ENFORCEMENT OF THE THERMOHYDRAULIC TEST AND CONSTRUCTION OF THE MOCK-UP FOR DRY STORAGE FOR SPENT FUEL ELEMENTS

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Abstract

The main objective was to validate that the natural convection refrigeration designed for the ASECQ Installations, to be built in the CNA I, will be enough to keep within a range of safe temperatures, and without risk to the integrity of the Fuel Element Pods Spent.

1. INTRODUCTION

As part of the dry storage project of spent fuels for the Nuclear Power Plant Atucha I (CNA-I), a Mock-up was built to perform the thermal and mechanical tests required to develop the Dry Storage for Spent Fuel Elements (ASECQ) engineering [1].

In order to verify the results obtained in the previous analyzes and simulations [1] and [2], corresponding thermal tests were performed in the mock-up.

The Mock-up has the following characteristics:

— Simulates a portion of the ASECQ in a 1:1 scale formed by 9 Silo Unit (SiU) with its corresponding Storage Unit (SU) that hosts 9 Equivalent Fuel Element (EFE) (Fig. 1 and 2);

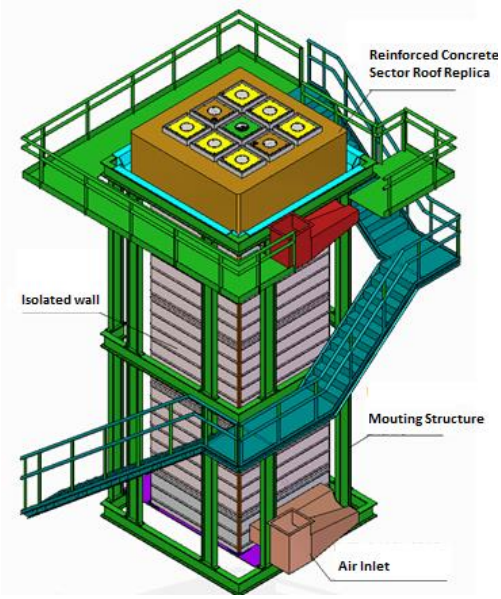

FIG. 1. Mock-Up General View

FIG. 2. EFE arrangement in SU inserted in the SiU

- The 81 Spent Fuel Elements were simulated through EFE armed with electric heaters. Of which 79 are generic (one heater per EFE) and two are detailed (one heater per fuel rod, 36 per EFE) (Detailed Equivalent Fuel Element, DEFE) [4] (Figure 2);
- It has the corresponding air inlet and outlet (chimney) ducts, similar to those of the final installation. All the ducts and chimneys have the real heights and are a smaller cross section to have the same circulation speeds as in the ASECQ;
- It also has a cooling system for forced air circulation;
- It has four valves in the air ducts, two to close the entrance and exit of outside air; and the other two to enable the forced circulation of air;
- It is instrumented with 104 thermocouples [5];
- The thermocouples were installed in order to measure (with redundancy) the temperatures in fuel rods, in the SU, in the SiU, in the ducts and air channels and in the reflecting panels;
- The design decay power of ASECQ per fuel element is 60 W [1]. To cover a wide range of power, the tests were carried out for 30W, 40W, 60W and 90W;
- In the paper report only the results of the 60 W tests are presented, design conditions. In addition, a comparative table is shown with the maximum temperatures obtained in all the tests. The complete results are registered in electronic spreadsheets available to be consulted and analyzed when necessary.

1.1 Trial types

1.1.1 Normal Operation Condition

The first type of test is the normal operating condition of ASECQ, with air circulating naturally in open circuit at steady state. The outside air entering through the entrance duct, circulating freely inside the channels of the mock-up and exiting through the chimney.

This test allows to compare the temperatures obtained in numerical simulations [2] [3] with the measurements through thermocouples installed in places of interest [5].

This series of tests was conducted for powers of 30, 40, 60 and 90 W by EFE [6], in such a way to cover a wide range that includes the power of nominal decay in the BFE (60 W)Accidental Condition

The second type of tests, is an accidental condition of the ASECQ: detection of activity in the chimneys (due to a puncture of a fuel rod simultaneously with the puncture of the corresponding SiU) that forces to close the air intake and discharge ducts and put into operation the system of forced circulation in closed circuit. In addition, there is a power cut that makes cooling by forced convection impossible.

This situation with very low probability of occurrence is simulated by closing the external air isolation valves and allowing the system to be cooled by the natural convection mechanisms in an enclosed space, conduction of heat through the peripheral components of the Mock-up and free natural convection to the external environment.

1.1.2 Test methodology

In order to optimize test times, all were started with a power by ECE of 90W to reach each stationary more quickly. The maximum temperatures were monitored and when they reached the expected values as predicted by the previous simulations, the power was reduced to the desired value.

The stationary state actually sought is a pseudo-stationary state, since once the transient temperature has been exceeded, temperatures vary following the change in ambient temperature. The ambient temperature oscillates between day and night and also varies day after day. The criterion applied to determine if this pseudo-stationary state had been reached was that the (maximum) pod temperatures would "copy" the variations in ambient temperature.

For the case of the accidental situation, the normal steady state of operation is reached at the required power and then the valves are closed to prevent the circulation of air in an open circuit to simulate the accident. In this state the evolution of temperatures is monitored.

1.1.3 Uncertainty in measurements

The uncertainties were estimated for the whole temperature range (10–90°C), in Table 1 and 2 the value of each uncertainty source and the value of the combined uncertainty are shown.

That is to say that the values of the temperatures reported have a confidence interval of ± 1.76°C, normal operating condition power 60 W.

TABLE 1. SOURCES OF UNCERTAINTY

	Expanded Uncertainty	Standard Uncertainty	Relative Uncertainty
Primary Sensor (thermocouples)	± 1.5 °C	0.866°C	0.0124
Instrument Specification	± 0.1 °C	0.058°C	$8.28\ 10^{-4}$
Cold Board Compensation	± 0.25 °C	0.144°C	$2.06\ 10^{-3}$
Statistics	± 0.08°C	0.0462°C	$6.6\ 10^{-4}$

TABLE 2. COMBINED UNCERTAINTY

Sum Quadratic Relative Uncertainties	1.58 10-4
Relative Relative Uncertainty (Square Root of the quadratic sum)	0.0126
Relative Combined Expanded Uncertainty (k = 2)	0.0252

1.2 Results obtained

1.2.1 Normal operating condition power 60 W

The trial lasted for 7 uninterrupted days: beginning at noon on 04/20/15 and ending at noon on 04/27/15. in figures 3 and 4 it can be seen that at the start of the test (the first 24 hours approximately) the temperature has a rapid rise due to the high power (90 W) and then an abrupt drop when the desired power of the test is established.

Evolutions:

The temperatures shown in figures 3 and 4 are the most representative of the thermal behaviour of the mockup and all are associated with SiU 5:

- Maximum in the pods of the DEFE -termocuplas T003 (SiU5) and T027 (SiU 8);
- Air in inlet duct - thermocouples T104 and T106;
- SiU surface at different heights - thermocouples T54, T55 and T56 (dimensions 2600, 2000 and 0);
- Upper air plenum - thermocouple T102;
- In the chimney - thermocouples T100 and T101.

After 48 hours you can see how the temperatures follow the variation of the ambient temperature (T104 and T106). This variation has two well differentiated patterns: the characteristic oscillation between day and night and a day to day variation. It can be seen that the maximum test temperature (76.8°C) recorded in T003, was reached during the night of the day in which the maximum ambient temperature was recorded is 30.2°C.

In Figure 4 we can observe the evolution of the temperature profile along the wall of SiU S5, as well as the evolution of the air inlet temperature T106 and the hotter sheath T003.

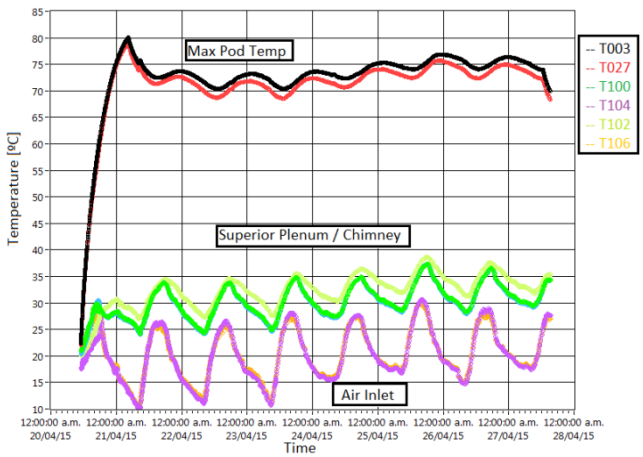

FIG. 3. Temp. in fuel pod, air inlet and upper plenum of SiU 5

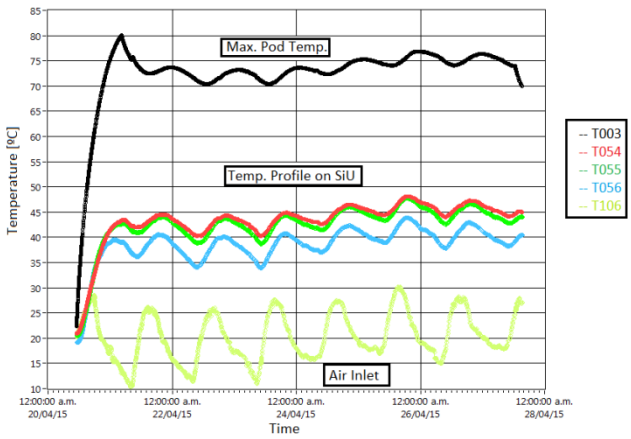

FIG. 4. Evolution Temperatures - Normal Operation - 60 W

Figures 5 show the maximum pod temperatures (T003 and T027) and the ambient temperatures above the central EFE (T51 and T71) of SiU S5 and S8.

Thermocouples T51 and T71 are 1 cm above the upper level of the DEFE sheaths, at the level of the bearing plate. These temperatures are very important because the ASECQ has instrumented 10 SiU in this position. Indirectly, these thermocouples inform about the maximum temperatures that ECQs have in the ASECQ.

The difference between the environment above the DEFE within the SiU and the maximum pod temperatures are approximately 12/13ºC. The maximum temperature reached in T51 is 64.2°C and in T71 it is 62.25°C; while in the pods they are 76.8°C and 75.75°C respectively.

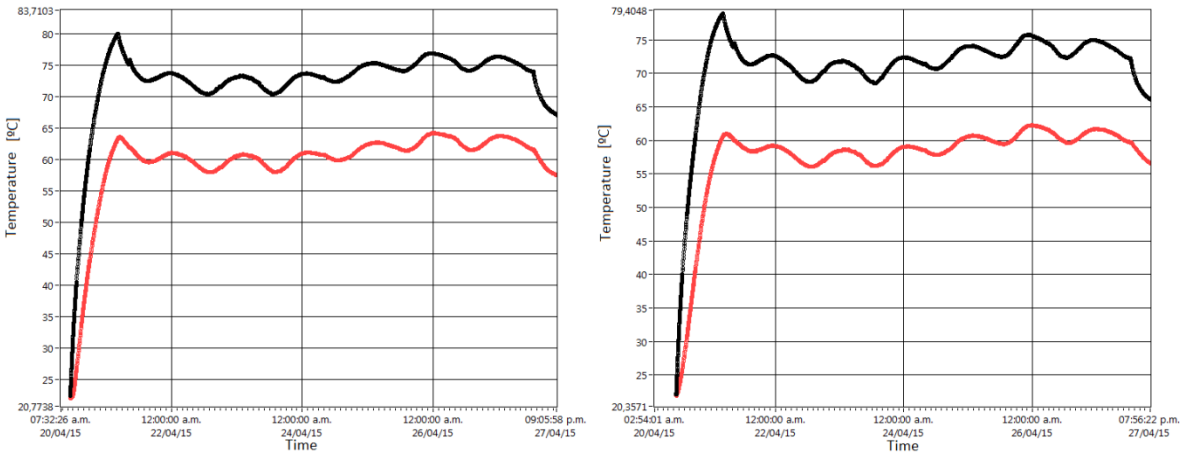

FIG. 5. SiU5 & 8 - Evolution Tmax of pod and Tair. on top of the ECED in SiU 5 & 8

Figure 6 shows the thermal gradients between the air inlet (T106) to the Mock-up and the exit from it through the chimney (T101), they hover around 10ºC. In addition, the air temperature at the outlet of the upper plenum (T102) that allows see the cooling of the air in the chimney is presented.

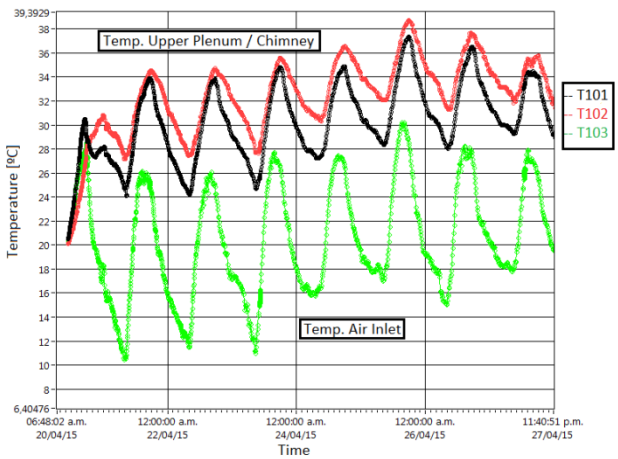

FIG. 6. Evolution of the air inlet and outlet temperatures in the Mockup

In Figure 7 a time interval is shown in which the pseudo-stationary state is maintained, that is, temperatures vary as a result of the change in ambient temperature. In this figure it can be clearly observed the temporal difference between the maximum temperatures reached in the pods and in the ambient air (entrance to the Mockup). The maximum pod temperatures occurred during the night (around midnight), when the ambient temperature passes through the lowest value of the whole day.

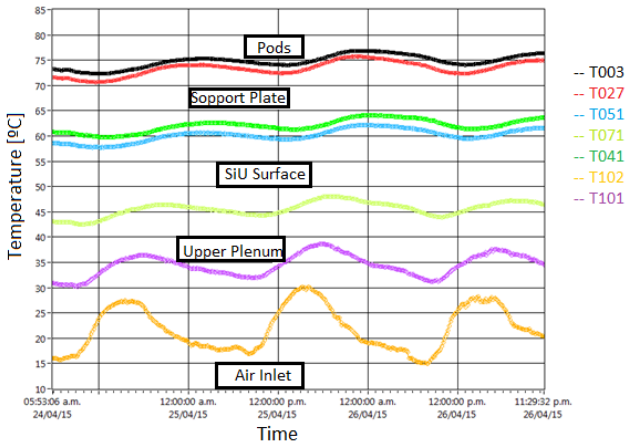

FIG. 7. Shift between maximum temperatures: Pods, SiU, Air channels

In figure 8 we can observe the temperatures reached by the air 5 mm below the lower limit of the cover of the silo units S2, S4, S5, S8 and S9, being the thermocouples T89, T92, T49, T69 and T96 respectively . The highest temperature is 44.1°C in the T49 belonging to the S5 silo

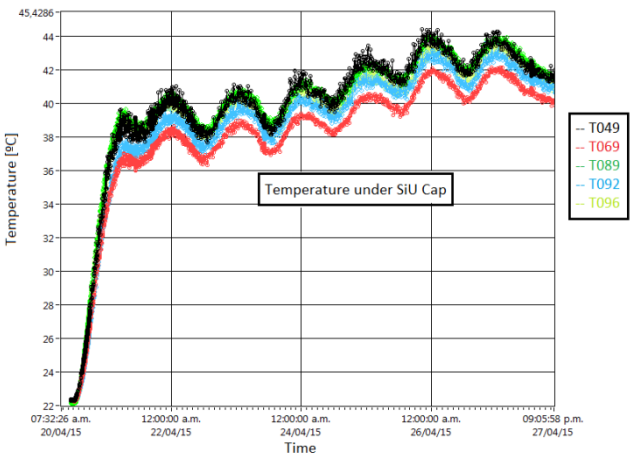

FIG. 8. SiU 5 - Evolution of the ambient temperature upper zone of the SiU

Table 3 shows the temperature values reached, in steady state, at different points of the Mock-up at different test powers. The points selected to show in Table 3 give a clear idea of the thermal behaviour of the Mock-up at different powers during the day (3 p.m.) and during the night (0 a.m.).

TABLE 3. TEMPERATURE IN DIFFERENT AREAS OF THE MOCK-UP

	30 W		40 W		60 W (Nominal)		90 W	
	Day	Night	Day	Night	*Day*	*Night*	Day	Night
Air inlet (T106)	26.6ºC	15.4 ºC	24.0ºC	17.9 ºC	30.0 ºC	19.1 ºC	30.0ºC	20.5 ºC
Max. Pods (T103)	47.4°C	49.0 ºC	56.8°C	59.4 ºC	74.5 ºC	76.9 ºC	86.1 ºC	90.5°C
Air Inside SiU sopport plate (T51)	38.9°C	41.0 ºC	47.2°C	49.5 ºC	61.6 ºC	64.2 ºC	70.2 ºC	74.7°C
Air Inside SiU under cap (T49)	28.0°C	29.4 ºC	35.7°C	34.6°C	42.6 ºC	43.8 ºC	46.6 ºC	49.6°C
Upper Plenum (T102)	27.8ºC	25.2 ºC	30.1°C	28.6 ºC	37.8 ºC	34.8 ºC	41.4 ºC	39.4 ºC
Chimney (T101)	27.8°C	22.8 ºC	27.7°C	26.34 ºC	36.3 ºC	31.8 ºC	35.6°C	34.7 ºC

Figure 9 shows the thermal gradients in the horizontal direction in SiU 5 and 8. That is to say, the temperature profile is presented in the elevation where the maximum pod temperature is produced and is compared against the results obtained in the computational simulations.

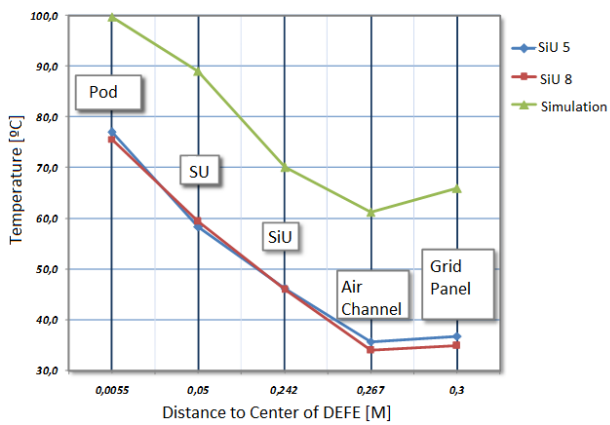

FIG. 9. Thermal Gradient Test vs Simulation

1.2.2 Accidental Condition - Power 60 W.

As mentioned, the accidental test situation was simulated by closing the air inlet and outlet valves, avoiding the natural circulation of air in an open circuit.

First the steady state of normal operation (open inlet and outlet air valves) is reached at the required power. Secondly, the valves are closed and the evolution of the temperatures is monitored. The test was extended for 10 days as the maximum temperatures did not reach unacceptable values.

Figure 10 shows the evolution of pod temperatures, upper plenum and air intake area. In this evolution, two pronounced temperature increases are observed both in the sheath and in the air of the upper plenum: the first is the transient of normal heating in open circuit until reaching the steady state and the second is due to the closing of the valves during the second day of rehearsal that simulates the accident. It can also be observed that the second temperature jump occurs earlier in the upper plenum than in the sheath, this is due to the thermal inertia of the system.

The test was completed after several days upon observing that the temperatures reached a steady state. The maximum temperature reached in the pods were 83.37ºC and 83.25ºC in the thermocouples T03 (SiU5) and T27 (SiU8) respectively

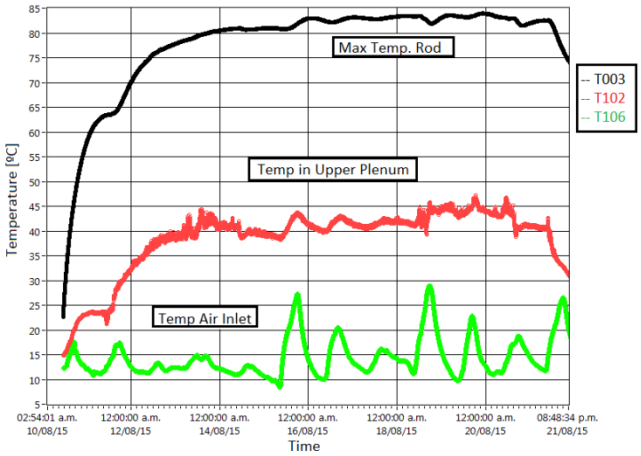

FIG. 10. Temp. in fuel pod, air inlet and upper plenum of SiU 5

Figure 11 shows the evolution of the maximum temperature of the pod and the temperature of the lance of SiU S5. The highest temperature in the area of the bearing plate is 71.15°C, giving a jump between the sheath and the lance of 12.8°C, maintaining the same relationship as in the case of natural convection in normal operation. In SiU S8 the maximum pod temperature is 83.25°C and the temperature in the lance is 70.45°C giving the same gradient.

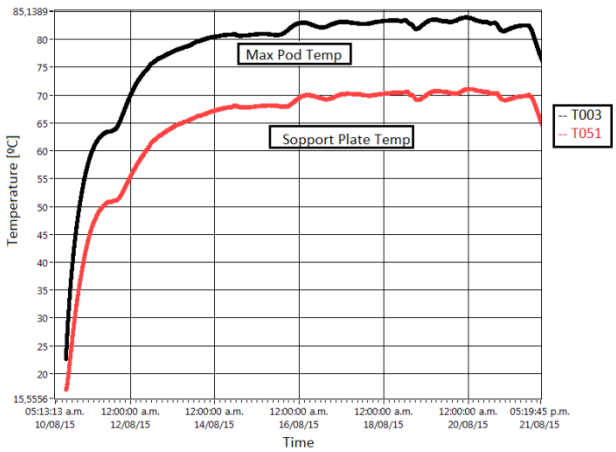

FIG. 11. Relationship of temperatures between sheath and bearing plate

In figure 12 we can observe the temperature jumps between inlet and outlet of external air. As the valves are closed and the system is isolated from the outside we can see that the thermocouples T100 and T101 that

remain under the valve accompany the temperatures of the day, however the T102, which is located at the outlet of the upper plenum, increases considerably its temperature, reaching a maximum value of 47ºC. The movements of the temperature in the thermocouple T102 show that the isolation valves did not close hermetically.

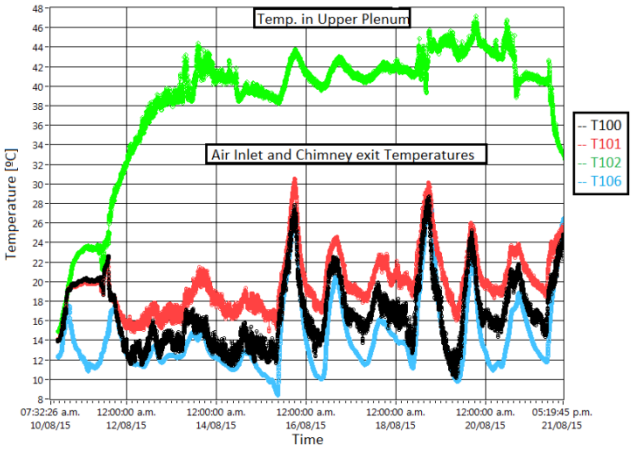

FIG 12: Temperatures in the external cooling air

In figure 13 we will show the temperatures reached in the lower edge of the lid, in thermocouple T49. Being the maximum of 50.7ºC. On the other hand, it was found that the lid serves as an insulator since you could touch it and verify that it was at a slightly higher temperature than the environment, this is due to the layers of air left between the plates that make up the lid for that finish.

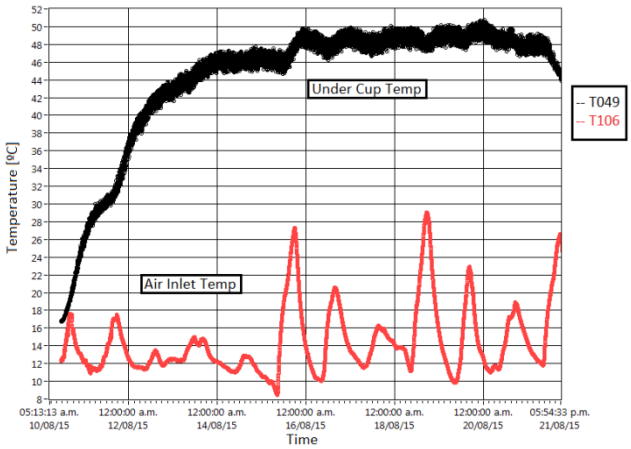

FIG. 13. Air inlet temperature and under cup temperature in SiU

1.3 Conclusions

The most relevant conclusions of this experimental work are:

Normal Operation Condition - Power 60 W.

— The maximum pod temperatures reached in the DEFE are less than 80°C, that is, less than half the maximum admissible value of 200ºC;

— Good adjustment with the previous simulations. Although the temperatures in the simulations were approximately 25°C higher than those measured in the tests, the air temperature used in them was 40°C (10 °C more than the largest of the tests). In addition, it must be borne in mind that in any simulation conservative criteria are used and that the measurements have an uncertainty of ± 1.04°C. This allows trusting the results obtained in the simulations of the complete installation and through them to predict the thermal behaviour of the same;

— A significant characteristic of the thermal behaviour of the mock-up is the thermal inertia of the assembly: the maximum temperatures in the pods are presented 9 hours after the ambient air reaches the maximum temperature, while the maximum temperatures in the upper plenum and in the SiU are

presented 1.5 and 2 hours later respectively. This is due to the fact that the air from the outside cools the walls of the silo unit and these are the ones that cool the interior air of the unit thus achieving the cooling of the fuel, all this makes the system have a great inertia;

— There is no significant influence on the temperature of the pod with the variation of the ambient temperature. A change in ambient temperature of 10.9 ºC (30.0 / 19.1) between day and night for the case of 60 W produces a variation in the temperature of the pod of 2.4°C (74.5 / 76.9);
— Maximum pod temperatures do not occur at the upper level (2600 mm) but a little lower (2000 mm);
— The temperatures measured in the SiU environment at the height of the bearing plates can be used in the ASECQ to estimate the maximum temperature of the pod.

Accidental Condition - Power 60 W.

— The maximum pod temperatures reached in the DEFE after 10 days of testing are less than 100°C. That is to say that, in the unlikely case of punctures in the pods and US, there is enough time to solve the problem.

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