13	57	9+30=39	-5.4	
TC4	39	9+30+40=79	5.4	
TC12	55	9+30+40=79	-5.4	
TC3	37	9+30+2*40=119	5.4	
TC11	53	9+30+2*40=119	-5.4	
TC2	35	9+30+3*40=159	5.4	
TC10	51	9+30+3*40=159	-5.4	
TC1	33	9+30+4*40=199	5.4	
TC7	49	9+30+4*40=199	0	
TC9	45	9+30+4*40=199	-5.4	
TC15	103	-2	18.2	
TC17	107	-2	-18.2	
TC16	105	-85	18.2	
TC18	109	-85	-18.2	
Heater 1		157-179		
Heater 2		77-99		

Table 2: PT100 probes on the front and back walls

#	Y, cm	Comment
111	40	
113	-25	On the flange
115	-40	
117	-60	Against a spacer
121	-80	
123	-100	Against a spacer
125	-120	
127	-140	Against a spacer
129	-160	
131	-180	Against a spacer
141	40	Back
143	-40	Back

Appendix A: The heaters and the plugs

Heater 1: V=25.00 VAC ±1.5%; I=1.67±0.02 A; typical ON duration: 115-120 s

Heater 2: V=25.00 VAC ±1.5%; I=1.60±0.02 A; typical ON duration: 105-110 s

Front plug (to close the warm tube cavity): a disk of 10 mm organic glass, with rubber joint, fixed on the flange with 3 bolts, covered by a "blanket" of super-insulation.

Back plug: a disk of ~15 mm organic glass, with rubber joint, tightly inserted into the warm tube.

17-Feb	17:20	H1=H2=**14/18°C** (V=50 VAC)
	18:30-19:55	The plugs are installed
	~19:00	Heater voltage is reduced by factor 2: V=25 VAC, Same temperature setting: H1=H2=14/18°C
19-Feb	14-17	Heaters are **off** (Alice)
	18:35	H1=H2=**6/10°C**
20-Feb	10:33	H1=**6/10°C**; H2=**10/14°C**;
	11:45	Tightness of the front plug is improved, superinsulation is added
	16:45	H1=H2=**10/14°C**
23-Feb	10:14	H1=H2=**12/16°C**
	16:10	H1=H2=**14/18°C**
	20:34	H1=H2=**17/21°C**
	~23h	Power cut. Heaters went **off.** Data recording - off.
24-Feb	~7:20	H1=H2=**17/21°C**, DAQ is still off, chart recorder is ON
	~9h	DAQ on
	~11:30	H1=**17/21°C (effectively, disabled)** H2=**36/40°C** (most of the time, keeps H1 within 17/21)
	~15:40	H1=**17/21°C (effectively, disabled)** H2=**56/60°C** (most of the time, keeps H1 within 17/21)
	~19h	Anticipated stop of heating, cooling down with the plugs installed, data recording ON

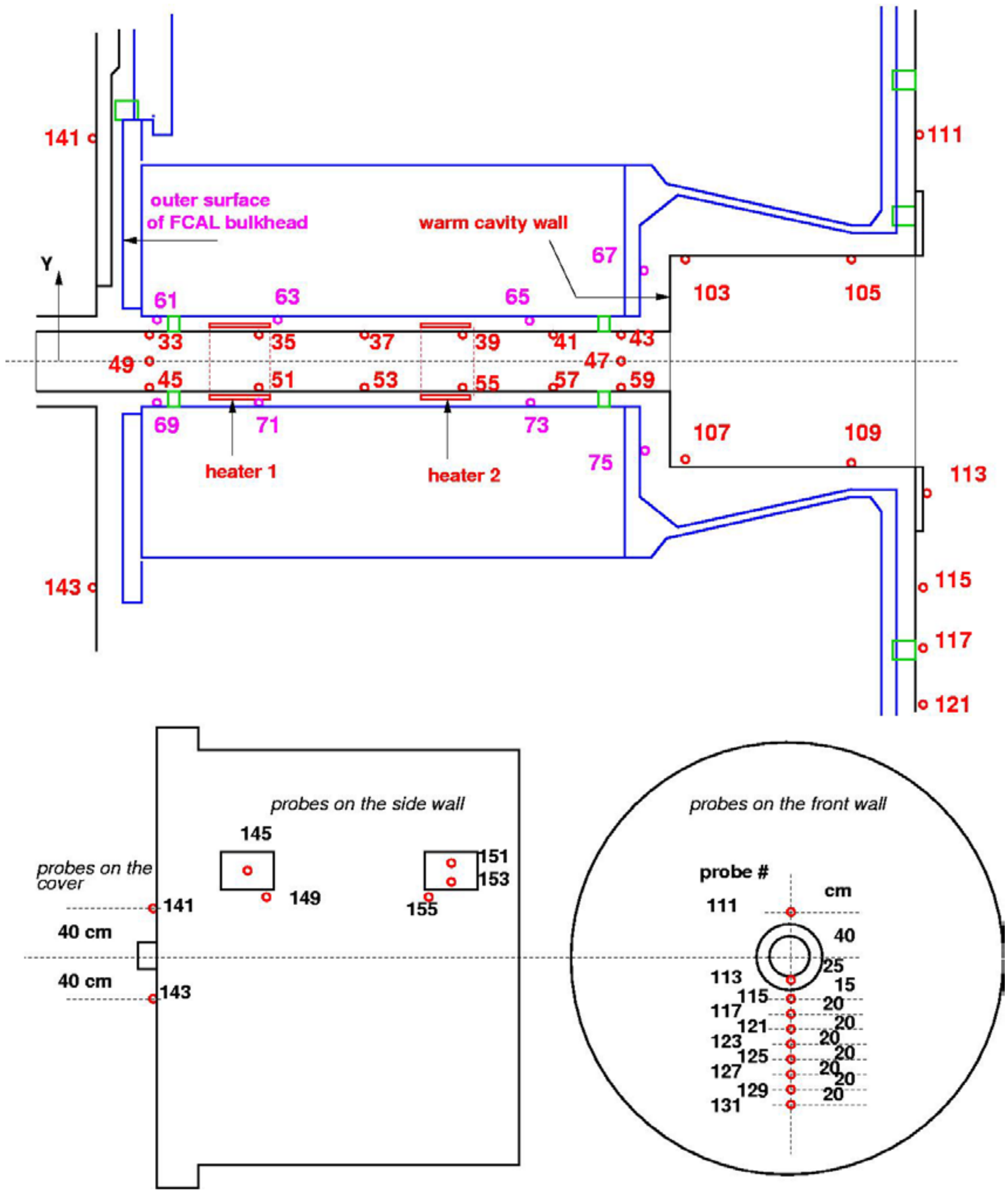


Figure 1: Locations of the PT100 sensors installed on the FCAL warm and cold tubes, as well as on the cryostat outer surface.

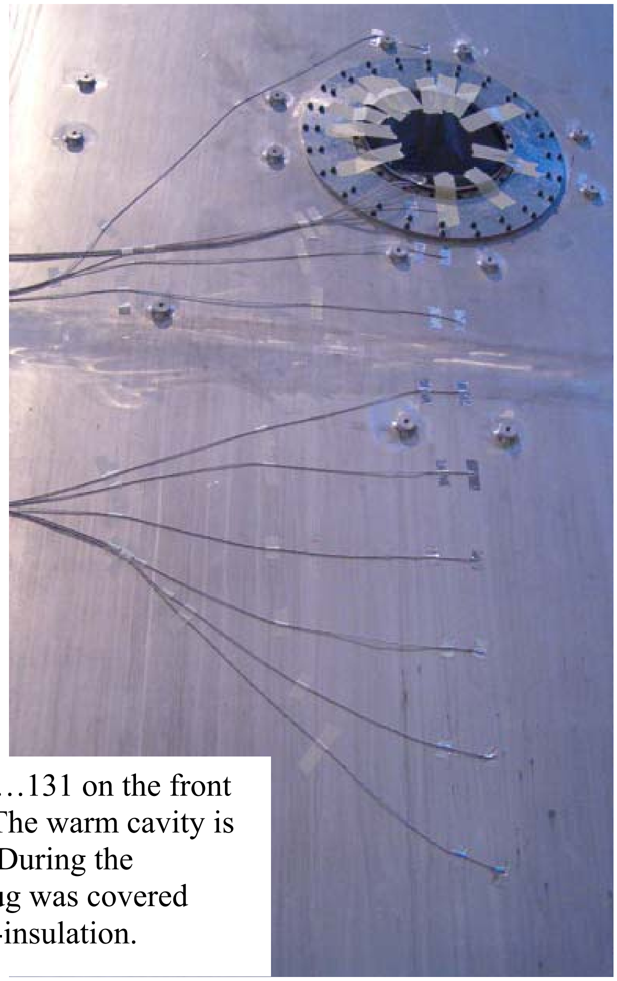


Figure 2: Probes 111…131 on the front wall of the cryostat. The warm cavity is covered with a plug. During the measurements the plug was covered with a piece of super-insulation.

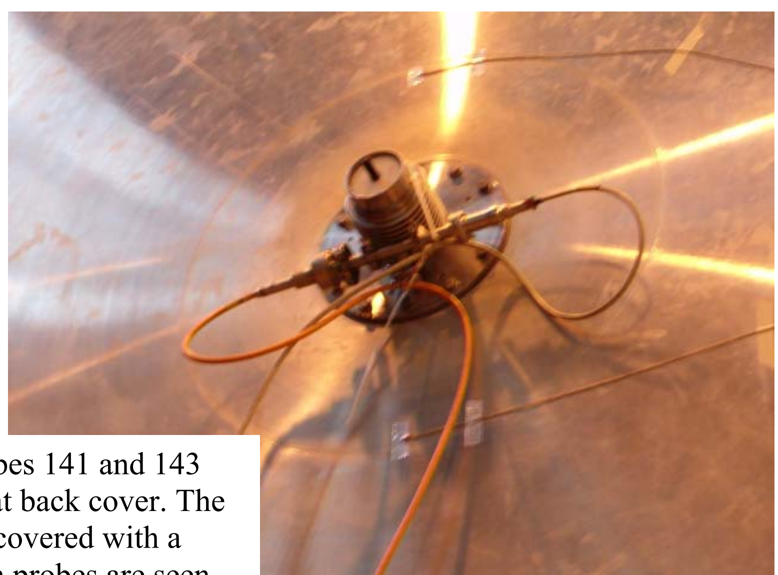


Figure 3: Probes 141 and 143 on the cryostat back cover. The beam pipe is covered with a plug. Vacuum probes are seen.

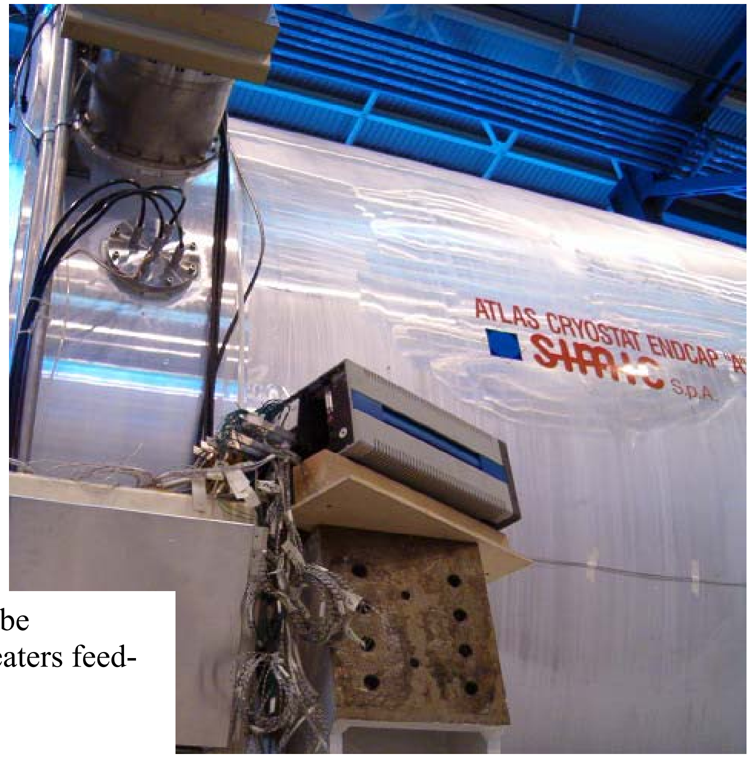


Figure 4: PT100 probe controller and the heaters feed-through.

Figure 5: Probes 151-155 on one of the cryostat back "feet" (near the front wall).

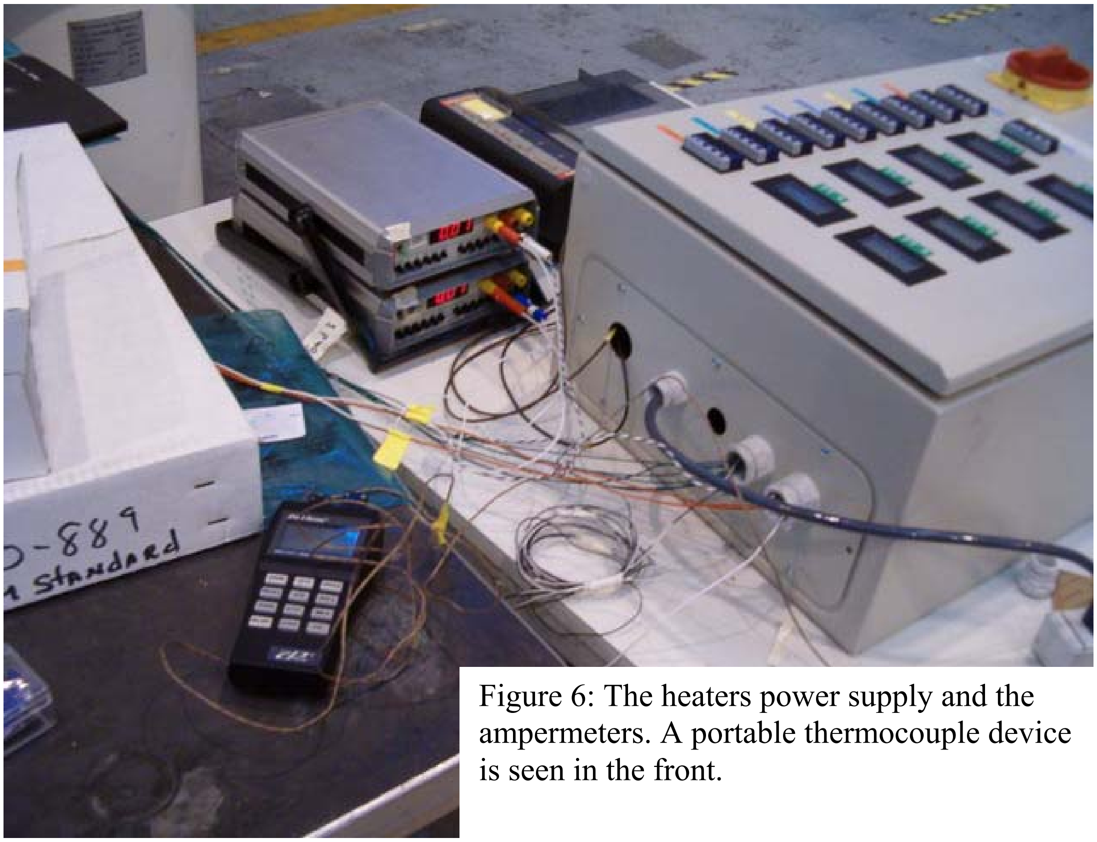


Figure 6: The heaters power supply and the ampermeters. A portable thermocouple device is seen in the front.

Figure 7: The chart recorder connected in parallel to the heaters, to monitor the heater voltage.

Figure 8: Alice is cutting the cables going to PT100 sensors installed on the warm and the cold tubes. All these cables were wound around the warm tube and filled the space near the edge of the cold tube.

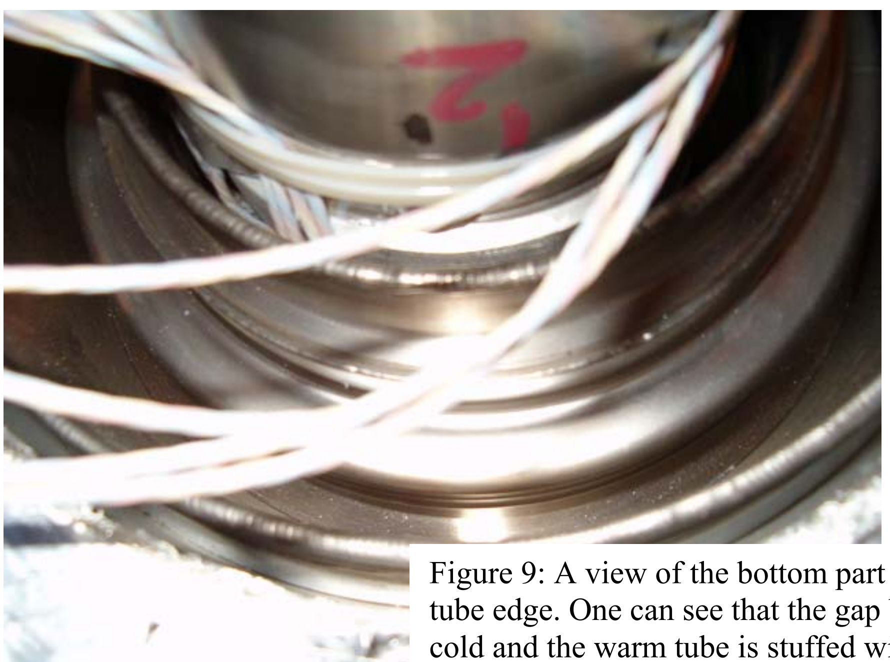


Figure 9: A view of the bottom part of the cold tube edge. One can see that the gap between the cold and the warm tube is stuffed with cables.

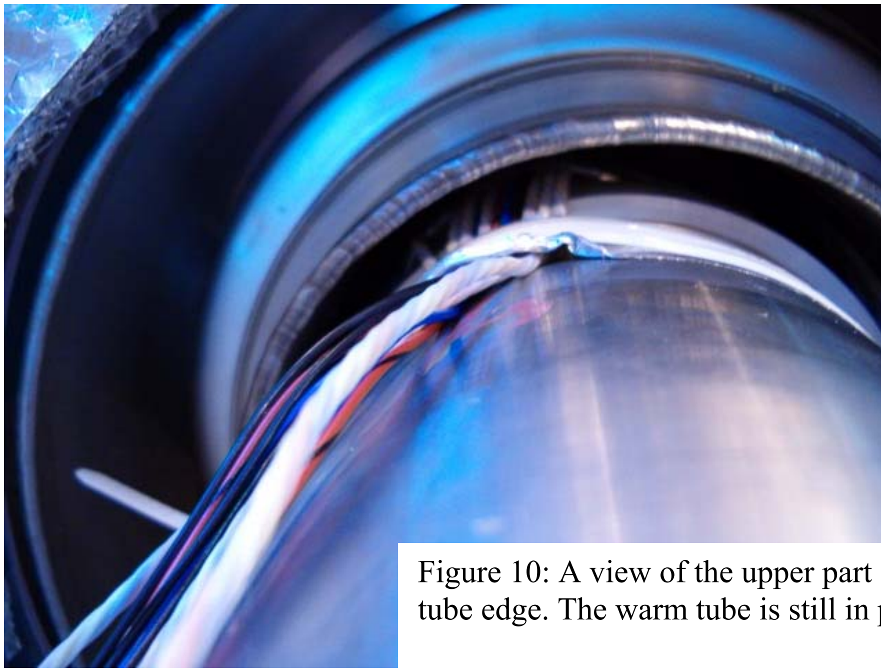


Figure 10: A view of the upper part of the cold tube edge. The warm tube is still in place.

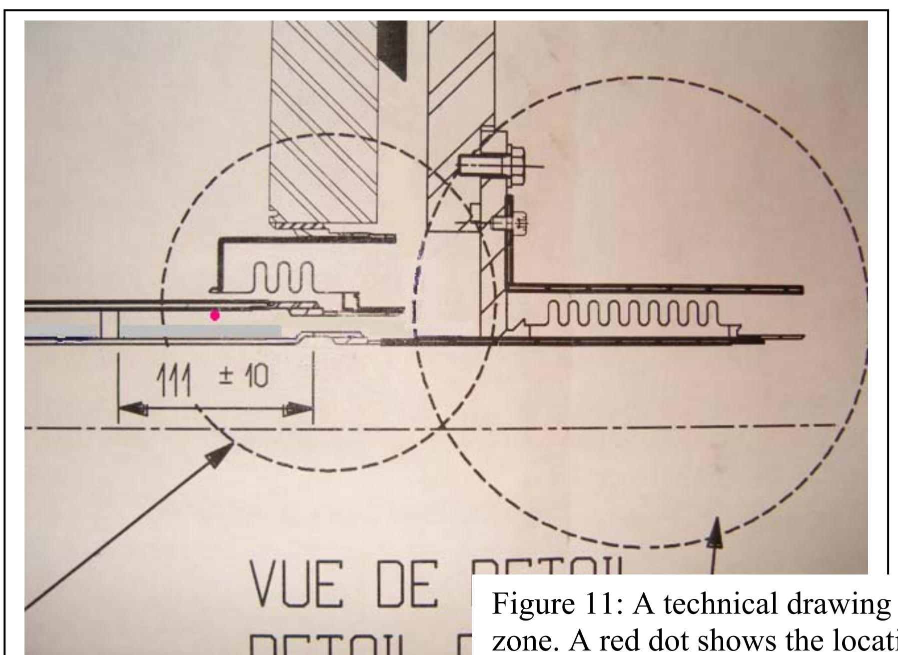
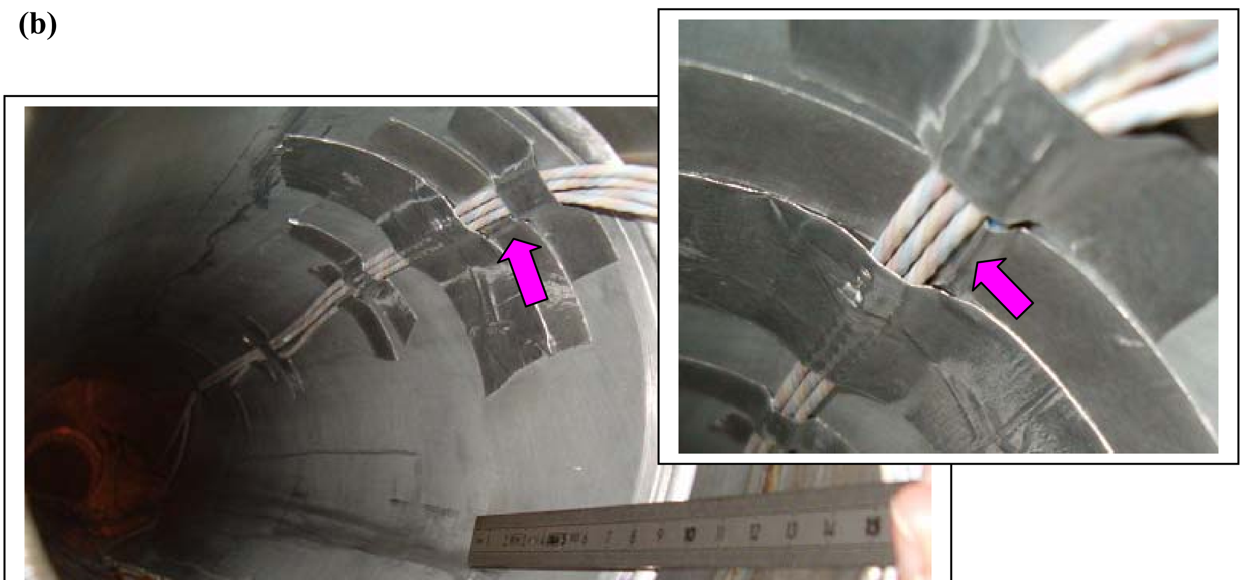


Figure 11: A technical drawing of the bellow zone. A red dot shows the location of sensors 61 and 69; the grey layers denote a super-insulation.

(b)



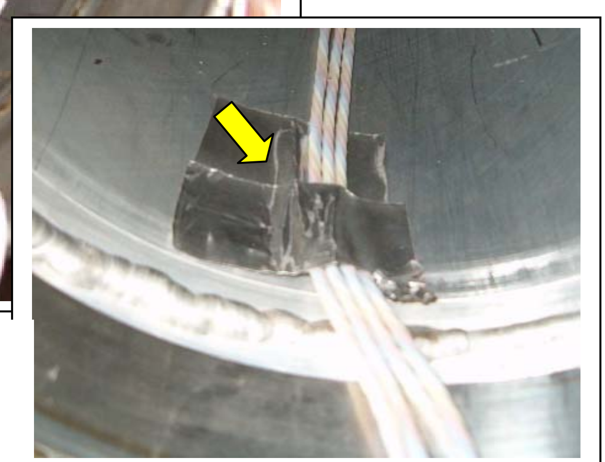


Figure 12: (a) A view of the cold tube, after removal of the warm tube; (b) the area near the cold bellow, with sensors 61 (violet arrow) and 69 (yellow arrow). The spacer was located in 15 cm from the edge of the cold tube.

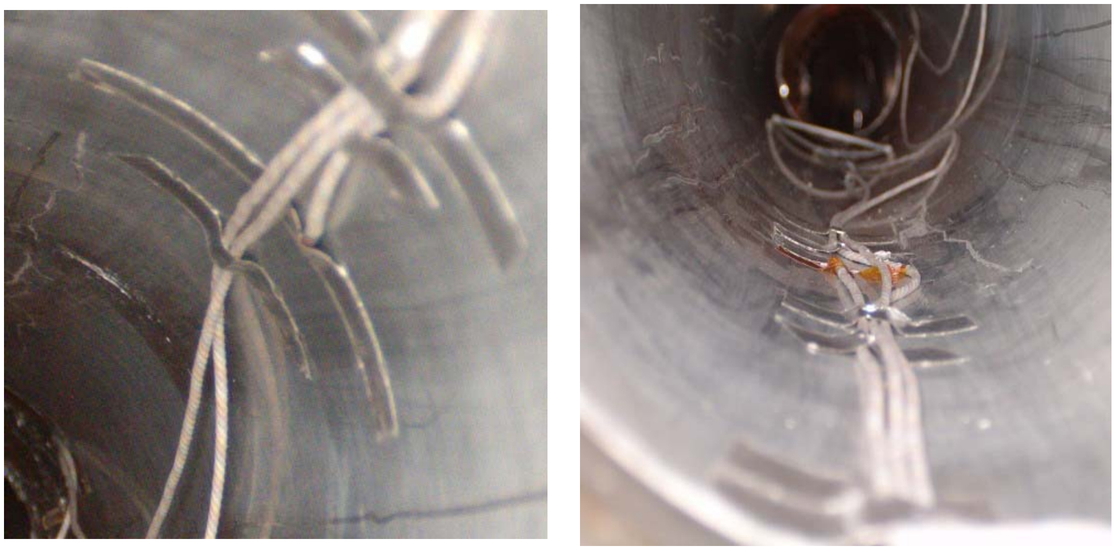


Figure 13: The “cold” sensors 63 (left) and 71 (right), located against the heater 1.

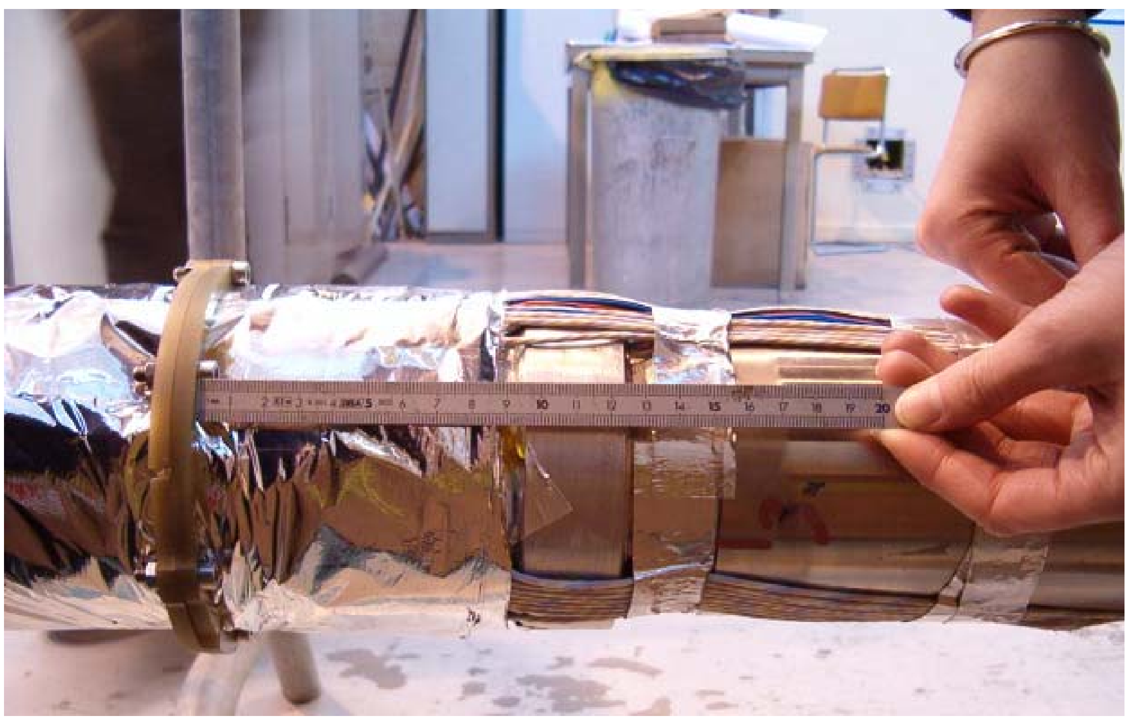


Figure 14: The warm tube. The 6-mm thick ring of the bi-metal junction, located in 11 cm from the spacer, is seen. A bunch of wires (PT100 probe signals, heater power) make the narrowest gap between the warm and the cold tube. The cold sensors 61 and 69 were located in about 5 cm from the spacer.

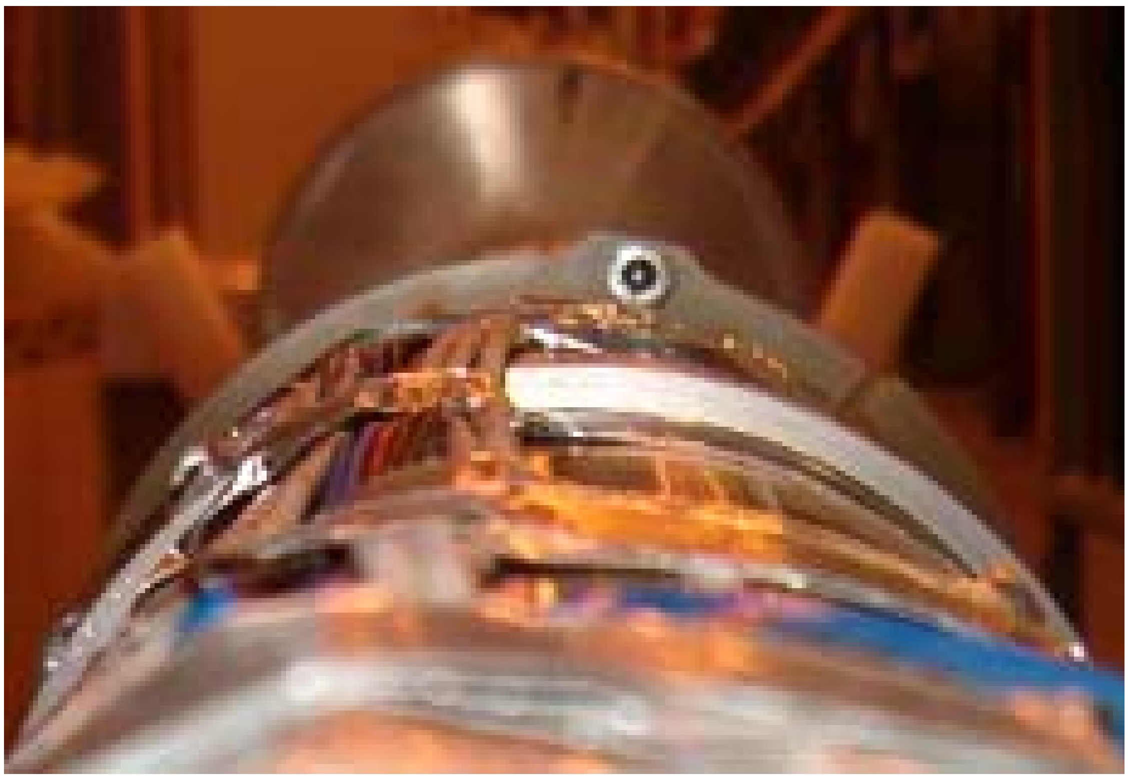


Figure 15: Another view of the spacer and the bi-metal joint.