RESEARCH REPORT

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The COOLOCE-2 coolability experiment with a conical particle bed

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Summary

The COOLOCE experiments and their modelling aim at investigating the coolability of core debris beds of different geometries. The second experiment aiming for the determination of dryout power in a conical (heap-like) particle bed using the new COOLOCE test facility is described. In addition, simulation results are presented and compared to the experimental results.

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1 Introduction

A porous particle bed that consists of solidified corium may be formed as a result of a core melt accident in a nuclear power reactor. Depending on the design of the reactor, such a debris bed may be formed in the containment, e.g. in the flooded lower drywell of the Finnish BWR's after the failure of the reactor pressure vessel, or inside the pressure vessel. In order to ensure the coolability of the core debris and to prevent dryout and possible re-melting of the material, the decay heat has to be removed from the material.

The COOLOCE test facility is used to investigate the coolability of porous particle beds of different geometries. The main objective of the experimental programme is to compare the dryout power of a conical (heap-like) particle bed configuration to that of a cylindrical (evenly-distributed) configuration. In addition to providing new data of the effect of particle bed geometry on coolability, the experimental results are used for code development.

The present report describes the COOLOCE-2 experiment investigating a conical particle bed. The experiment is a pressure variation of the preceding COOLOCE-1 experiment which was the first experiment aiming for dryout with the new test facility. According to the test plans, COOLOCE-1 was to be conducted at nominal 2 bar absolute pressure and the COOLOCE-2 at atmospheric pressure. The pressure control turned out to be rather stable during the first experiment, and the recorded pressure at the time of dryout was approximately 1.9 bar. However, during the latter COOLOCE-2 experiment it was found out that it was not possible to maintain the atmospheric pressure, and the pressure level at the time of dryout was approximately 1.6 bar.

In addition to the description of the test, a comparison of the experimental results to the dryout power predicted by MEWA 2D simulations is given. A description of the test facility and the first experiment aiming for dryout (COOLOCE-1) can be found in the report by Takasuo et al. (2010). The particle bed configuration and the test set-up in COOLOCE-2 are similar to the ones in COOLOCE-1. Description of the previous analytical work and background information of the studies can be found in the report by Takasuo et al. (2011).

2 The test facility

The main components of the COOLOCE test facility are the pressure vessel which houses the test particle bed, the feed water and steam removal systems and instrumentation. The custom-made pressure vessel has a design pressure of 7 bar. The pressure vessel with the condenser of the steam line in front is shown in Fig. 1. The total volume of the conical particle bed is 17.5 l.

The test particle bed consists of ceramic beads that are being held in shape by a dense wire net. The particle bed is heated by resistance heating system that uses ∅ 6.3 mm vertically installed cartridge heaters of different lengths. The configuration aims at achieving a uniform temperature distribution within the test bed. To measure the particle bed temperature and detect dryout, K type thermocouples are installed in a distributed configuration striving for maximal coverage of the particle bed volume between the heaters. The heaters and the thermocouples are connected through the pressure vessel bottom. The heating and temperature sensor configuration prior to the installation of the particle material and the complete particle bed filled with the ceramic beads are shown in Fig. 2.

Fig. 1. The COOLOCE presure vessel (with thermal insulation) and the condenser during the first experiments with conical particle bed.

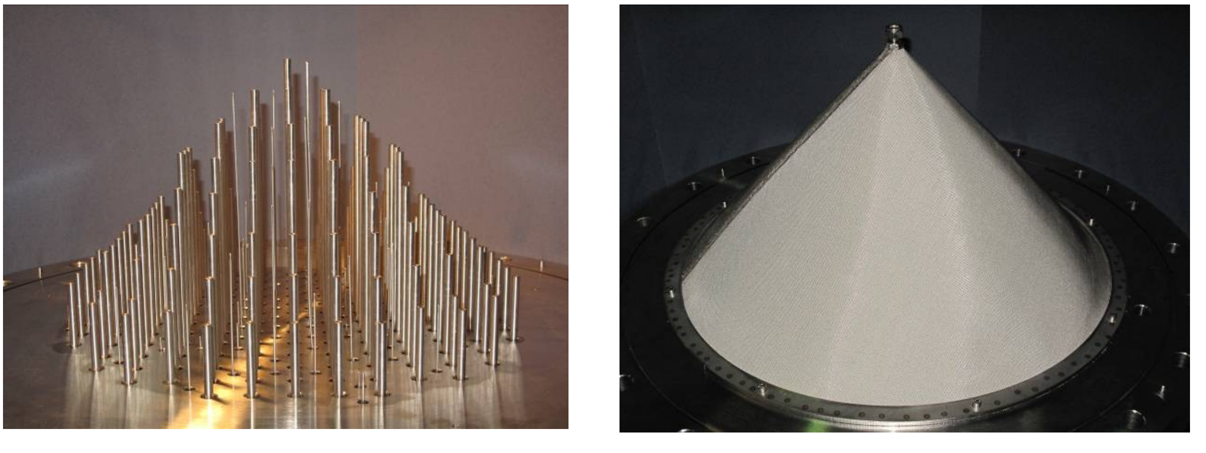


Fig. 2. The heater and thermocouple arrangement and the test bed filled with particles for the COOLOCE-1 and COOLOCE-2 experiments. The diameter of the cone is 500 mm.

2.1 The test procedure

The test procedure consists of a heat-up sequence and the main test sequence. Prior to the experiments, the test pressure vessel is filled with demineralized water. During the heat-up sequence the facility is heated up to the saturation temperature and steady-state boiling is reached. In the test sequence, a stepwise power increase is conducted until a dryout is indicated by one or more thermocouples within the test particle bed. Dryout is seen as a stable increase of the sensor temperature from the saturation temperature. A waiting time of 20 to 30 minutes is applied between the power increases. This is necessary because the boil-off of liquid inside the particle bed after the critical power level has been reached takes some time (the amount of which depends on the excess power).

The heating power is manually controlled by adjusting the input voltage of a purpose-tailored power transformer as percentage of the full output. The heaters are arranged in three groups according to the electrical phase. The mapping of the heaters on the bottom lid of the pressure vessel is presented in Appendix A.

The control power and temperatures in the centre of the test bed during the warm-up sequence in Fig. 3 show how the temperatures gradually increase until saturated (or nearly saturated) conditions are reached. The temperature readings are taken from the multi-point thermocouple near the centre of the cone. It is seen that the thermocouples near the bottom of the system heat-up slower than the ones near the top due to the vicinity of the uninsulated bottom plate of the pressure vessel. The bottommost sensors remain slightly below saturation temperature even after a heap-up of 1.5 hours, at the power level of 20 kW.

The control power and temperature log near the central region of the cone in the COOLOCE-2 main test sequence are presented in Fig. 4. The sensors numbered 201-210 refer to the multi-point sensor next to the longest heating rod in the centre of the configuration. The sensors 211-213 are the other three sensors around the central heater. Numbering of the sensors is found in Appendix B. The power step was 2 kW as can be seen in the graph.

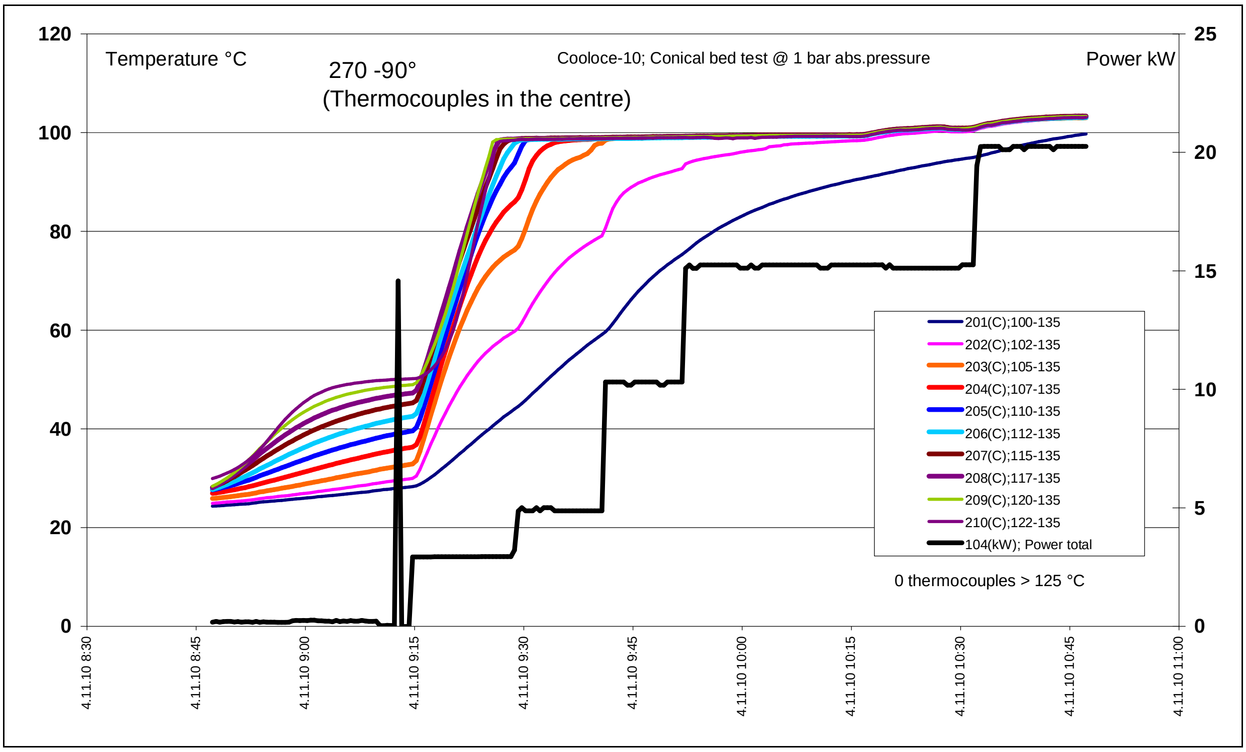


Fig. 3. The control power and temperature in the centre of the particle bed during the heat-up sequence.

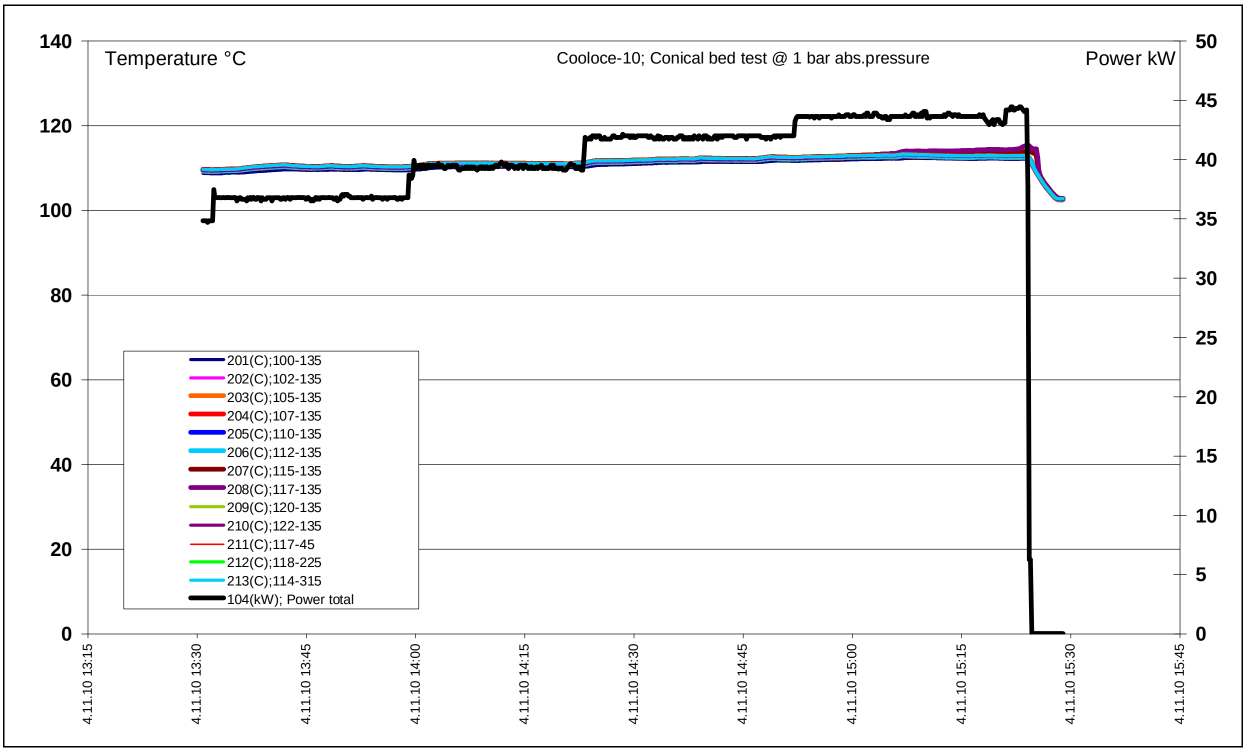


Fig. 4. The power log of the COOLOCE-2 test run and the temperatures of the sensors near the centre of the particle bed.

It should be mentioned that during the COOLOCE-1 experiment, a heater malfunction was suspected due to a slight change in the power output of one of the three phases (central heaters) in the final stages of the experiment. After the experiment, the malfunction was verified by separate tests of the heaters near the centre of the cone. It was discovered that one of the heaters near the central heater had failed presumably due to overheat, causing a slight asymmetry in the power distribution. This means that the total heating power was decreased by 850 W.

Because in the COOLOCE-1 experiment the value of dryout power was verified by two repeated power increase sequences (Takasuo et al. 2010), and the latter of these sequences already contained the failed heater, it was decided to proceed to the COOLOCE-2 experiment without replacing the damaged heater at this point of the experiments. The heating configuration in the COOLOCE-2 experiment is fully comparable to the latter dryout point in COOLOCE-1.

2.2 Estimation of dryout power by steam flow

Heat losses through the walls and connections of the facility cause the power consumed by boiling to be smaller than the control power. Also, since the capacity of the feed water pre-heater is not high enough to increase the feed water temperature to boiling point, maintaining the saturation temperature at the test vessel pressure has to be done by the heaters. The pre-heater increases the feed water temperature up to about 60-80°C.

The heat losses and the feed water heat-up within the test vessel reduce the heat flux directed to evaporation. Because of this, the boiling rate is verified by measurements of the condensing steam mass flow rate. The power calculated from the mass of steam gives an estimate of the actual dryout power and the heat losses of the system (even though possible condensation in the pressure vessel is not taken into account).

The condensate mass flow rate converted to power, and the control power during the experiment are presented in Fig. 5. Fig. 6 shows the difference between the control power and the calculated power as a function of the control power in the COOLOCE-1 and -2 experiments (i.e. an estimate of the heat losses of the facility at different power levels).

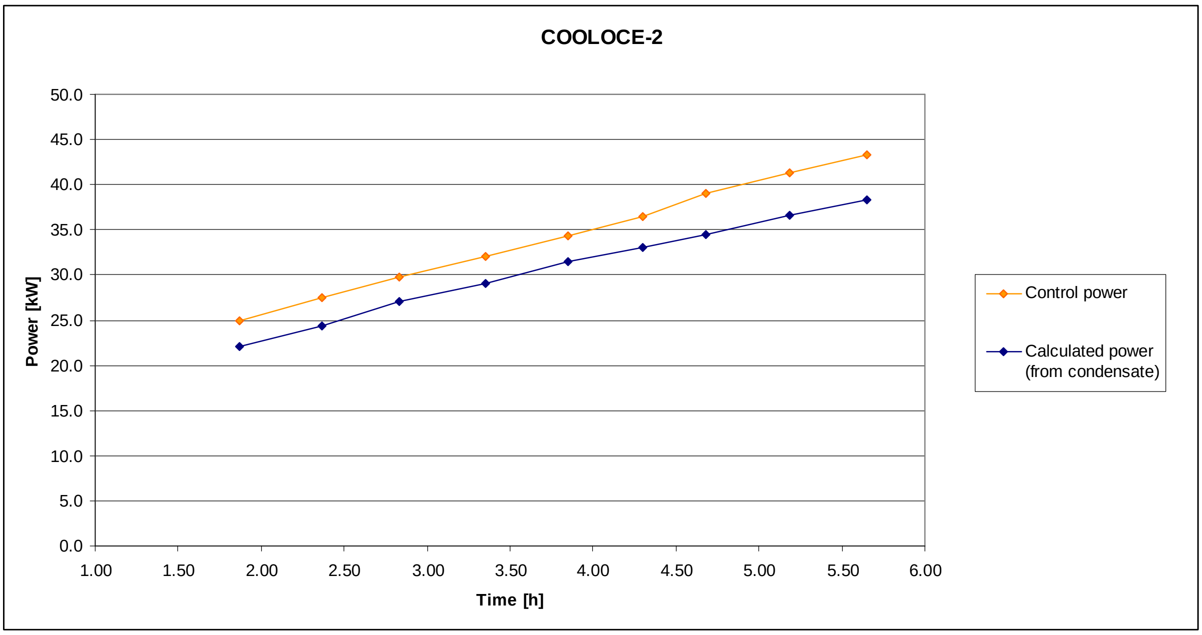


Fig. 5. Condensate mass flow rate converted to power in comparison to input power (based on 10 minute averages).

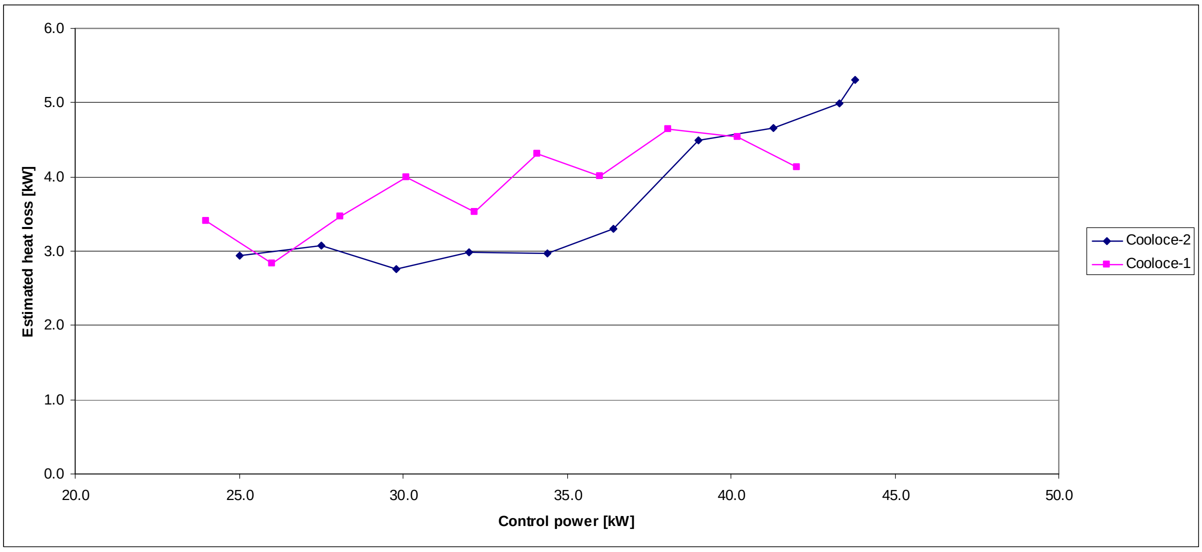


Fig. 6. Estimated heat losses of the test facility as a function of control power (based on 10 minute averages) in the COOLOCE-1 and -2 tests.

3 Experimental results

Dryout was observed at the control power of 43.8 kW at the pressure level of 1.57 bar near the centre of the cone, indicated by a temperature sensor at 170 mm height from the bottom. The power and temperatures during the final power steps leading to dryout are presented in Fig. 7. The temperatures in Fig. 7 are taken from the "hottest" sensors in centre of the test particle bed between 14 and 17 cm from the bottom. The pressure and water level in the test vessel as well as the vessel water and feed water temperature histories during the test are shown in Fig. 8.

At the power level leading to dryout, the average mass flow rate of condensate was 0.173 kg/s. The power corresponding to this steam production rate is 38.6 kW. This indicates total heat losses the order of 5 kW as already shown in Fig. 6. Since the calculated power gives a better estimate of the heat consumed by boiling (and dryout power) than the control power, the calculated power is considered as the dryout power of the experiment. The total power of 38.6 kW corresponds to a volumetric heat flux (power density) of 2206 kW/m³.

It should be noticed that there is uncertainty also in the calculated power because possible condensation in the presure vessel is not taken into account, and the measurement is based on 10-minute averages using a scale whose accuracy is 50 g. Furthermore, the reduction caused to the steam production rate by the dryout itself is not taken into account in the conversion of the steam flow to heating power. In principle, this might lead to underestimated dryout power. However, the contribution of reduced boiling in the dried-out zone to the average of the steam flux from the particle bed prior to the observation of dryout by the sensors (and the subsequent termination of the test sequence) can be expected to be very small.

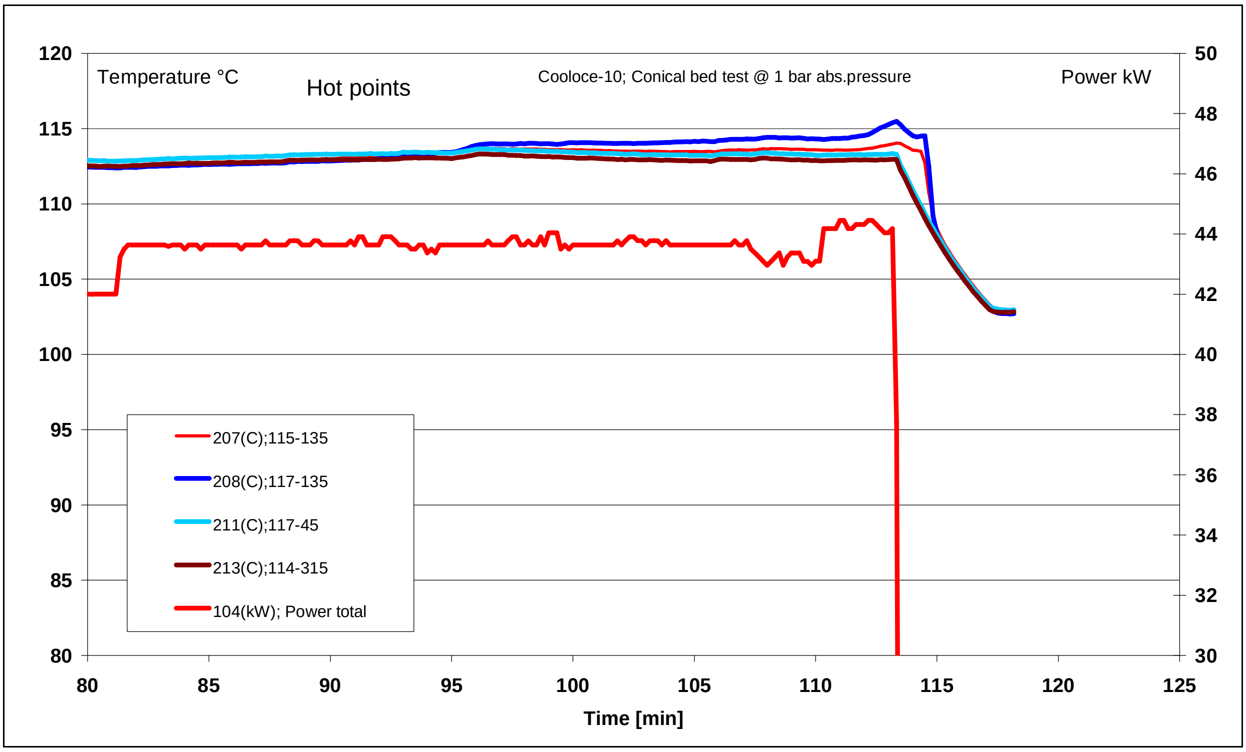


Fig. 7. Control power and temperatures in the centre of the cone during the final power steps leading to dryout.

The experiment was planned to be conducted at the nominal absolute pressure of 1 bar, to be achieved with a fully open steam line valve. However, it was seen during the test sequence that the pressure kept increasing along with the increase of power and the mass flow of steam, despite of the open valve. This was apparently due to the constriction of flow in the steam line and the steam line valve which have not been designed for such great amounts of steam. The COOLOCE-1 and -2 were the first experiments in which heating power levels greater than 40 kW were necessary.

The overpressure, water level in the test vessel and the feed water and vessel water temperature histories during the four final power steps are presented in Fig. 8. At the pressure level at the time of dryout (1.6 bar), the saturation temperature was 113°C. It was decided to finish the test when the temperature had climbed above 115°C in the sensor 117-135 after approximately 20 minutes of waiting after the reading of the sensor had started to deviate from the neighbouring sensors.

The moderate increase in temperature suggests that the measured dryout power was very close to the actual dryout power in the present conditions. It is expected that further waiting and/or power increase would have led to a drastic increase of temperature as in the COOLOCE-1 experiment. However, in order to avoid the overheating encountered in the previous experiment, the power was shut down prior to this.

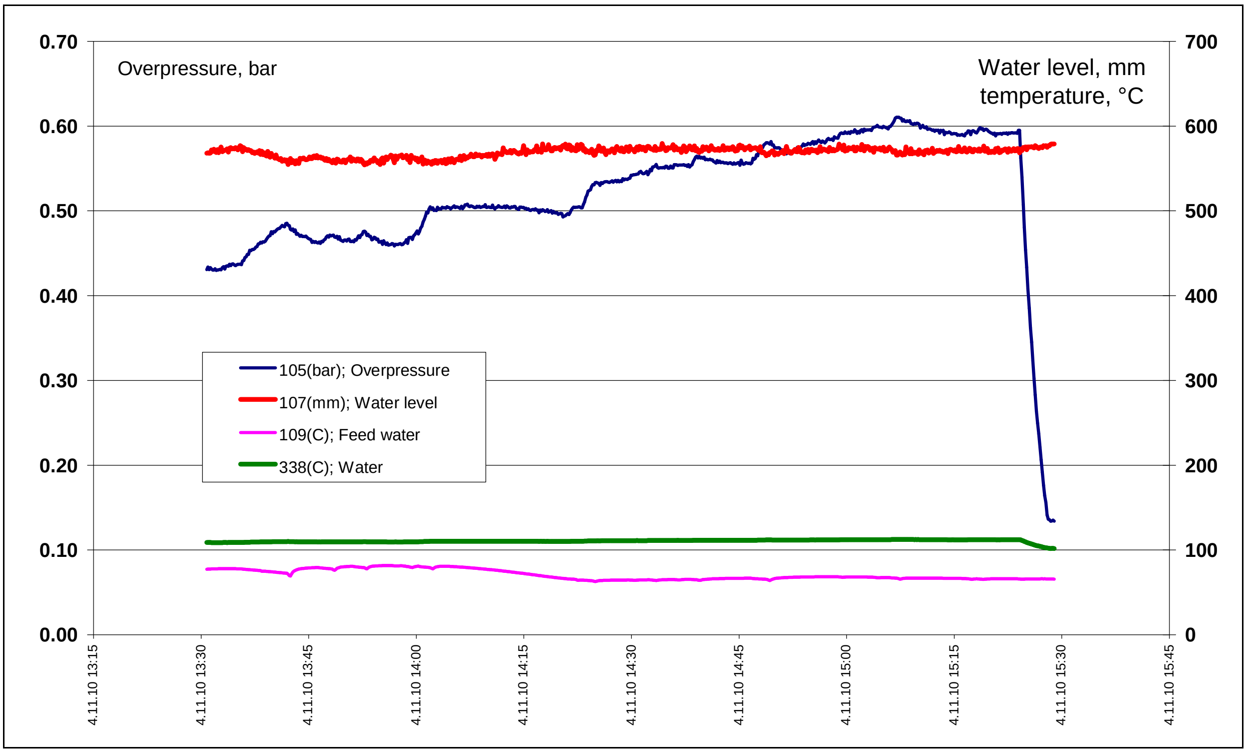


Fig. 8. Water level and pressure in the test vessel and water temperatures in the feed water line and the test vessel.

4 Comparison to simulation results

The COOLOCE-2 experimental conditions have been simulated by the MEWA 2D code developed by the IKE institute at Stuttgart University for severe accident analysis (Bürger et al. 2006). The solution in MEWA is based on the basic conservation equations for two-phase flow, connected to the friction and heat transfer models suitable for porous media. The pressure loss in the particle bed is evaluated by models based on the Ergun's equation.

4.1 Simulation set-up

The simulation set-up for the MEWA calculations is summarized in Table 1.

Table 1. Simulation set-up.

Particle diameter	0.9 mm / 0.8 mm / 1.0 mm
Porosity	0.37
Pressure	1.9 bar
Material density	4000 kg/m³
Thermal conductivity	2.0 W/mK
Specific heat capacity	775 J/kgK
Grid size (radial x axial cells)	25 x 89
Time step size	Controlled by the code
Heating method	Constant power density
Power step size	2 kW

The material properties used in simulation are (roughly) those of the ceramic zirconia/silica used in the experiments. Because the size distribution of the particles (0.8-1.0 mm) is presently unknown, we take 0.9 mm for the particle diameter as a reference case. Parameter variations using diameters of 0.8 mm and 1.0 mm are also conducted in order to estimate the range of variation of the dryout power with respect to particle diameter. Porosity is the approximate maximum packing density of randomly mixed spherical particles and it is taken to be constant for the simulated particle bed. The heating power is assumed to be uniformly distributed within the particle bed. This is because of the following reasons:

1) The assumption of evenly distributed heating power is valid for reactor scenarios in which the decay heat is generated internally in the particle material. Constant power density helps to estimate the effect of the heating arrangement in comparison of the test configuration to realistic scenarios.

2) Using the 2D approach, it is not possible to simulate the heating arrangement in detail. The heating arrangement is expected to cause some channelling in the flow field inside the particle bed due to the local heat generation and increased porosity near the heaters (this is due to the mechanics of packing of the spherical particles against surfaces). Since there is no straightforward method to scale the varying porosity and power density to 2D, we choose to treat the particle bed in an averaged manner with respect to these parameters.

Also, note that the simulation is not an attempt to repeat the power increase scheme in the experimental sequences. Since we do not have experimental data on the void fractions in the particle bed at different pre-dryout power levels, detailed numerical investigations of pre-dryout conditions would be of limited use. The main objective is to predict the dryout power. This means finding out the minimum power level that leads to dryout and the maximum power level at which the particle bed just stays in a coolable steady-state. This pair of heat fluxes determines the “allowed limit” for decay heat generation in reactor scenarios.

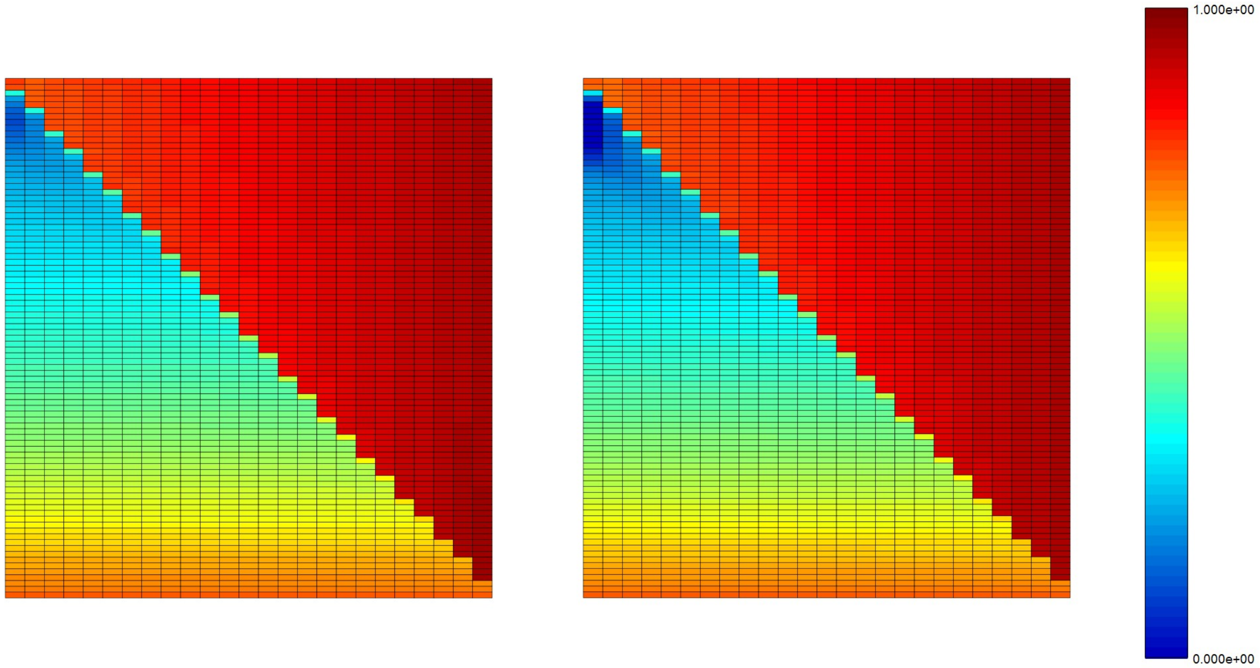
4.2 Results

According to the MEWA calculation, the maximum coolable power in the modelled system is 26.0 kW and the minimum dryout power is 28.0 kW, calculated with the accuracy “window” of 2 kW for the particle diameter of 0.9 mm. The experimental dryout power is 38% greater than the simulated value. The deviance in the results is possibly caused by the effect of the heating arrangement: channelling tends to increase the dryout power (and coolability). Future experiments and analyses are expected to shed more light on the issue.

For the particle diameter of 0.8 mm, the minimum dryout power is 24.0 kW. For the particle diameter of 1.0 mm, the dryout power is 32.0 kW. The inaccuracy of the dryout power of the reference case in this respect is of the order of 15%.

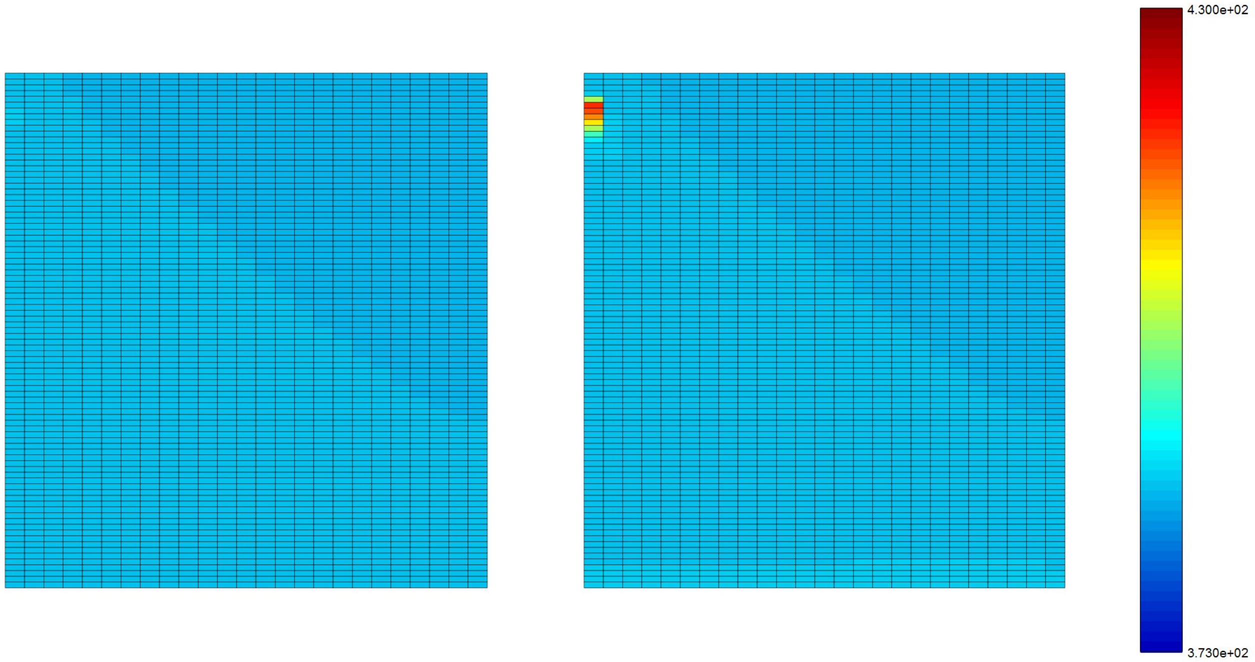
The simulation results for the reference case are illustrated in Fig. 9 - Fig. 11. Fig. 9 shows the pre- and post-dryout saturation fields. Fig. 10 shows the corresponding particle temperature fields. The vertical saturation profiles at different simulation times in the centre of the cone are presented in Fig. 11. The saturation profiles illustrate the process of dryout development. Note, however, that the profile to be plotted has to be selected near the axis of the geometry since the saturation distribution is not radially uniform in the conical configuration.

As can be seen in Fig. 9 and Fig. 11, the distribution of saturation (fraction of liquid in the pores) is nearly similar in both pre- and post-dryout conditions. The minimum saturation is located near the top of the cone throughout the simulation. This zone becomes the dried-out zone after the dryout power has been exceeded.



P = 26.0 kW P = 28.0 kW

Fig. 9. Pre-dryout (left) and post-dryout (right) saturation (liquid fraction in the pores) in the COOLOCE-2 simulation.



P = 26.0 kW P = 28.0 kW

Fig. 10. Pre-dryout (left) and post-dryout (right) solid temperature in the COOLOCE-2 simulation.

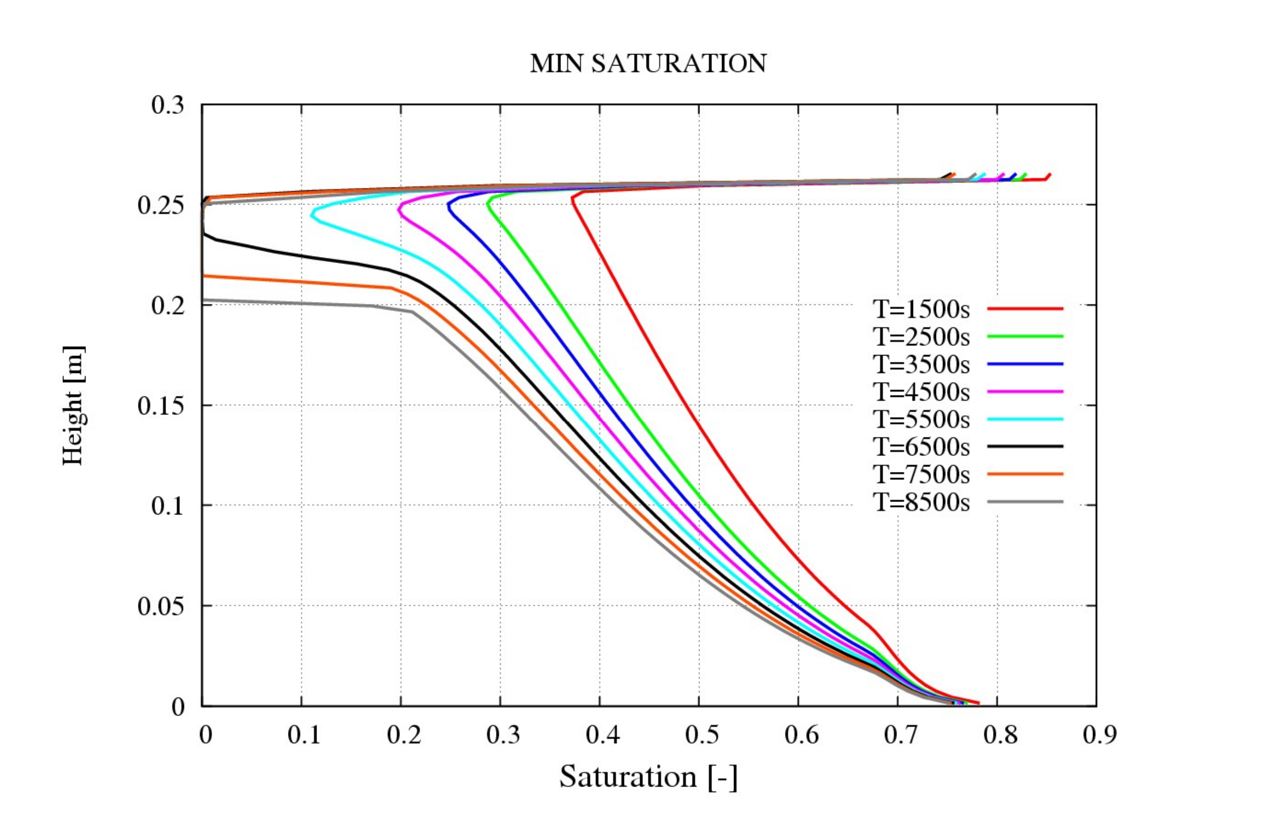


Fig. 11. The saturation profiles during the development towards dryout in the COOLOCE-2 simulation.

4.3 Effective particle diameter

In the simulation approach above, the power density, porosity and particle size is homogenized over the particle bed. The deviation from the experimental results suggests that this approach may not be representative of the volumetrically non-homogenous configuration. Next, we determine an "effective" particle diameter by fixing the heating power to the level of the measured dryout. In this effective diameter, the heaters and the porous matrix between them are implicitly included. Instead of power in the previous calculation, the minimum coolable and maximum dryout particle diameters are pin-pointed by several simulations. Greater particle diameter tends to increase dryout power and coolability due to decreased solid-fluid friction (which is a result of the decreased particle surface area).

The simulation results indicate that the minimum particle diameter for which coolable steady-state can be reached for the power level of 38.6 kW is 1.2 mm and the maximum diameter for which dryout is seen is 1.1 mm. Thus, the effective particle diameter for the present test bed is 1.1 mm. This means a 20% increase in particle diameter and 40% increase in dryout power compared to the reference case.

In general, the effects of non-homogenous particle diameter and particularly porosity and power density inside the bed may be significant, and they can change the void profile in the bed. Even the dryout location may be changed as a result of downcomer effect. Because of this, it is not always possible to describe the particle bed behaviour using average values. However, in the present particle bed in which the heaters are evenly distributed within the test bed and the usual direction of fluid flow is upwards, we see this as a reasonable way to estimate the particle bed properties and to get an idea of the uncertainties present in the configuration.

5 Discussion and summary of the results

The experiments conducted within the COOLOCE test programme until the publication of this report have been summarized in Table 2. The COOLOCE-0 test was a preliminary experiment conducted in order to verify that heaters and instrumentation were working as required. The maximum control power applied in this experiment was 20 kW (for which no dryout was seen).

Table 2. Summary of the COOLOCE experiments.

Experiment	**Date**	**Geometry**	**Pressure [bar]**	**Dryout power [kW]** (control / from condensate)	**Dryout power density [kW/m³]** (control / from condensate)
COOLOCE-0 (preliminary test)	Aug 31, 2010	Conical	2.0	-	-
COOLOCE-1 T	Oct 21, 2010	Conical	1.9	46.2 / 40.7	2640 / 2326
COOLOCE-2 he	Nov 4, 2010	Conical	1.6	43.8 / 38.6	2503 / 2206

The above experiments have provided experience on using the new test set-up and it has been verified that dryout can be achieved with the new configuration. Visual observations of both dryout experiments have been done using sightglasses and a video recorder. However, it has been found out that the high levels of heating power pose a risk of overheating and damage to the heaters. Also, the high dryout power values indicate that it is not possible to obtain dryout for much higher pressures than 2 bar with the present set-up.

After the 1.6 bar test sequence, it was attempted to measure dryout for the pressure level of 2.4 bar but the re-heating of the facility caused another heating rod in the centre of the particle bed to fail (in addition to the one damaged in COOLOCE-1). This led to the termination of the test sequence and repairs to the facility were started prior to further experiments.

Another unexpected observation was the difficulty to maintain the atmospheric pressure in the COOLOCE-2 experiment. This was apparently because of the constriction of flow in the steam line and the steam line valve, significant due to the high steam flux related to the high power levels.

For instance, at the point of dryout for 1.57 bar pressure, the density of steam is 0.90 kg/m³. The steam mass flow rate from the condenser at the dryout control power of 44 kW was 0.017 kg/s. For the volume of steam that is lead through the valve this gives 18.9 l/s. The steam removal system (as well as the feed water system) had originally been designed for the STYX experiments in which the maximum measured dryout power had been approximately 37 kW at 7 bar. For a lower pressure of 2 bar, the highest measured dryout power had been 24 kW (see the journal article by Takasuo et al. 2011). Converting this power to steam production rate, and taking into account the density of steam at 2 bar, the corresponding volume flow rate for this experiment is 9.6 l/min. Note that the above calculation is indicative only, no condensate mass was measured in the STYX experiments.

6 Conclusions

A description of the particle bed dryout experiment COOLOCE-2 has been presented. The experiment is a part of the COOLOCE experimental programme which aims for investigating dryout power in particle debris beds of different geometries: conical and cylindrical. Dryout was measured at the relatively high power level of 38.6 kW in the upper part of the cone. The pressure level in the experiment at the time of dryout was 1.6 bar.

The experiment has been simulated by using the MEWA 2D code. The goal of the simulation was to obtain an estimate of the dryout power and compare the simulated power to the experimental result. It was found out that the experimental dryout power was about 38% greater than the simulated power. The difference may be due to the heating arrangement and the resulting non-homogeneity of the particle bed. Continuation of the test programme and the increase in the experience in using the new test facility are foreseen to increase the knowledge in this matter.

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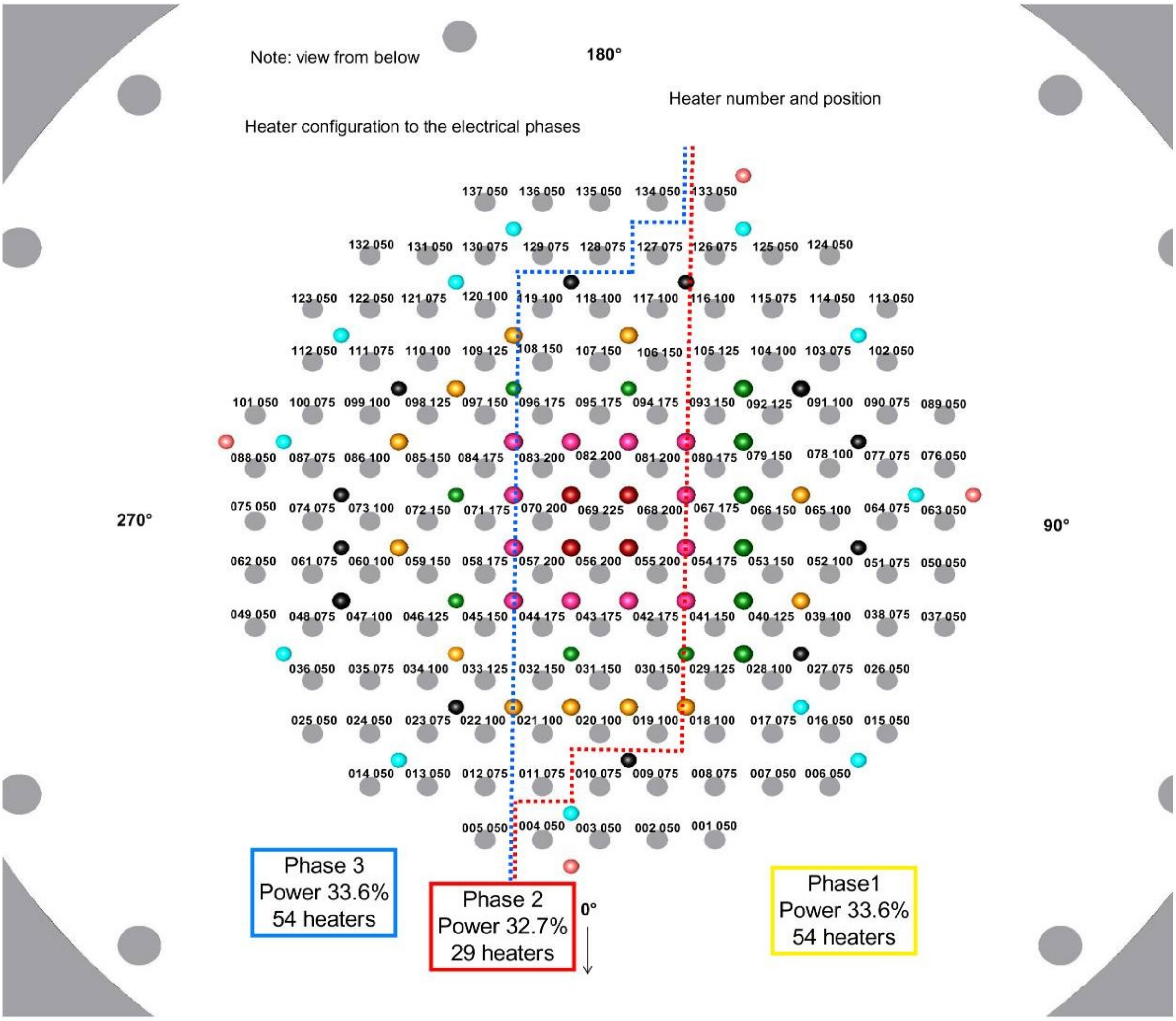
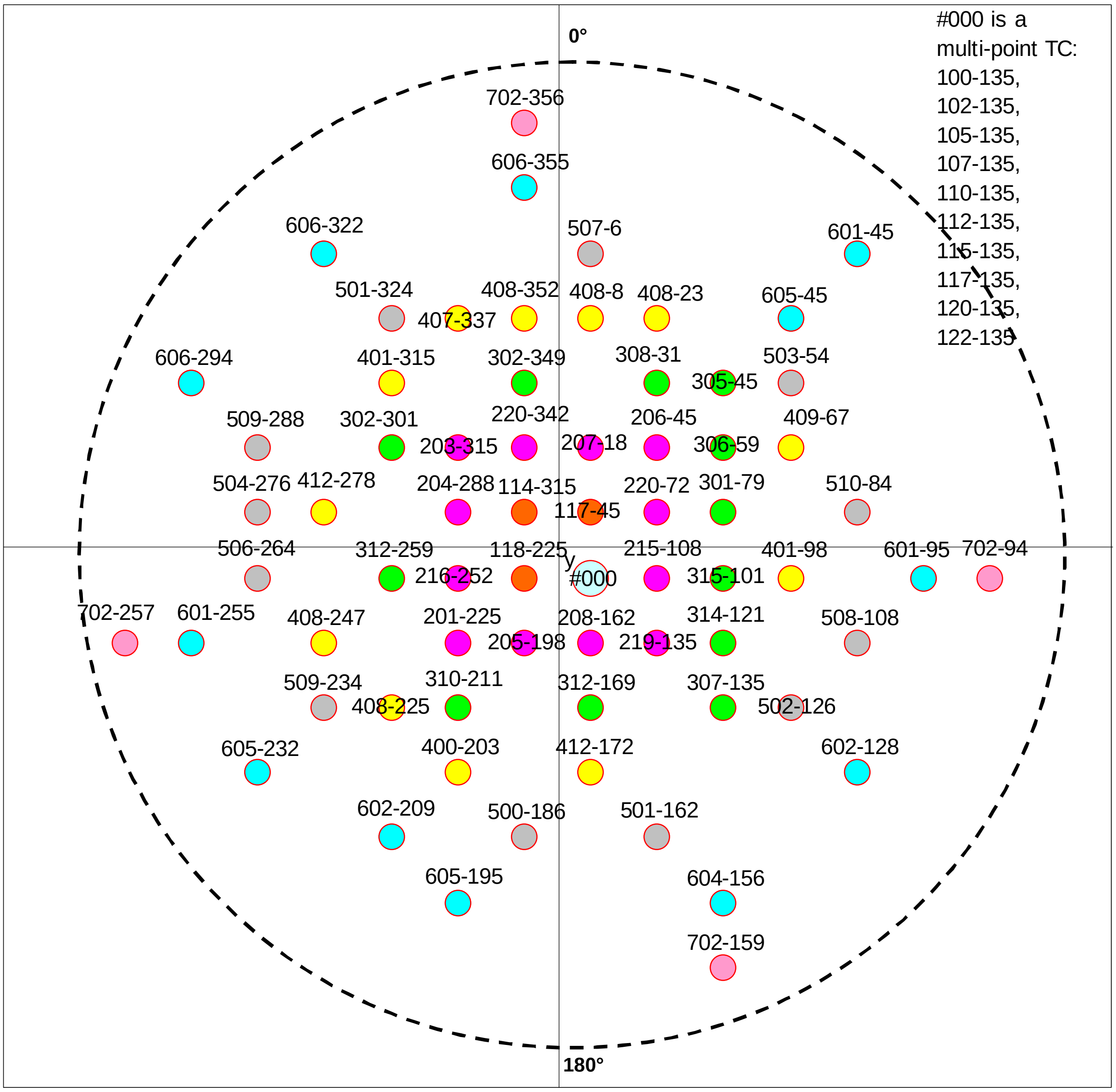
APPENDIX A. Heater arrangement (view from below)



APPENDIX B. Thermocouple arrangement (top view)



Example of how to read the map:

117-45

1 – number of the ring to which the thermocouple belongs to, indicated by different colors (1 indicates the central sensors, 7 the outermost)
17 – height of the thermocouple from the bottom in cm
45 – angle between the thermocouple location and 0°