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**D7.1 Design and fabrication of the 7-pin heated bundle and
integration into 15-15Ti cladding tubes**

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DOCUMENT SUMMARY

This deliverable describes the fabrication of 7 electrical heaters and their integration into MYRRHA cladding tubes to form fuel pin simulators. The instrumentation of the new MEXICO loop test section is described in details, focusing on the mounting steps of thermocouples onto fuel pins and fuel pins into the hexagonal wrapper. The entire test section is now installed in MEXICO loop at SCK CEN, and ready for the new experimental campaign of chemical blockages and corrosion of MYRRHA fuel clad.

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1. Introduction

In MYRRHA, one mechanism by which a full core blockage can be envisaged to occur is by particle accumulation or deposition, originating from chemical processes in the LBE [1]. Two sources of particles and deposits can be identified, depending on the operational mode.

During normal operating conditions, steel elements (e.g. nickel, iron and chromium) originating from corrosion of the fuel cladding and structural materials are continuously released into the LBE and transported with the coolant. These corrosion products may react with dissolved oxygen present in the LBE, forming solid oxide deposits or particles. The continuous deposition of corrosion products and/or accumulation of oxide particles may cause blockages in narrow channels such as those of the fuel assembly (FA) [2]. In incidental conditions, in which the LBE conditioning system cannot be assumed to be operational, also solid lead oxide (PbO) particle and deposit formation is a concern. PbO can be formed if the oxygen content in the system exceeds the metastable limit of oxygen in LBE [3], due e.g. to uncontrolled oxygen in-leak.

Experimental measurements are necessary to investigate potential blockage mechanisms due to chemical processes and to ensure that the reactor is safe during normal operating conditions as well as incidental scenarios. In this task, a new experimental campaign is performed in order to study FA blockages during long term normal operation. An experiment that as close as possible represents the real chemical, hydraulic and geometrical conditions of MYRRHA fuel assembly is necessary. The fuel pin prototypes should also be composed of the actual 15-15Ti cladding materials of MYRRHA in order to reproduce accurately the impurity source term during long term operation. Consequently, corrosion of fuel cladding material under nominal operation with local thermal hydraulics and chemistry conditions that are close to that of the MYRRHA bundle (hottest) sub-channel can also be studied. A full-length 7-pin heated bundle will be designed and installed in a new test section of the MEXICO loop, SCK CEN, to perform such integrated experiment.

In summary, the specific objectives of this experimental study are, in order of decreasing importance:

- Plugging risk analysis in a 7-pin full-length heated FA during long-term (up to 1 year) normal operation under representative thermal-hydraulic and chemistry conditions of the MYRRHA core.
- Assessment of corrosion behaviour of 15-15Ti cladding material under representative nominal thermal-hydraulic and chemistry conditions of the MYRRHA core.
- As a side project, validation of CFD code in terms of wire-pitch, and calibration of the CFD models in term of local temperature prediction at available thermocouple locations.

This deliverable describes the new test section to be installed in the MEXICO loop for the experiment. Furthermore, the fuel pins design and fabrication is described and reported.

2. Fuel pins design and fabrication

2.1 Technical characteristics of a fuel pin

A fuel pin simulator (Fig. 1) is composed by an electrical heater designed by Thermocoax and inserted into a SCK CEN 15-15Ti cladding tube of MYRRHA. The fuel pin is completed with a custom-designed multi-point thermocouple which replaces the wire spacer functionality, while enabling temperature measurement at 4 different axial positions starting from the beginning of the pin heated length.

The main geometrical characteristics are similar to that of MYRRHA pin, with the first 615 mm of the heater length non-active (about 640 mm from the plug inlet) and then an active part of 650 mm. After the active part, another cold section is required in the experimental pin for the connection to the top flange, with a length of about 1700 mm. The total wire-pitched length is about 1375 mm. The external diameter of the clad is 6.55 mm, previously measured by ultrasound and recorded at SCK CEN. The hot/cold sections of the heater are showed in Fig. 1.

The different parts also shown in the figure include the insulation material of boron nitride, separating the positive and negative wires made of Inconel 600 and copper.

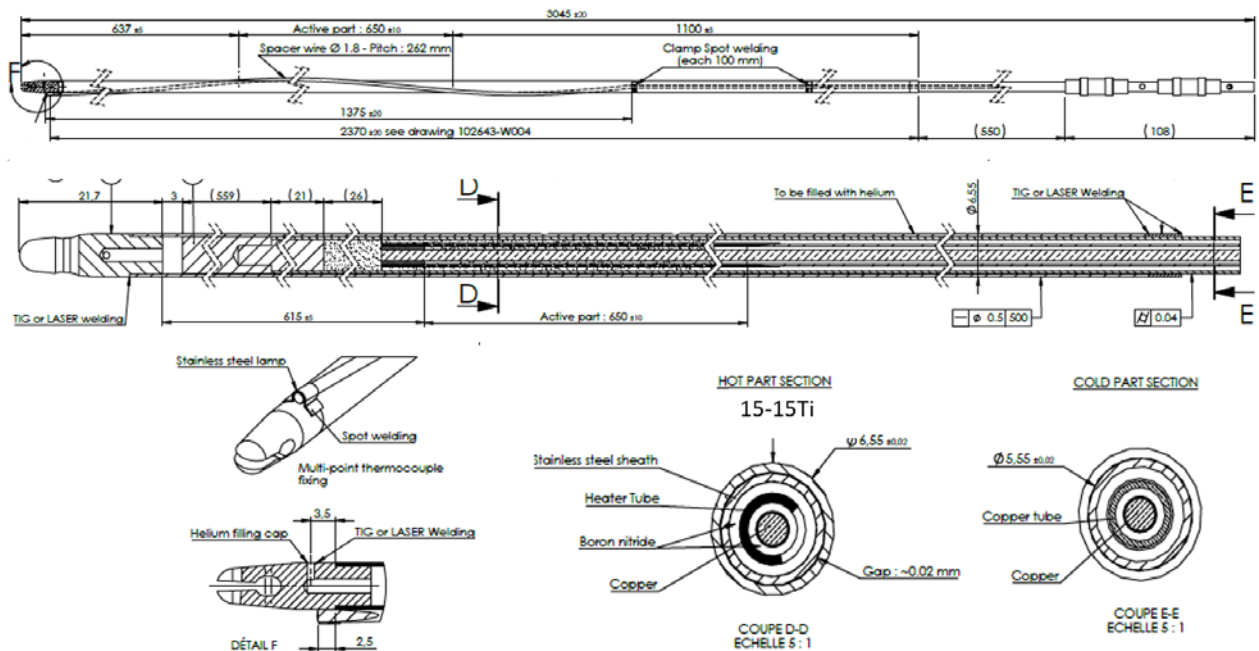


Fig. 1. Technical drawing of a fuel pin simulator.

An important design requirement is to minimize internal resistances between the clad and the heater external sheath of 316L, after insertion. The residual gap is hence filled with helium at atmospheric pressure to increase local thermal conductivity. The helium filling is done with a small later whole on the plug as indicated in the figure-Detail F, which is then welded after the filling. Furthermore, a gap of about 3 mm between electrical heater and pin plug is designed to compensate different thermal expansion between heater and clad, during pin power.

Concerning the electrical performance, each fuel pin power is about 12 kW by design (linear power of 185 W/m), at 230V and 52A. The electrical connector is made of ceramic material and can withstand temperatures above 200°C.

2.2 Fabrication process

The reason of the gap between clad and heater, is that the 15-15Ti cladding tube cannot be compressed to the heater sheath or cold worked at temperature above 400 °C. This is to preserve the mechanical properties of the clad as designed and fabricated for MYRRHA, which guarantee representative corrosion tests. The most critical step of the fabrication is hence the assembly of heater with clad without damaging or modifying the surface of the clad. After testing an insertion procedure, the method of assembling was optimized and the final external diameter of the heater was fixed.

The heater sheath is then welded by TIG method to the clad at the top and bottom parts of the pin. The welding parameters were optimized beforehand; particularly the weld between 15-15Ti and 316L sheath was challenging probably due to the slightly different properties of the two steels and non-optimal welding parameters. The effected heated zone after optimized welding parameters appears normal, as shown in Fig. 2.

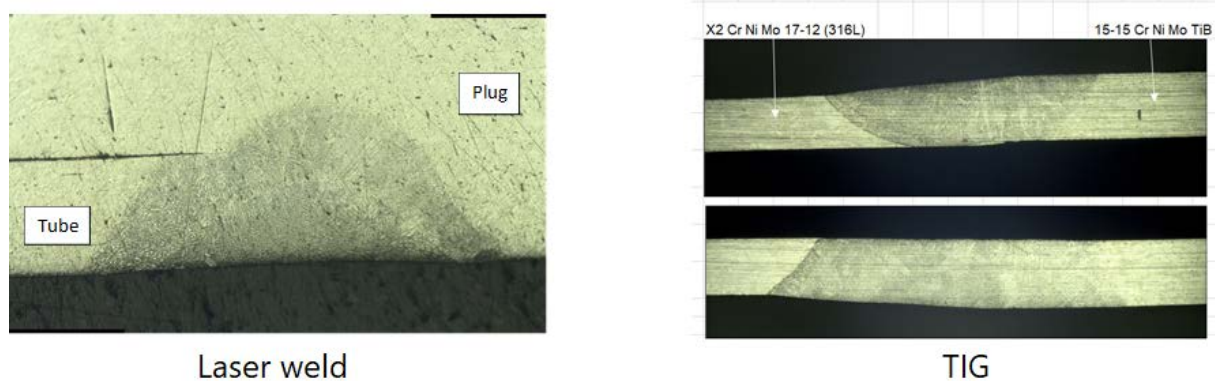


Fig. 2. Effected heated zone of the tube/plug side (left) and clad-heater side (right).

After insertion of the heater and welding with the clad, the helium filling was performed in a chamber at atmospheric pressure with several vacuum and filling cycles. The plug hole designed for the filling was then laser welded after the helium filling was completed.

After the assembling procedure the pins were verified and qualified in terms of line resistance and insulation resistance with respect to given electrical criteria from SCK CEN.

The characteristics of the fabricated pins, which satisfied the performance criteria, are reported in table 1. In the table one can see different powers of each pin resulting from the different active lengths of the pins, as build. The initial tolerance on the active length of ± 1 cm was respected by the manufacturer so that the power differences reported in the table are within expected values. The differences are however relatively small; this is important because during the experiment each pin can be operated just at design (full) power, without a more complicated automatic control of each pin power output.

The fuel pin simulators were delivered at SCK CEN on March 2021, and the mounting of the thermocouples was performed on site, as described in the next chapter.

One multi-diameter thermocouple for each pin (0.25 mm tip, 0.5 mm bulk, 1 mm feedthrough) enables to measure local temperature at the end of the heated length.

The fuel pins and thermocouples were delivered with already mounted electrical connectors, having a diameter larger than the respective feedthrough diameter at the top flange. Consequently, the pins and thermocouples had to be inserted from the top into the top flange sealing. The insertion was straightforward even though the length of the pins/thermocouples was longer than two meters: the feedthrough diameters (pin and multi-point thermocouple diameters are 6.55 and 1.8 mm, respectively) were machined from a standard dimension to an optimized diameter, previously tested for both optimal insertion and leak resistance.

Each pin and its associated thermocouples were mounted in blocks, with the insertion order indicated in Fig. 4. More specifically, the procedure was the following: first, a pin was inserted from the feedthrough. The length between top flange and electrical connector was measured because it ensures the desired axial position of the inlet grid in the wrapper, which is about 28 mm above the wrapper holes corresponding to the LBE collecting tubes for differential pressure measurement. Then, the multi-point thermocouple was inserted from the top into the respective feedthrough. The multi-point thermocouple was manually wrapped around the pin by turning the pin itself (still not tighten in the feedthrough) until the correct pitch of 262 mm was obtained up to an axial length of about 1375 mm from the wire starting position. The thermocouple was fixed to the clad with a 0.1 mm clamp spot welded on the clad surface. The clamps were fixed at a different axial positions for each pin in order to minimize the effect of neighbor clamps on the space available while maintaining the correct pitching after each manual wrapping.

After the multi-point thermocouple, the multi-diameter thermocouple associated with the inserted pin was mounted. The end of the heated length was marked for each pin. The tipping point of 0.25 mm was fixed at the end of the heated length with a clamp, similarly to the previous step. The radial position was determined with the aim of capturing different features typical of a wire-wrapped fuel bundle temperature distributions. For example, the maximum cladding temperature at the central pin, swirls effects and maximum radial temperature gradients for the other pins. The mounting procedure of one pin was repeated until all pins and the associated thermocouples were mounted.

The following figures (Fig. 5 to Fig. 11) show the position of the multi-diameter thermocouples with respect to the wire-thermocouple and the wrapping of the multi-point thermocouple.

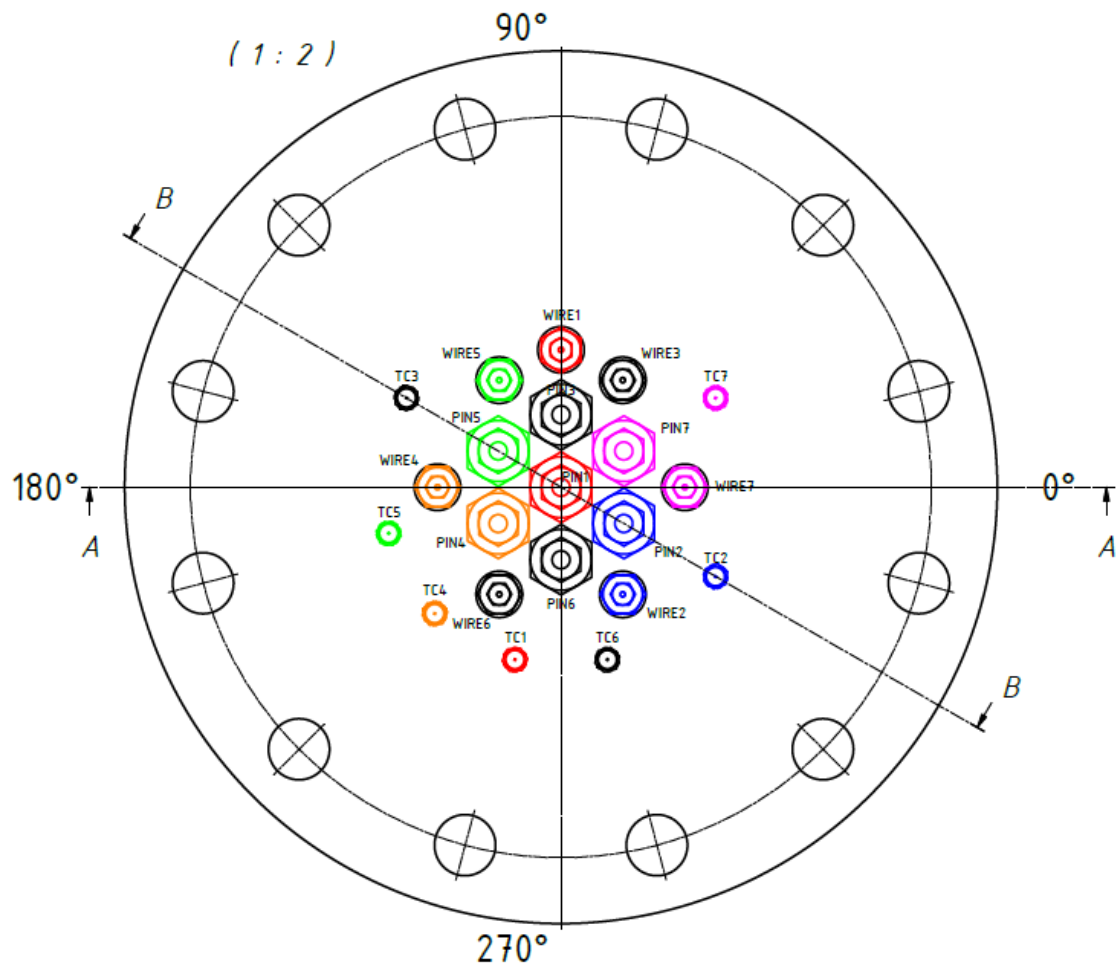


Fig. 4 Top view scheme of the top flange with pin labels and associated thermocouples positions. The mounting steps: pin7-pin3-pin5-pin1-pin2-pin6-pin4. The reference 0° is taken as for the wire starting position.

-Pin 7

The mounting started with Pin 7. The multi-point thermocouple starting position was fixed radially at the 0° reference and axially about 14 mm from the plug start. This tip position was the same for all pins.

It should be noted that the multi-point thermocouple starting position is 90° from the plug hole, contrary to the MYRRHA configuration where the starting position is at the same angle of the plug hole: the heated pins present a lateral hole in the plug for the helium filling; consequently the spot welds for the helium filling hole and that for the thermocouple would have been too close to each other. On the other hand, such a choice does not impact the flow pattern and the wire pitch, which is maintained as the MYRRHA configuration.

For Pin 7 the multi-point thermocouple was fixed with a clamp exactly at the wire starting position. After wire pitching, Pin 7 thermocouple was fixed with clamps also at pitch 3 and 5, respectively.

The figure below shows also the position of the multi-diameter thermocouple at the end of the pin heated length, which for Pin 7 was about 1266 mm from the wire starting position. Radially, the thermocouple was fixed at about 6 mm from the wire, left hand side looking from

bottom to top. The thermocouple is hence expected to measure a low temperature region near the wrapper wall at the specified axial position.

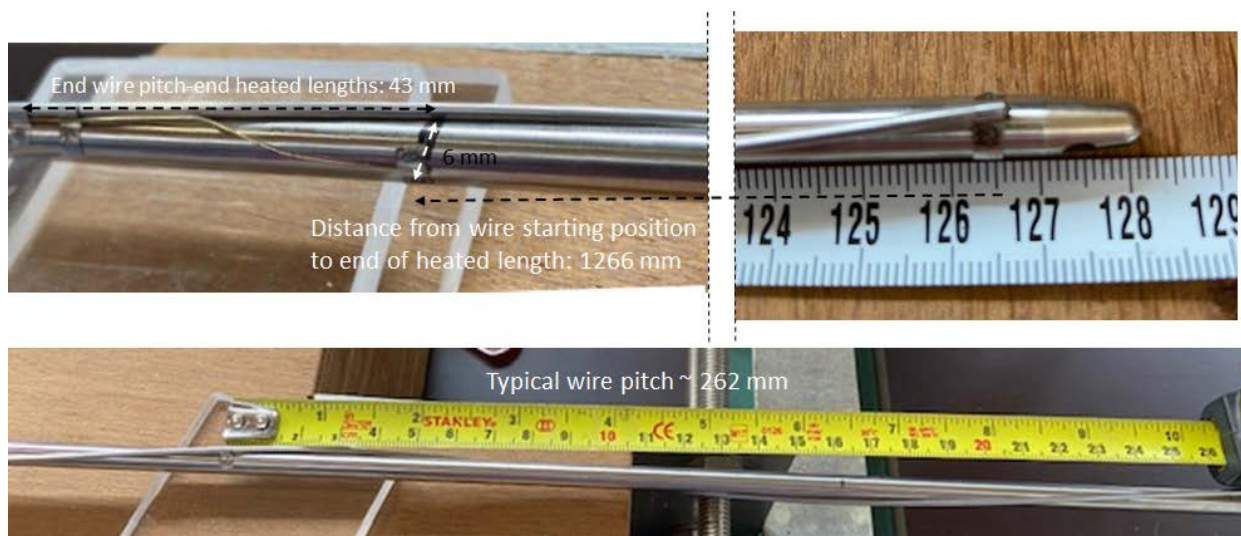


Fig. 5. Pin 7 Multi-point thermocouple and multi-diameter thermocouple tipping point.

-Pin 3

For Pin 3 the multi-point thermocouple was fixed with a clamp exactly at the wire starting position. The multi-diameter thermocouple at the end of the pin heated length, which for Pin 3 was about 1270 mm from the wire starting position, is shown in Fig. 6. Radially, the thermocouple was fixed at about 2 mm from the wire, left hand side looking from bottom to top.

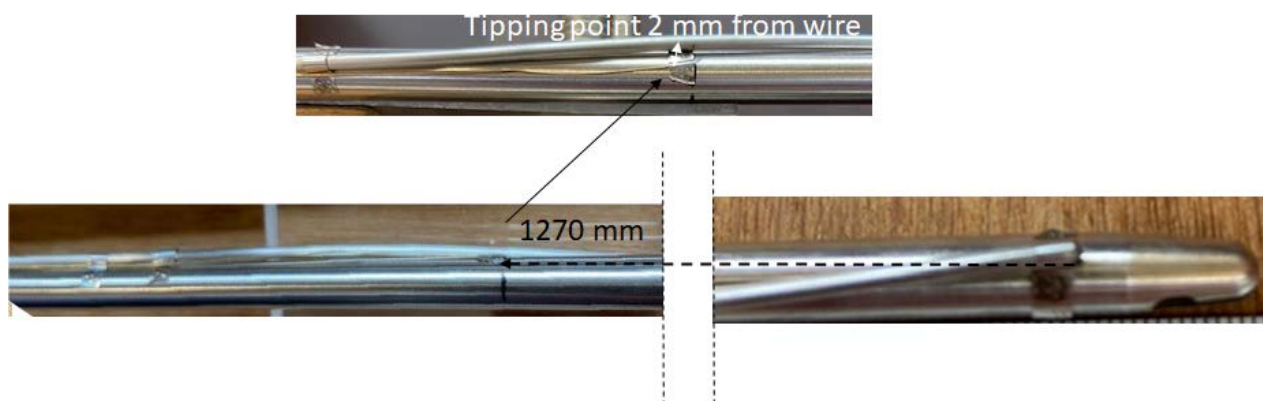


Fig. 6. Pin 3 Multi-point thermocouple and multi-diameter thermocouple tipping point.

-Pin 5

The multi-point thermocouple starting position for Pin 5 was fixed with the clamp, about 1 cm higher than the tipping point (which is at the same position for all pins) to minimize space issues. After wire pitching, pin 5 thermocouple was fixed with clamps also at the end of pitch 1, 3 and 5, respectively.

The multi-diameter thermocouple to measure temperature at the end of the pin heated length was fixed with its clamp at the tipping point at a distance of about 1270 mm from the wire starting position. Radially, the thermocouple was fixed at about 2.4 mm from the wire,

left hand side looking from bottom to top. The 0.5 mm section was further fixed with additional clamps only outside the active length of the pin.

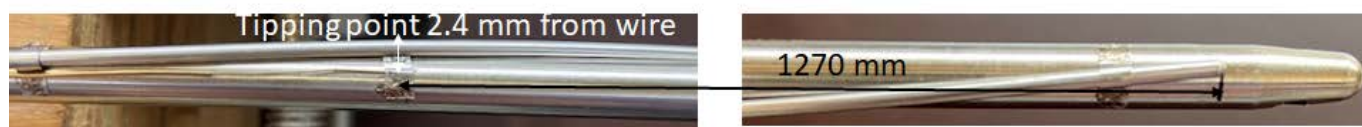


Fig. 7. Pin 5 Multi-point thermocouple and multi-diameter thermocouple tipping point.

-Pin 1: central pin

Pin 1 is the central pin of the bundle and the most relevant for the corrosion experiment being exposed to the hottest cladding temperature. This pin will be used for post-test analysis of clad corrosion damage. The function/position of the multi-diameter thermocouple is very important in this case because it aims at identifying the maximal cladding temperature of 400 °C, at maximum pin power. From CFD pre-test analysis (see WR and later report) the maximum cladding temperature is expected within a thin portion of surface close to the wire. Based on simulations, the thermocouple was fixed in correspondence to the end of the heated length (which is 1269 mm from the wire start for the central pin) and a radial distance from the wire of about 1 mm, right hand side, looking from bottom to top, as in Fig. 8.



Fig. 8. Pin 5 Multi-point thermocouple and multi-diameter thermocouple tipping point.

During spot welding of the clamp that fixes the thin tipping point of the multi-diameter thermocouple, the thermocouple was damaged (insulation resistance), and had to be replaced. The clamp used for the broken thermocouples remained partially attached to the clad surface (see Fig. 8): it was not straightforward to remove it entirely without damaging or excessively scratching the active surface of the clad. The new thermocouple was then fixed with a shorter clamp, partially overlapping the old clamp. In term of space, the new clamp and the old piece well merged with limited impact on flow distribution. However, in term of maximum temperature, a small effect of the additional material present at the surface could slightly impact the maximum cladding temperature as a result of a higher thermal resistance at that region. Concerning the multi-point thermocouple, the first fixing point was few mm upstream the starting position of the wire-thermocouple for space optimization, as previously

discussed. The thermocouple was also fixed with clamps at the end of pitch 3 and pitch 5, respectively.

-Pin 2

The multi-point thermocouple starting position for Pin 2 was also fixed with the clamp about 1 cm higher than the tipping point. After wire pitching, Pin 2 thermocouple was fixed with clamps also at the end of pitch 3, 4 and 5, respectively.

The multi-diameter thermocouple to measure temperature at the end of the pin heated length for Pin 2 was fixed with a clamp at the tipping point about 1280 mm from the wire starting position. Radially, the thermocouple was fixed at about 7 mm from the wire (or 90° from wire tipping point reference), left hand side looking from bottom to top. A colder temperature region near the wrapper will hence be measured.

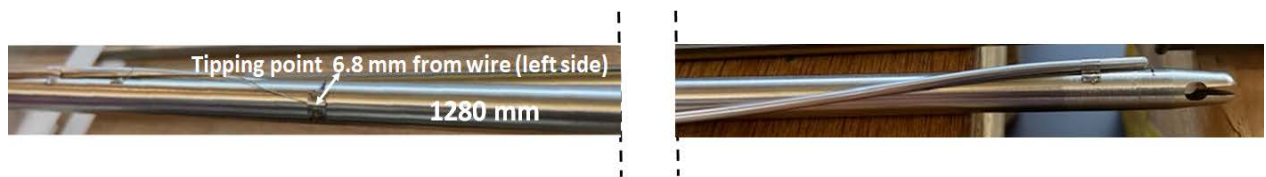


Fig. 9. Pin 2 Multi-point thermocouple and multi-diameter thermocouple tipping point

-Pin 6

The multi-point thermocouple starting position for Pin 6 was fixed with the clamp exactly at the tipping point. After wire pitching, the multi-point thermocouple was fixed with clamps also at the end of pitch 1, 2 and 5, respectively.

The multi-diameter thermocouple to measure temperature at the end of the pin heated length was fixed with a clamp at the tipping point of 0.25 mm at about 1277 mm from the wire starting position. Radially, the thermocouple was fixed at about 1.2 mm from the wire, left hand side looking from bottom to top. The temperature in a hot sub channel will be monitored.

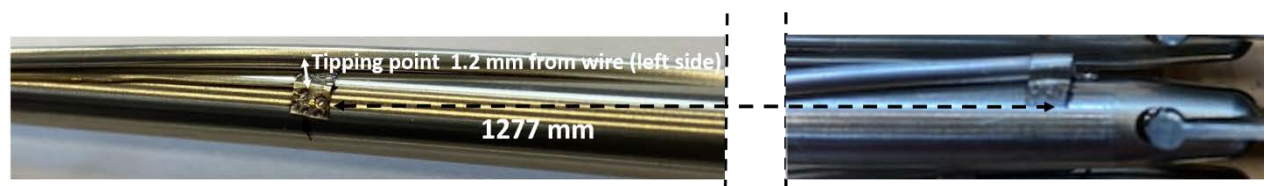


Fig. 10. Pin 6 Multi-point thermocouple and multi-diameter thermocouple tipping point.

-Pin 4

The multi-point thermocouple starting position for Pin 4 was fixed with the clamp about 1 cm higher than the tipping point. After wire pitching, the multi-point thermocouple was fixed with clamps also at the end of pitch 2, 4 and 5, respectively.

The multi-diameter thermocouple to measure temperature at the end of the pin heated length was fixed with a clamp at the tipping point of 0.25 mm at about 1271 mm from the wire starting position. Radially, the thermocouple was fixed at about 7.2 mm from the wire, left hand side looking from bottom to top.

Besides the tip, the section of 0.5 mm was fixed by another clamp to the wire about 1 cm upstream the end of the heated length.

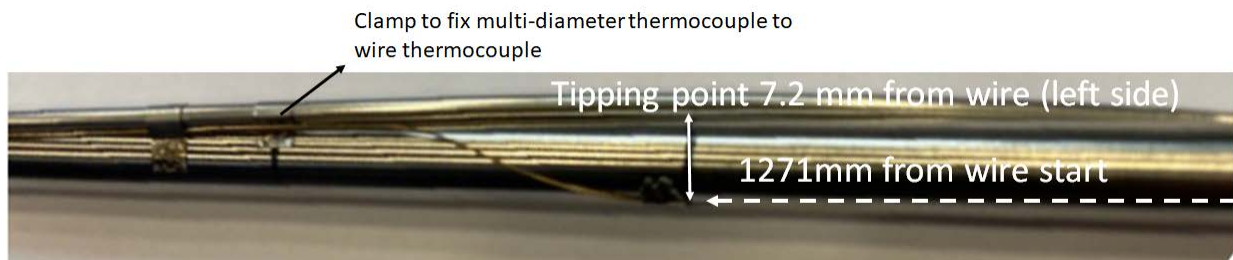


Fig. 11. Pin 4 Multi-point thermocouple and multi-diameter thermocouple tipping point.

4. Test section assembly

4.1 Pin bundle

The 7-pin bundle assembly, including inlet grid, is shown in Fig. 12. In the figure one can see the wire starting positions from different views. The starting position is always at 0° degree from the reference, as specified in Fig. 4. It should be noted that the wire (thermocouple) starting position is 90° from the pin plug hole, contrary to the MYRRHA configuration where the starting position is at the same angle of the hole, as previously mentioned.

During operation, all pins attached to the grid will thermally expand downstream due to the axial temperature increase in the flow direction (pins are locked at the top flange). However, the central pin and the radial pins are also subject to relatively large radial temperature gradient. To accommodate different axial thermal expansion between each pin due to radial temperature gradients, a small gap of about 1 mm between the plug holes and the grid supports was foreseen. This gap is clearly visible in Fig. 12, after locking the pins to the grid supports.

The inlet grid design of the heated bundle experiment is slightly different than the MYRRHA inlet grid. While the functionality is respected, the measured pressure drop contribution of the grid to the total bundle pressure drop is not directly comparable to the MYRRHA case. This is however outside the scope of this experiment.

Overall, the manual wrapping of the multi-point thermocouples around the fuel pins was acceptable and well reproducible, as shown in Fig. 13.

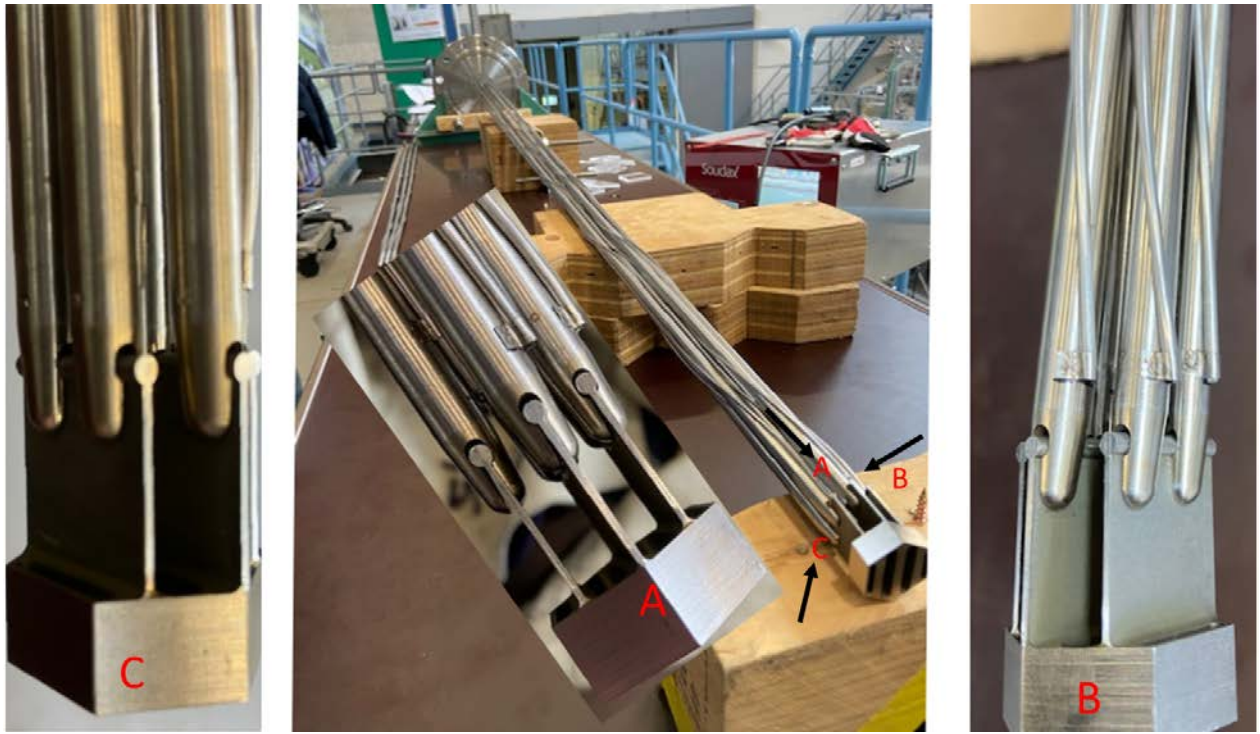


Fig. 12. Fuel bundle assembly and inlet grid positions.

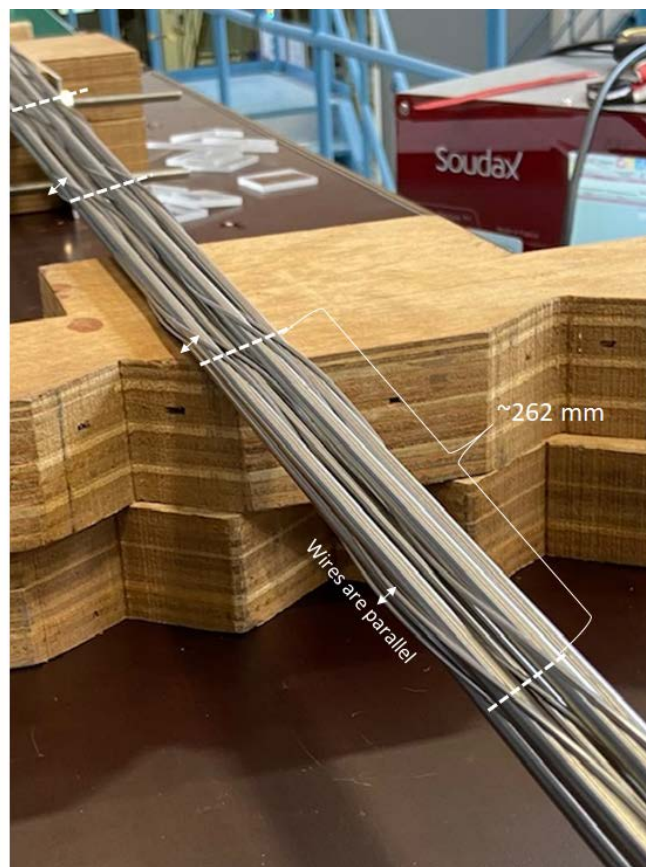


Fig. 13. Wire (multi-point thermocouple) pitch.

4.2 Tube vessel and hexagonal wrapper insertion

The hexagonal shell containing the fuel bundle was designed with scaled dimensions to preserve a similar Reynolds number between the 7-pin configuration and the MYRRHA assembly. The hexagonal shape cylinder was obtained by fabricating two symmetric shells which were then TIG welded as in Fig. 14.

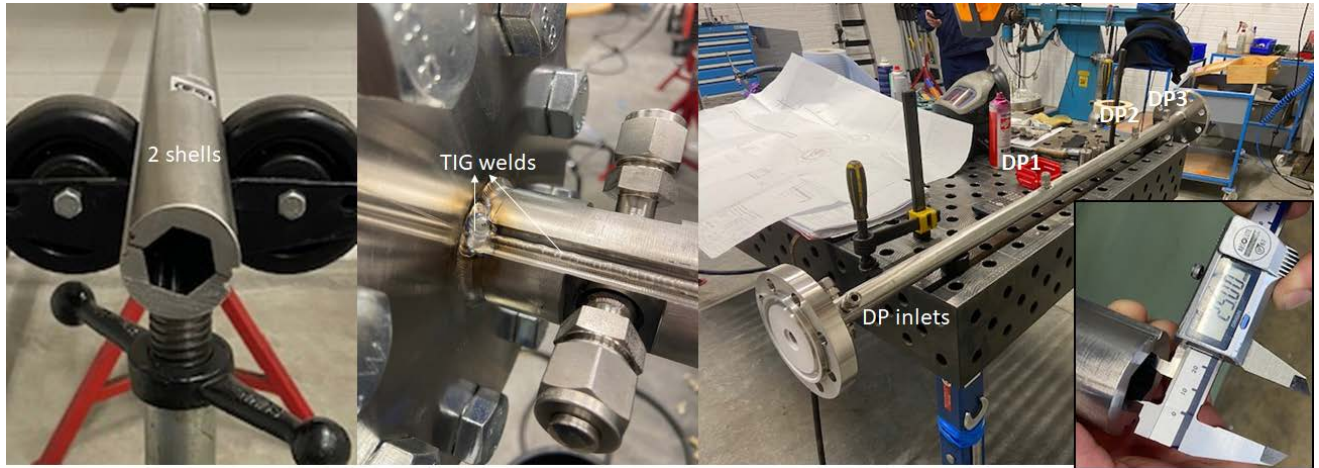


Fig. 14. Hexagonal wrapper.

Three differential pressure transducers are installed to capture potential blockage mechanisms occurring either in the cold or in the hot part of the bundle.

Three inlet Swagelok connectors for each differential pressure measurements are shown in the figure, with the associated outlet connector located: after 2 wire pitches (DP1), 4 pitches (DP2) and 5 pitches (DP3), respectively. Three separate inlet lines were foreseen for redundancy, in the event of a single line failure the other lines should not be affected.

The wrapper shell was pressured tested with argon gas at about 10 bar, for about six hours. Pins insertion into the wrapper was also tested with available pins before mounting the heated pins in order to verify tight fitting with small tolerances in the hexagon dimensions.

After all heated pins were inserted as previously described and connected to the inlet grid, the first pipe component of the test section was inserted from the bottom and connected to the top flange (Fig. 15).

In the figure one can also see the wires of the thermocouples not fixed to the pin surfaces over the last length of the pin, close the top flange. This gave more flexibility to connect wires with their respective sealings, while maximizing the limited available space for connectors in the top flange at the design phase. A possible drawback of such configuration is that lead oxide may deposit in the event of oxygen in leaks on the wires, especially during draining.

The last step of the mounting was the insertion of the wrapper, to be connected to the flange of the first tube-module. The insertion process was smooth, and the pin bundle was tightly compressed to the wrapper walls, confirming the correct fabrication tolerances of both hexagonal dimension and pins/multi-point thermocouples. The fuel pins compression by the flange nozzle, the inlet grid and wrapper led to an angle of about 3 degree with respect to the initial position at the top flange connectors. Fig. 16 shows the desired axial position of the inlet

grid inside the wrapper, which is about 28 mm above the wrapper holes of the LBE collecting tubes for the reasons previously mentioned.



Fig. 15. Insertion tube connector.

After completing the mounting steps correctly, pins and thermocouples were tightened and the test section was leak-tested with helium detector.

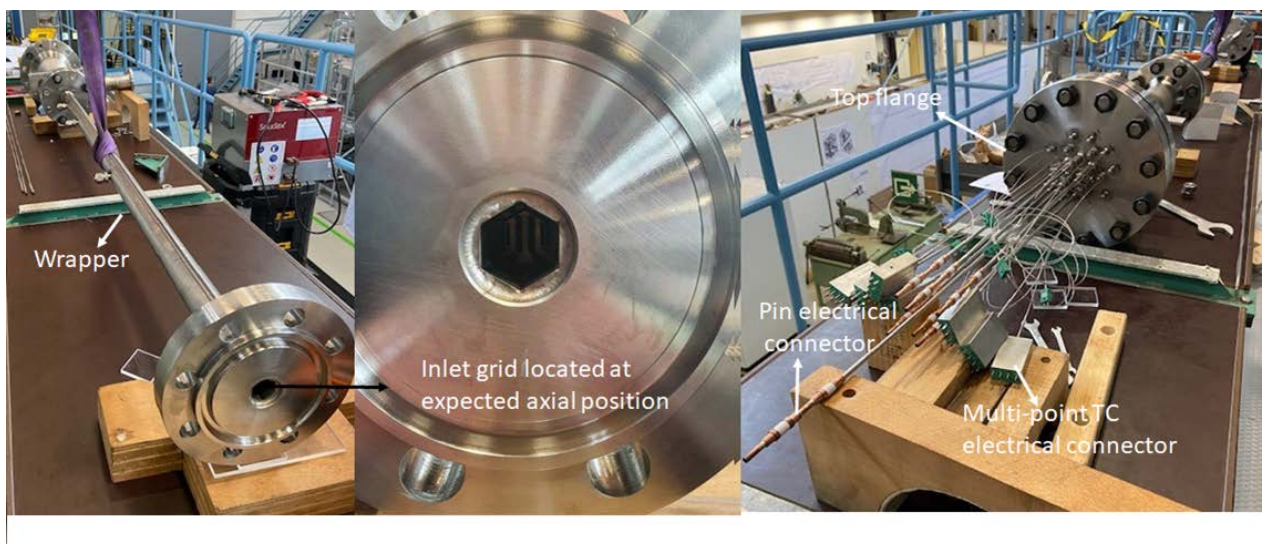


Fig. 16. Test section assembly.

Concerning electrical aspects, the electrical connectors of thermocouples and pins are visible in Fig.16, right-hand side. One can notice the large connectors of multi-point thermocouples with 4 separate mini-pugs within the box, one for each axial reading foreseen.

A final step prior to moving the test section to the MEXICO loop, was the assembly of a Rittal insulation box (IP54 protection) placed around the top of the fuel pins and including all pin electrical connections. The clamps for each pin electrical connection were also mounted inside

the box. Each clamps go with a single conductor towards terminals (also inside the box). From the terminals a 3G16 cable for each pin is foreseen up to electrical cabinet; the latter cables were mounted once the test section was assembled in the MEXICO loop.

4.3 Pressure station

The so-called pressure station consists in the differential pressure measurement equipment. The low pressure and high pressure lines are connected to the respective low and high pressure flanges, where the transducers are placed, which measure the absolute pressure difference. The low and high pressure flanges are mounted at the same axial coordinate so that the zero-setting is not required or minimal. Furthermore, a venting line between DP1 and DP3 is foreseen to remove residual air which could influence the measurement. Also each flange present a flushing line to remove from air pockets from the transducers which is important for a reliable measurement. For this task, valves are all open during draining and filling (venting). Then, flushing can be performed for each flange and valves are then all fully closed (two valves per flange for redundancy).

Fig. 17 shows the inlet collecting tubes of each pressure measurement, which go to the low pressure flange for the actual measurement, and to the high pressure flange for the flushing. Two valves are also visible in the flushing line. The first pressure measurement DP1 has only one valve for the high pressure flange flushing due to the limited space available.



Fig. 17. Inlet tubing pressure station.

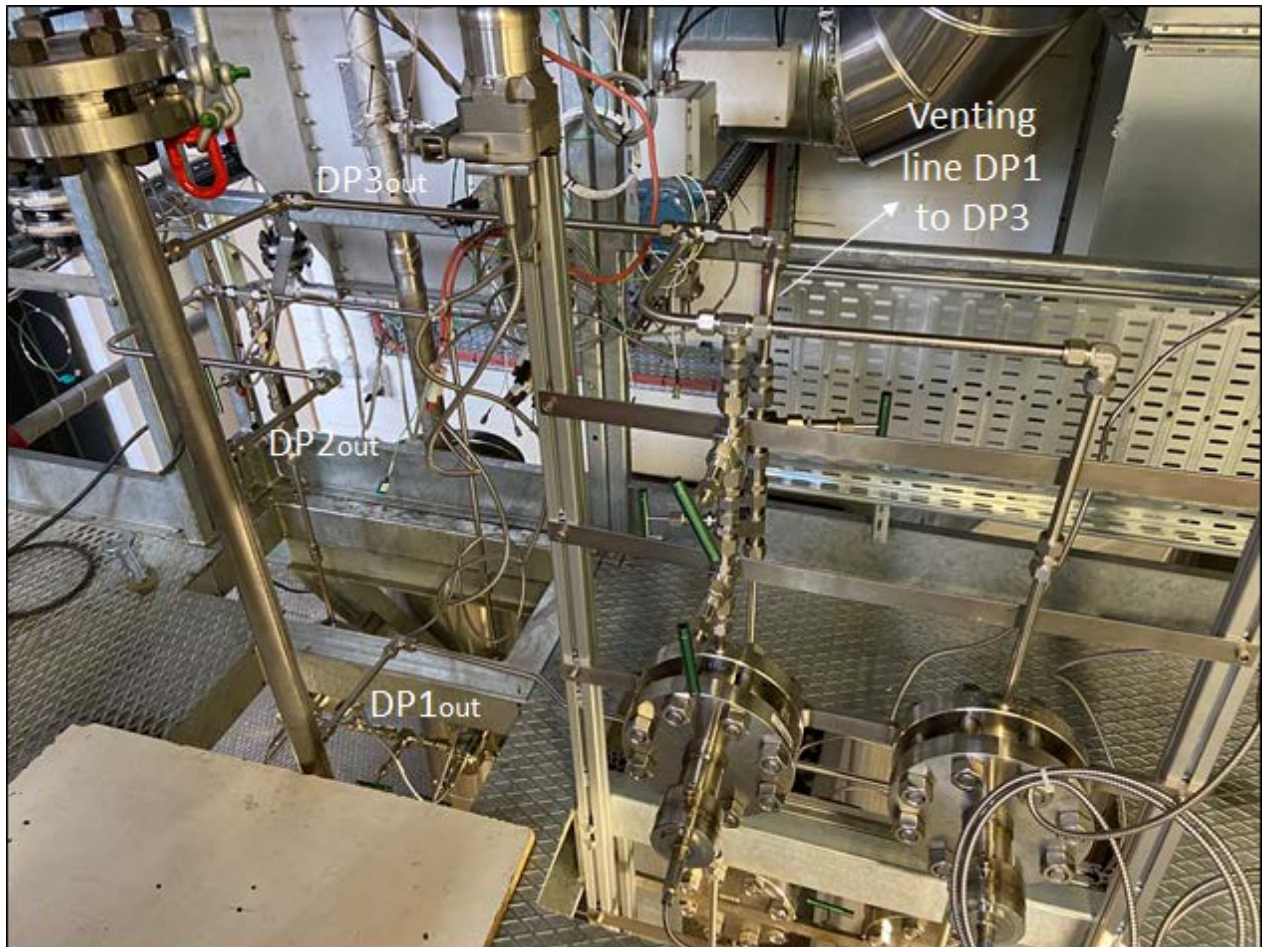


Fig. 18. Outlet tubing pressure station.

An important feature of the pressure measurement is to have a constant temperature along the inlet/outlet LBE collecting tubes, as well as at high/low pressure flanges. This is achieved by providing several temperature PID controller along the pressure station. More specifically, a separate temperature controller is placed for each component with different thermal inertia and dynamics, e.g. one controller for each pressure transducer flange, one controller for each pair of valves and separate controllers for each tubes. In each segment and especially in longer tubes also monitor thermocouples were added to the reference control thermocouple, as summarized in Fig. 19.

Finally, before operation, the test section and pressure station were isolated from the rest of the loop and pressure tested also with helium test.

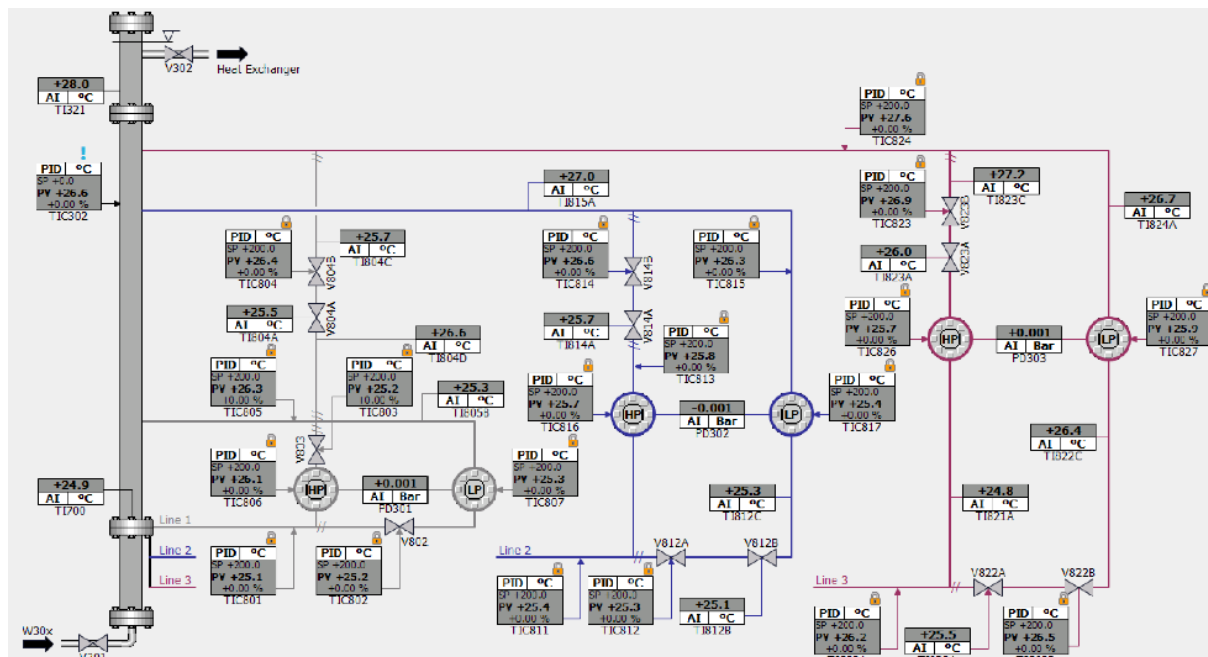


Fig. 19. Scheme of the PID of the differential pressure measurement (pressure station).