H2020-ICT-25-2016-2017

**<u>HY</u>brid <u>FL</u>ying roll<u>I</u>ng with-snak<u>E</u>-a<u>R</u>m robot for contact in<u>S</u>pection**

# HYFLIERS

## D6.1

## *Prototype HMR test protocol, test report, data analysis and conclusions*

| | |
|---|---|
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**Abstract**:

This document is related to the site tests of the HMR prototype organized in the Chevron Oronite plant near Gonfreville (France).
These site tests contribute to the qualification of the HMR robotic system and the demonstration of its capabilities in an industrial environment.
The document provides the following information:

1) Presentation of Chevron Oronite plant
2) Description of the HMR prototype
3) HMR test protocol and validation plan
4) Specifications for the test protocol and selection of the test locations on site
5) Risk assessment to identify and mitigate the risks associated with the HMR operation
6) Pre-requisites prior to organize the site tests in Chevron Oronite (HMR outdoor bench tests validation, French civil aviation authorization, Chevron site authorization, safety plan…).

The outdoor tests, included in WP5, shall demonstrate the key functionalities and the safe operation of the HMR integrated system on a mock-up bench under outdoor conditions before allowing HMR site tests in an industrial plant. The detailed planning of the HMR site tests at Chevron Oronite plant were defined once the WP5 outdoor tests were completed and validated.



**Keywords**:

HMR, prototype, site test, protocol, Chevron, Oronite, Gonfreville

# Executive summary

This document is the first deliverable (ref. D6.1) of the work package WP6.

It is related to the site tests of the HMR prototype organized in the Chevron Oronite plant near Gonfreville (France).

These site tests contribute to the qualification of the HMR robotic system and the demonstration of its capabilities in an industrial environment.

The document provides the following information:

- Presentation of Chevron Oronite plant
- Description of the HMR prototype
- Site test objectives and end users' requirements
- Specifications for the test protocol and selection of the test locations on site
- Risk assessment to identify and mitigate the risks associated with the HMR operation
- Pre-requisites prior to organize the site tests in Oronite (HMR outdoor bench tests validation, French civil aviation authorization, Chevron site authorization, safety plan…).

The outdoor tests, included in WP5, shall demonstrate the key functionalities and the safe operation of the HMR integrated system on a mock-up bench under outdoor conditions before allowing HMR site tests in an industrial plant.

The detailed planning of the HMR site tests at Chevron Oronite plant were defined once the WP5 outdoor tests were completed and validated.

# Abbreviations and symbols

| | |
|---|---|
| ATEX | explosive atmosphere |
| DGAC | Direction générale de l'aviation civile (French Civil Aviation Authority) |
| DSAC | Direction de la sécurité de l'aviation civile (French Civil Aviation Safety Directorate) |
| GNSS | global navigation satellite system |
| GPS | Global Positioning System |
| GS | ground station |
| HMI | human-machine interface |
| HMR | hybrid mobile robot |
| HR | hybrid robot |
| MSP | mobile support platform |
| NDT | non-destructive testing |
| PC | personal computer |
| UT | ultrasonic transducer |
| UTM | ultrasonic testing measurement |

# Table of Contents

# 1. Introduction

This document is related to the site tests of the hybrid mobile robot (HMR) prototype organized in the Chevron Oronite plant near Gonfreville (France).

These site tests contribute to the qualification of the HMR robotic system and the demonstration of its capabilities in an industrial environment.

The document provides the following information:

1. Presentation of Chevron Oronite plant
2. Description of the HMR prototype
3. Site test objectives and end users' requirements
4. Site test protocol and selection of test locations on site
5. Risk assessment to identify and mitigate the risks associated with the HMR operation
6. Pre-requisites prior to organize the site tests in Oronite:
    - Outdoor bench tests validation of the HMR integrated system (part of WP5),
    - Accreditation of the HMR prototype by the French civil aviation (DGAC/DSAC),
    - Certification and registration of the HMR telepilot
    - Flight plan registration
    - Chevron Oronite site authorization, Safety plan (“Plan de Prévention”).

...

# 2. Presentation of Chevron Oronite site

Chevron Oronite site is located in the north of France in Gonfreville near the port of Le Havre. It is a live industrial facility, Europe's largest additive manufacturing facility. As the plant processes hydrocarbon products, some areas of the plant as rated as explosive atmosphere (ATEX) zones. For the purpose of the experiments as part of this project, all testing will be carried out in safe zones with no ATEX regulations.

The plant is a large industrial complex which offers multiple opportunities to test inspection procedures at height making it an ideal candidate for the HYFLIERS project, addressing UT thickness measurements at height.

**Figure 1.** A general view of the Chevron Oronite plant.

**Figure 2.** A detailed view of the Chevron Oronite plant with piping.

**Figure 3.** A detailed view of the Chevron Oronite plant with a pipe rack.

# 3. Description of the HMR

The HMR focuses on magnetic pipes inspection applications. The main goal was to design a hybrid robot that could take-off, fly, land and move on a magnetic pipe to perform ultrasonic transducer (UT) inspection. The final robot is composed of an aerial platform and a robotic satellite vehicle with the capability of crawling along the pipe. The self-propelled semi-independent robotic satellite has a roller probe to accomplish the inspection operation. Both subsystems have been designed with different but complementary functionalities to meet the requirements of the project.

Figure 4 presents the HMR and Figure 5 illustrate its global architecture. The HMR has been decomposed in two main subsystems, the essential aerial platform, and the inspection subsystems.

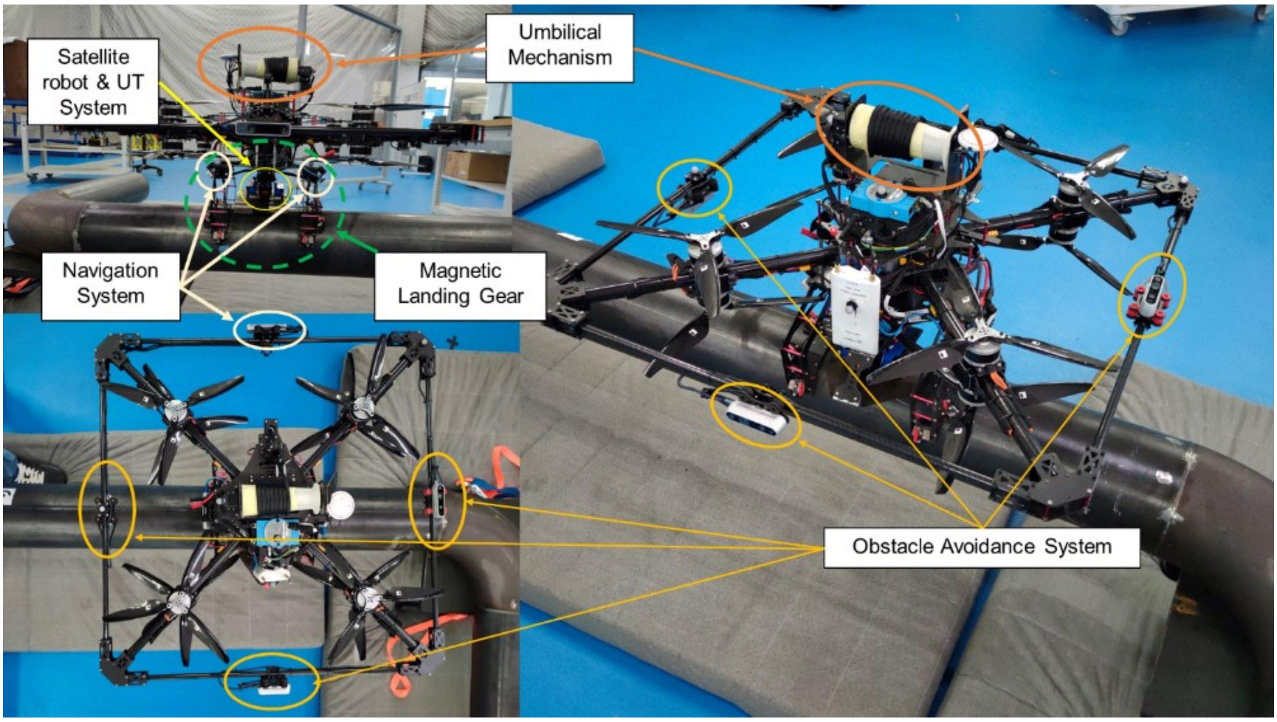



**Figure 4 HMR overview.**

Figure 4 shows that as part of the essential aerial platform, we can find the actual aerial system (autopilot, airframe, propulsive system…), the localization, the obstacle avoidance, and the pipe detection systems. All those components are in change of guaranteeing the safe behaviour of the aerial robot while flying. The inspection subsystem is composed by the new concept of magnetic landing gear, the umbilical mechanism, the UT system, and the satellite robot. This part of the HMR is involved on gathering the inspection data while accomplishing the inspection action. All the software except the low-level attitude controller of the aerial system is executed in the main on-board computer through different interfaces.

Figure 5 shows that there are two main processor units the autopilot that executes the low-level controller of the aerial robot and the on-board PC that runs the high-level controller, monitors the mission and executes the sensor fusion algorithm and the pipe detection nodes.

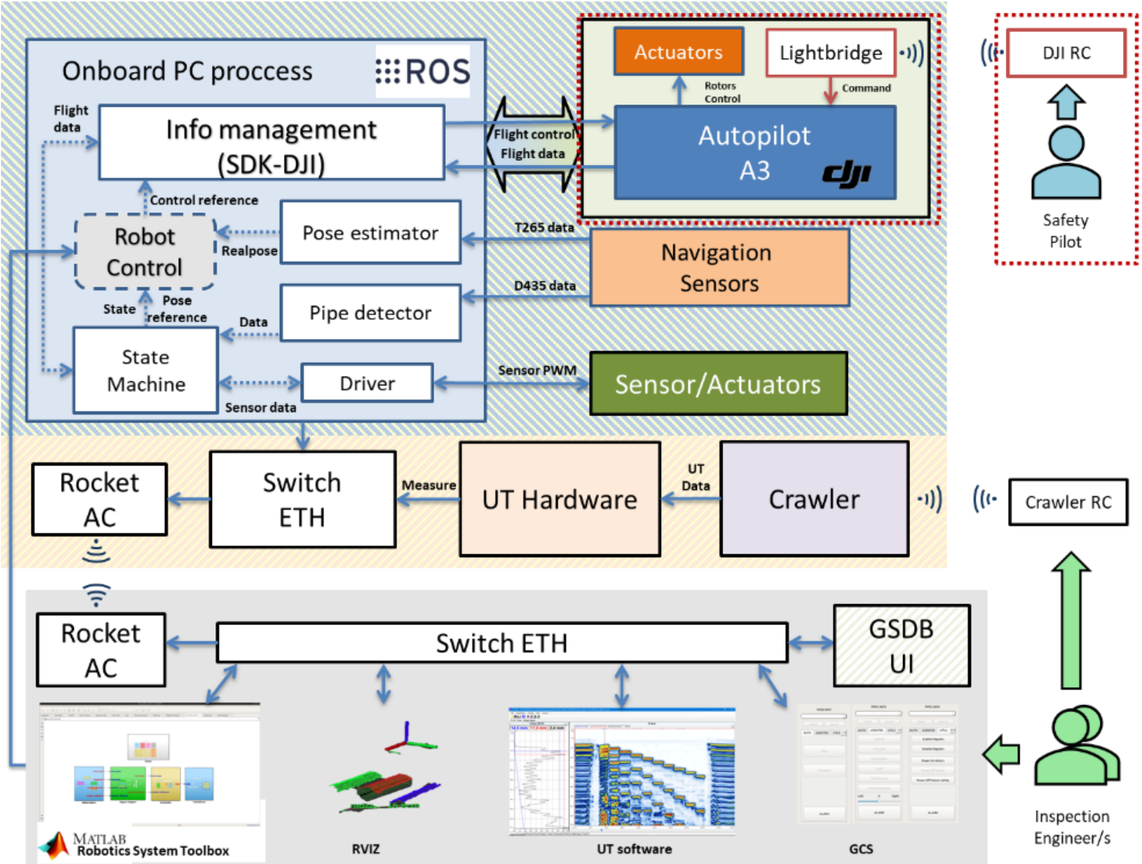



**Figure 5.** HMR final software architecture. See D5.2 for details.

# 4. Test protocol and validation plan

The HMR validation were split in two experimental campaigns. The first phase was accomplished in Seville and the second one at the Chevron Oronite plant, Le Havre. The idea was to do a preliminary internal review of the system by Chevron and TotalEnergies before testing the system in the actual scenario. The consortium aims to minimize the risk of the refinery experiments then, this first validation round was specifically focused on analysis the safety of the different systems of the HMR and their potential risks. Those systems or functionalities that would be acceptable to be used in the actual refinery will pass to the second validation phase in Chevron.

## 4.1. HMR functionalities for end-users' outdoor validation in Seville.

Table 1 summarizes the functionalities tested for outdoor environments.

**Table 1:** List of functionalities of the HMR robot for outdoor environment

| ID | Functionality | Description |
|---|---|---|
| **Fun-01** | Autonomous flying in GNSS (global navigation satellite system)-denied environments | Robust navigation in industrial environments where GNSS signals can be degraded. However, the validation will be performed in a qualitative level, due to the difficulty to implement a ground-truth system that allows us to have a quantitative metrics of this functionality in an industrial scenario. |
| **Fun-02** | Autonomous detection and avoidance of obstacles while flying | Due to the potential risks and the requirements imposed by the facility owners, it is expected that the validation missions will be planned without forcing a potential conflict in the trajectory with the infrastructure. Also, facility owner requirements to operate in their facilities impose that the aerial robot cannot make any decision by itself or change the trajectory that was not previously planned. Then, this functionality will not be able to validate in the industrial relevant environment and the aerial robot will be guided with high level commands by the operator. However, the detection system will be activated (for safety reasons), and in case an obstacle is too close to the flying robot, it will be automatically detected and the system will not allow the operator to fly against it (creating a "virtual wall"). |
| **Fun-03** | Autonomous landing on pipes | Land on different pipe sizes but with an active supervision of the operator (due to safety reasons coming from the requirement of the facility owners). |
| **Fun-06** | Navigation of the satellite robot over the pipe | Camera-based remote-controlled operation with manual steering. |
| **Fun-10** | Advanced human-machine interface | Mobile support platform (MSP) functions will include: Developing compliant systems for power storage and charging |

| ID | Functionality | Description |
|---|---|---|
| | (HMI) for the system operator | functions, especially battery switching/charging can have environment specific requirements to be performed safely; Networking support compatible with industrial environments.<br><br>HMI will include: Incorporating necessary hardware between the hybrid robot (HR) operating platform, its operators, and the industrial inspection site systems. |
| **Fun-12** | Measurement data management service | Measurement data provided by the UT to the HR and from the HR to the ground station (GS)/MSP. Visual inputs provided by the HR to the GS/MSP.<br><br>Inspection plan is executed and inspection report is generated. |
| **Fun-14** | Calibration velocity with UT block | Before starting any measurements with the drone, the functionality of the ultrasound unit will be verified. For this, the Calibration block that best adapts to the curvature of the pipes will be selected. It is verified that the measured thickness is within a 3% error. The internal delay of the ultrasound transducer and the velocity in the pipeline (at the site temperature) will also be recorded.<br><br>Once the measurements are completed, it will be verified again with the same standard that the system continues to measure correctly |

# 5. HMR validation results

## 5.1. First validation phase in Seville

This plan is based in D1.4, but in this case, it has been reorganized in order to compress in one single day all the tests to be shown to the end-users so they can validate the correct operation of the aerial robot before giving their approval of taking it to their refineries.

### 5.1.1. Description of test location and conditions

The mock-up scenario created for the first validation phase consists of a metallic structure in which we placed several pipes. Those pipes aim to simulate a realistic pipe distribution and the main goal of this scenario is to enable testing of the complete version of the HMR safely before moving to the actual refinery. During this phase, the goal was mainly focused on analysis the HMR safety and decide which kind of systems are safe enough to be used in the plant.

### 5.1.2. Complete standard operation

| Step | Linked functionality | Description | Involved Partners | Test validation |
|---|---|---|---|---|
| 1 | Fun-14 | Before starting any measurements with the drone, the functionality of the ultrasound unit will be verified. We will use a pipe with an integrated calibration block. Measurements after calibration should be reliable. | DASEL<br>WTR<br>CATEC | Yes |
| 2 | Fun-12 | Visualization of an inspection plan in the database. | UOULU | Yes*. The visualisation of the inspection plan has |

| Step | Linked functionality | Description | Involved Partners | Test validation |
|---|---|---|---|---|
| | | | | been validated before the Chevron Oronite plant validations. |
| 3 | Fun-10 | The aerial robot will be turned on and all the systems and information needed to perform the operation should be visualized at the ground systems on real time. Drone status and telemetry, satellite cameras and control, and UT electronics working. | CATEC<br>WTR<br>DASEL | Yes |
| 4 | Fun-1 | The navigation system telemetry should be checked before flight. This system is based on visual cameras. The robot will take-off and fly in assisted mode commanded by the pilot. The drone will arrive near the pipes. | CATEC | Yes |
| 5 | Fun-1<br>Fun-3 | Once close to the pipes, the operator will command a search of pipes. The robot will localize the pipe and ask confirmation to the operator. Once the desired pipe is located under the robot, the operator will command a landing operation. The pipe is identified and localized autonomously. The robot starts approaching to the pipe once it is stable. | CATEC | Yes |
| 6 | Fun-1<br>Fun-3 | The drone will proceed to land on the pipe once all the stability conditions are validated. The landing operation is the most critical part of the flight. Maximum wind limitations will apply for each pipe diameter. Non-GNSS localization and pipe position estimation systems will be used | CATEC | Yes |
| 7 | Fun-6 | Once landed, the satellite robot will be deployed and perform a simple inspection operation of the pipe. Detailed inspection tests of the satellite robot will come in subsequent operations. | WTR<br>DASEL | Yes |
| 8 | Fun-10 | The whole UT inspection will be monitored from the ground. UT data will be stored locally. | DASEL<br>WTR<br>CATEC | Yes |
| 9 | Fun-1 | The navigation system telemetry should be checked again before taking-off from the pipe. The | CATEC | Yes |

| Step | Linked functionality | Description | Involved Partners | Test validation |
|---|---|---|---|---|
| | | magnets will be deactivated, and the drone will take-off. The robot will take-off and fly in assisted mode commanded by the pilot. The pilot will take the drone to the ground and land. | | |
| 10 | Fun-12 | Once in the ground, the stored UT data will be sent to the database. Then a user should access the database and visualise the inspection information. | UOULU DASEL | Yes*. The transfer of the inspection data from the UT subsystem to the GSDB subsystem (see D5.1 Section 4, D5.2 Sections 2 and 5, D5.3) and their visualisation has been validated before the Chevron Oronite plant validations. |

### 5.1.3. Flight safety validation

#### *Flying in a non GNSS reliable environment (Fun-01)*

One specific flight will be focused on demonstrating the capabilities of the GNSS free navigation system. The drone will not have GNSS available covering the GPS antennas. The aerial robot will take-off and perform a hover operation with no pilot intervention. The non-availability of GNSS will be shown to the validators so they can confirm the stability of the system. The positioning system could be also validated making use of other sensors, like a topographic total station, that will provide millimetre-precision localization of the robot.

| Test validation | Yes |
|---|---|

#### *Obstacle avoidance (Fun-02)*

The aerial robot will take-off commanded by a pilot. The pilot will send the robot in the direction of an obstacle. The aerial robot will stop automatically.

| Test validation | Yes |
|---|---|

#### *Landing operation reliability (Fun-03)*

The landing on top of a pipe operation will be repeated so a minimum number of landing operations are shown. Furthermore, this operation will be repeated but on a different diameter pipe (8 and 12 inch – Crawler ramp not suitable for 6” pipe).

| Test validation | Partially | Landing operations not deemed ‘reliable’. System experienced a mix of successful, aborted or unsuccessful landings. |
|---|---|---|

#### *Gas detection*

The gas detection system will be shown, and the emergency procedure explained in detail.

| | |
|---|---|
| **Test validation** | Yes |

***Comms problems***

The ground operator communication link loss will be tested and validated. The drone should continue flying after a communication problem.

| | |
|---|---|
| **Test validation** | Yes |

### 5.1.4. Satellite UT inspection validation

***Quadrant longitudinal B-Scan***

- Straight pipe section

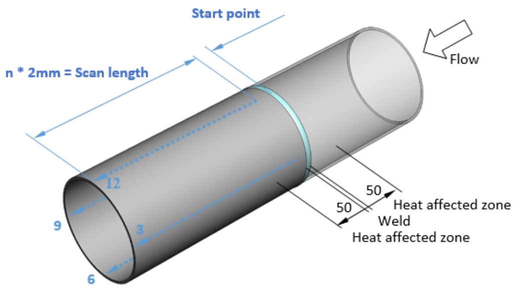



**Figure 6** Straight pipe section.

| | | |
|---|---|---|
| **Test validation** | No | UT grid scan for this mock-up was already tested in system integration. See D5.3. |

- Horizontal/vertical elbow

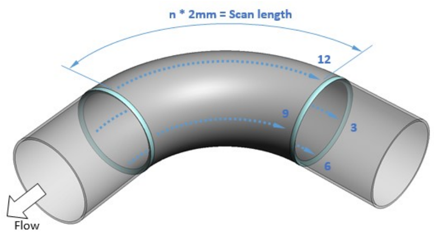



**Figure 7** Elbow section.

| | | |
|---|---|---|
| **Test validation** | No | UT grid scan performance for this mock-up was already tested in system integration. See D5.3. |

- Reducers

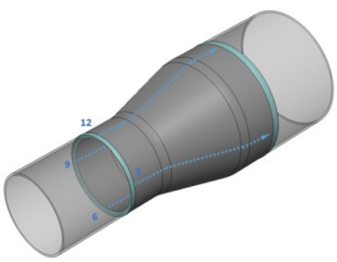



**Figure 8** Reducer section.

| | | |
|---|---|---|
| **Test validation** | No | No reducer available. |

### 5.1.5. First validation phase report

Two days of extensive testing was conducted at an outdoor mock up facility in Seville, Spain. Weather conditions were optimal, and testing was conducted on both 12” and 8” pipe sections.

The result of testing was that the whole technology concept was viable and could achieve the project requirements, but not reliably or safely.

The landing procedure of the HMR was deemed too risky to deploy at a live industrial setting due to the number of failed and/or aborted landings, or landings resulting in manual intervention during the validations tests. The UT crawler component worked well and a decision was made following the validation tests to proceed to test only this part of the solution at the industrial site.

The end users, Chevron and TotalEnergies, agreed that it was very important for the project to test the satellite UT crawler at the industrial facility under operational conditions, as the outdoor mock ups could not fully reflect the real-world conditions of an operational site, namely:

- Condition of internal pipe surface / corrosion
- Variation in external protective coating application (paint thickness)
- Delamination of paint coating
- External surface rust scabs, surface Verdigris
- Height and length of external pipe welds

Therefore, it was important to determine how the UT crawler would perform at the industrial site, navigating these features and taking reliable UT readings of pipe thickness.

## 5.2. Second validation phase in Chevron Oronite

### 5.2.1. Pre-requisites

Preparation of the site tests is key and shall include the following validation and authorizations before deciding mobilisation and operations at site:

#### *Outdoor test validation*

The outdoor tests, included in WP5, shall demonstrate the key functionalities and the safe operation of the HMR integrated system on a mock-up bench under outdoor conditions before allowing HMR site tests in an industrial plant.

The scenarios to be considered for the outdoor tests should be similar to the scenarios defined for the site tests in Chevron Oronite, as per section 5.

#### *Prototype accreditation by the French civil aviation*

The HMR prototype shall be accredited by the French civil aviation authority.

#### *Pilot certification and registration*

The HMR telepilot shall be qualified and certified in accordance with the applicable regulation.

#### *Flight plan registration*

The flight registration shall be done in the ALPHATANGO site at least 7 days before the site test.

***Chevron Oronite authorization and Safety Plan***

A site authorization shall be given by Chevron Oronite in compliance with the Company rules and the French regulation.

A dedicated form shall be used in order to prepare and approve the safety plan (so called “Plan de Prévention”). A template is provided for reference in **Appendix 4**.

### 5.2.2. Site tests protocol

The test locations selected for the site tests at Chevron Oronite are described in **Appendix 2**.

***Full process spot measurement parkour***

For all manoeuvring and measurement operations of the satellite, both the pilot and inspector are to be located at a significant distance (>5 m) and out of line of sight of the system.

1. Take off from safe zone -> manual transport
2. Land on pipe -> manual placement
3. Deploy crawler from garage
4. Unreel tether cable
5. Perform spot measurements on straight pipe close to weld
6. Cross weld to adjoining pipe element
7. Perform spot measurements on T-piece close to welds
8. Perform spot measurements on T-piece in middle
9. Cross T-piece and weld to adjoining pipe element
10. Perform spot measurements on Elbow close to welds
11. Perform spot measurements on Elbow in middle
12. Cross elbow and weld to adjoining pipe element
13. Return to flyer
14. Load back into garage
15. Reel up tether
16. Take off from pipe -> manual retrieval
17. Land in safe zone -> manual transport
18. Refill couplant reservoir on satellite

***UTM grid on pipe straight pipe***

1. Position satellite at 12, 3, 6 or 9 o’clock around circumference
2. Position satellite at starting distance from weld to adjoining pipe element
3. Start line scan recording
4. Scan move crawler along pipe for inspection distance
5. Stop and save line scan locally
6. Initial evaluation of result locally

***UTM grid on elbow***

7. Position satellite at 12, 3, 6 or 9 o’clock around circumference
8. Position satellite at starting distance from weld to adjoining pipe element
9. Start line scan recording
10. Scan move crawler along elbow up to weld to next adjoining pipe element
11. Stop and save line scan locally

12. Initial evaluation of result locally

***Move between racks***

1. Move crawler in gap between two adjoining pipes with distance of 100 mm.

### 5.2.3. Risk assessment related to HMR operation

A Risk Assessment is required as part of the job preparation before HMR mobilisation and operation on site.

Objectives of the risk assessment:

- identify the different risks associated with the utilisation of the HMR prototype in an industrial plant
- define mitigations to reduce these risks at acceptable levels.

The Risk Assessment methodology will be based on Chevron standards using the Company risk assessment template and risk matrix.

A risk assessment related to drone operations in Chevron oil and gas plants is provided for reference in **Appendix 3.**

### 5.2.4. Description of Test Location and conditions

| **Plant / Area Description** | |
|---|---|
| Plant | Oronite additives plant in Gonfreville, France. |
| Experiment Area | The water pumping station in NW area of facility. Provided accessible pipe work of sufficient size (8") to test the HMR and UT Crawler robot. |

| **Pipework** | |
|---|---|
| Pipe material | Carbon Steel |
| diameter and thickness | 8 Inch Schedule 40 8.18mm nominal thickness |
| Coating material and thickness | Unknown thickness. Most likely 2-3 coats/layers. |
| (See diagram) | Pipe support structure was I-beam construction with process piping resting on 1/2" open-ended pipe. |
| Pipe support separation (along the pipe) | 13.5ft (4100mm) |
| Parallel pipe distance separation | minimum 100mm |
| parallel pipe characteristics | Rack of high-level pipes of varying thickness. 4-6-8-10" diameters. 8" pipe used for testing consists of T-section, elbows and straight pipe. |
| Other equipment or obstructions present | N/A |
| Pipe elevation | Elevation approx. 7-8 meters above ground level |

| **Plant / Area Description** | |
|---|---|
| **Environmental conditions** | |
| Temperature | 18 deg C ambient temp. |
| light conditions | Natural lighting. Overcast with no overhead obstructions |
| humidity | Approx 60% humidity |
| wind velocity (potentially not that important as not flying) | 3-10 knots |
| wind direction (same as above) | East-Northeast |

Figure 9 depicts test location, details of pipe racks used along with diagram of pipe support structure.

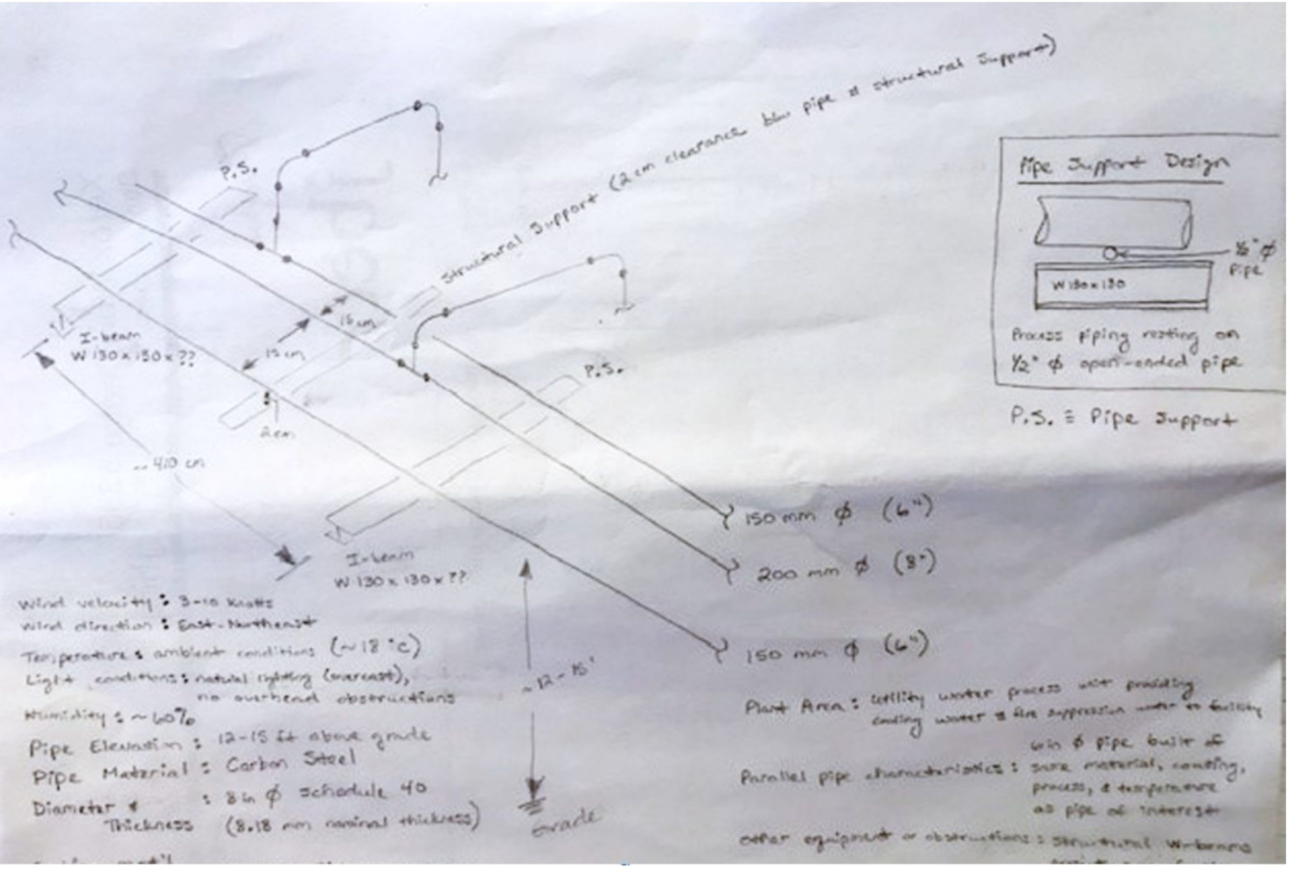



**Figure 9** Sketch diagram showing the support design of the raised Pipe rack and parallel piping details.


**Figure 10** Showing raised pipe rack with piping diameter. Testing was conducted on the 250mm Diameter piping (8 inch).

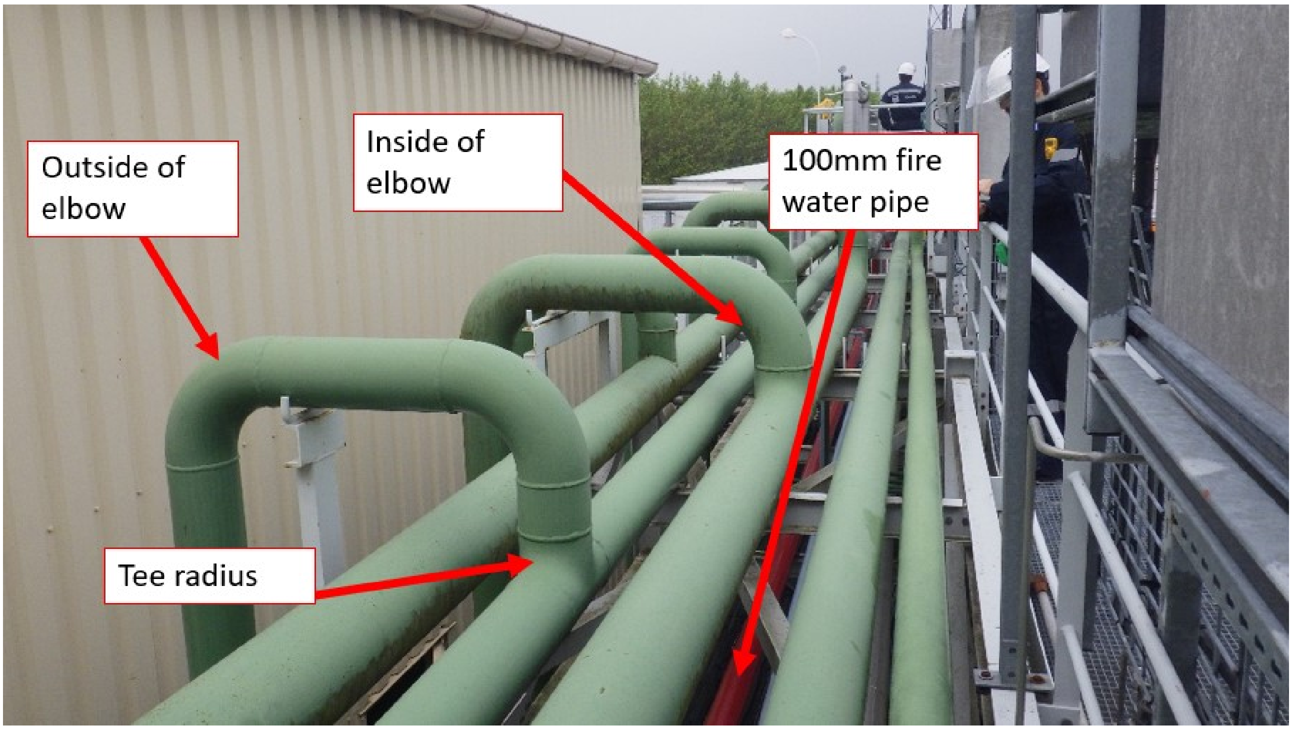



**Figure 11** Description of pipe features to be tested with UT crawler.

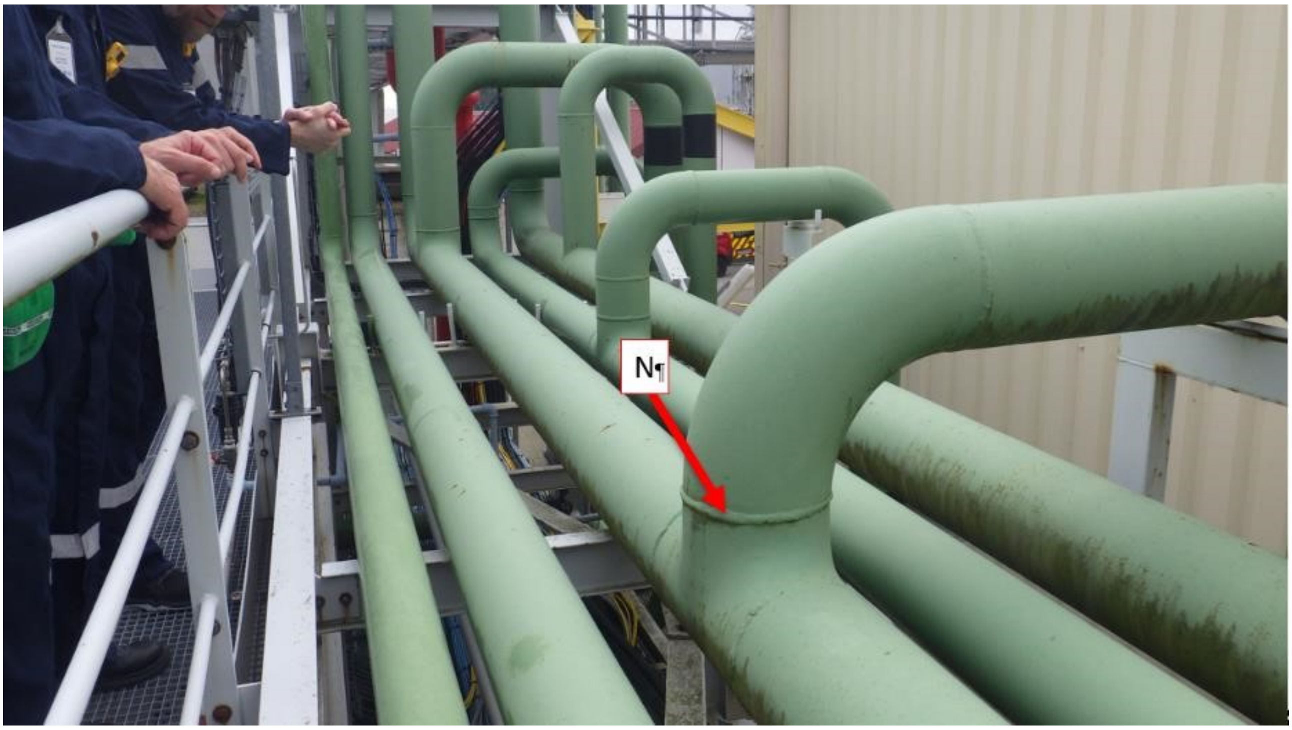



**Figure 12** Shows large T-section and Elbow used (delineated by N) to test UT Crawler.


**Figure 13** Showing the HMR on location on 8-inch piping with UT crawler deployed on T-section.

### 5.2.5. Complete standard operation

| Step | Linked functionality | Description | Involved Partners | Test validation |
|---|---|---|---|---|
| 1 | Fun-14 | Before starting any measurements with the drone, the functionality of the ultrasound unit will be verified. We will use a pipe with an integrated calibration block. Measurements after calibration should be reliable. | DASEL<br>WTR<br>CATEC | Yes |
| 2 | Fun-12 | Visualization of an inspection plan in the database. | UOULU | Yes*. The visualisation of the inspection plan has been validated before the Chevron Oronite plant validations. |

| **Step** | **Linked functionality** | **Description** | **Involved Partners** | **Test validation** |
|---|---|---|---|---|
| 3 | Fun-10 | The aerial robot will be turned on and all the systems and information needed to perform the operation should be visualized at the ground systems on real time. Drone status and telemetry, satellite cameras and control, and UT electronics working. | CATEC<br>WTR<br>DASEL | Yes |
| 4 | Fun-1 | The navigation system telemetry should be checked before flight. This system is based on visual cameras. The robot will take-off and fly in assisted mode commanded by the pilot. The drone will arrive near the pipes. | CATEC | No – HMR system was not permitted to fly during live site tests. |
| 5 | Fun-1<br>Fun-3 | Once close to the pipes, the operator will command a search of pipes. The robot will localize the pipe and ask confirmation to the operator. Once the desired pipe is located under the robot, the operator will command a landing operation. The pipe is identified and localized autonomously. The robot starts approaching to the pipe once it is stable. | CATEC | No – HMR system was not permitted to fly during live site tests. |
| 6 | Fun-1<br>Fun-3 | The drone will proceed to land on the pipe once all the stability conditions are validated. The landing operation is the most critical part of the flight. Maximum wind limitations will apply for each pipe diameter. Non-GNSS localization and pipe position estimation systems will be used | CATEC | No – HMR system was not permitted to fly during live site tests. |
| 7 | Fun-6 | Once landed, the satellite robot will be deployed and perform a simple inspection operation of the pipe. Detailed inspection tests of the satellite robot will come in subsequent operations. | WTR<br>DASEL | Yes |
| 8 | Fun-10 | The whole UT inspection will be monitored from the ground. UT data will be stored locally. | DASEL<br>WTR<br>CATEC | Yes |
| 9 | Fun-1 | The navigation system telemetry should be checked again before taking-off from the pipe. The magnets will be deactivated, and the drone will take-off. The robot will take-off and fly in assisted mode | CATEC | No – HMR system was not permitted to fly during live site tests. |

| Step | Linked functionality | Description | Involved Partners | Test validation |
|---|---|---|---|---|
| | | commanded by the pilot. The pilot will take the drone to the ground and land. | | |
| 10 | Fun-12 | Once in the ground, the stored UT data will be sent to the database. Then a user should access the database and visualise the inspection information. | UOULU DASEL | Yes*. The transfer of the inspection data from the UT subsystem to the GSDB subsystem (see D5.1 Section 4, D5.2 Sections 2 and 5, D5.3) and their visualisation has been validated before the Chevron Oronite plant validations. |

### *Flight safety validation*

Decision not to fly the HMR system in the live industrial site tests was made following the first phase validation testing in Seville, Spain. This decision was supported by both end users Chevron and TotalEnergies who were involved in the project.

The landing procedure and mechanism of the system was deemed to be unsafe for use in a live setting based on observations of multiple failed or aborted landings, multiple landings which involved manual intervention and handling and also an event with uncontrolled rotor movement during manual handling of the system.

Without this landing procedure there was deemed to be little or no value in flying the system in the refinery environment. Instead, the system was manually placed onto the pipe rack of interest and the UT satellite crawler component was tested.

### *Satellite UT inspection validation*

### *Quadrant longitudinal B-Scan*

- Straight pipe section

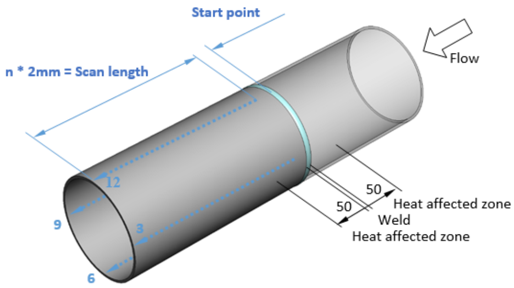



**Figure 14** Straight pipe section.

| **Test validation** | Partially | • Line scan at 3 and 12 o'clock positions<br>• Point measurement at 12 o'clock |
|---|---|---|

- Horizontal/vertical elbow

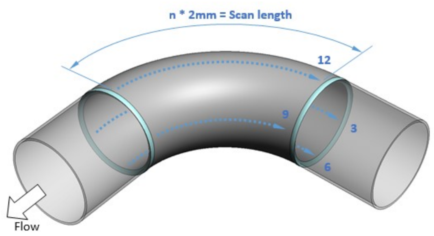



**Figure 15** Elbow section.

| **Test validation** | Partially | • Line scan at 3 o'clock position<br>• Point measurement at 3 o'clock first weld, middle and second weld<br>• Point measurement at 6 / 12 o'clock in middle |
|---|---|---|

- T-Sections

This type of inspection was not available for testing at the outdoor mockup, but it is stated here for reference.

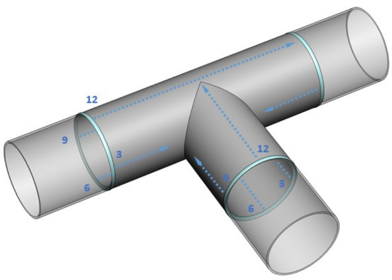



**Figure 16 T section.**

| **Test validation** | Partially | • Point measurements at 12 o'clock first weld, second weld and middle<br>• Point measurements at 3 o'clock first weld and second weld |
|---|---|---|

- Reducers

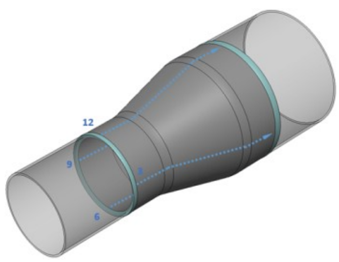



**Figure 17** Reducer section.

| **Test validation** | No | No reducer was available in the testing area. |
|---|---|---|

### 5.2.6. Results from Live Site Testing.

The following section described the results obtained from the UT crawler during live site testing.

***Calibration***

The ultrasonic thickness measurement system was first verified using three reference points on a standard step gauge.

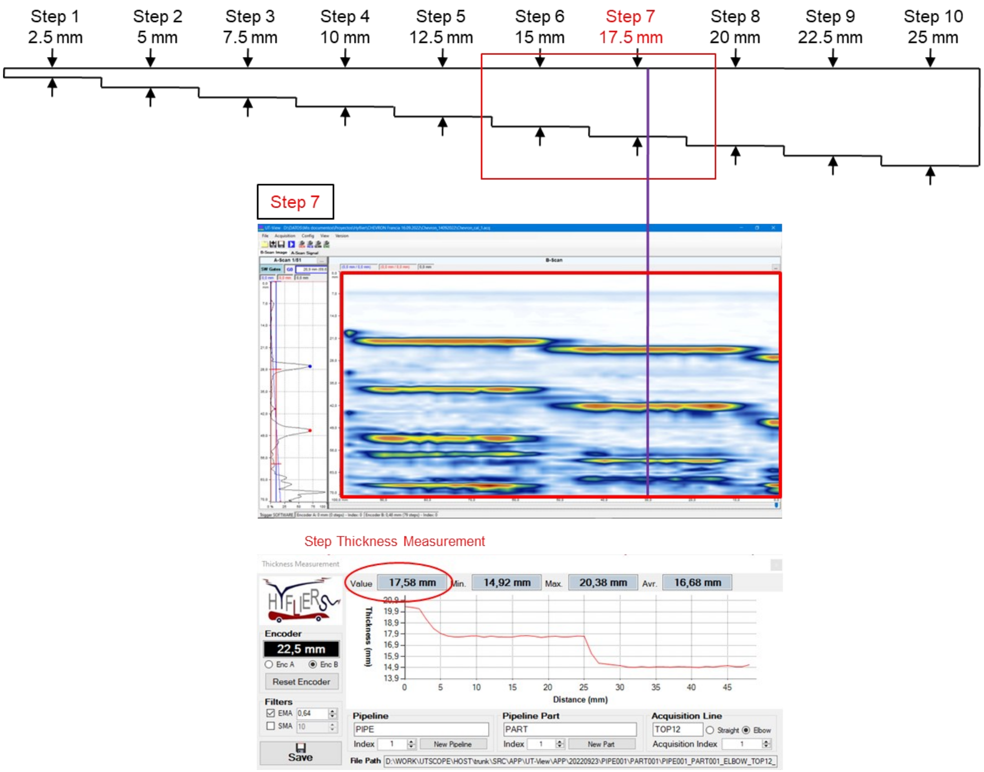



**Figure 18: UT calibration step 17.5 mm**

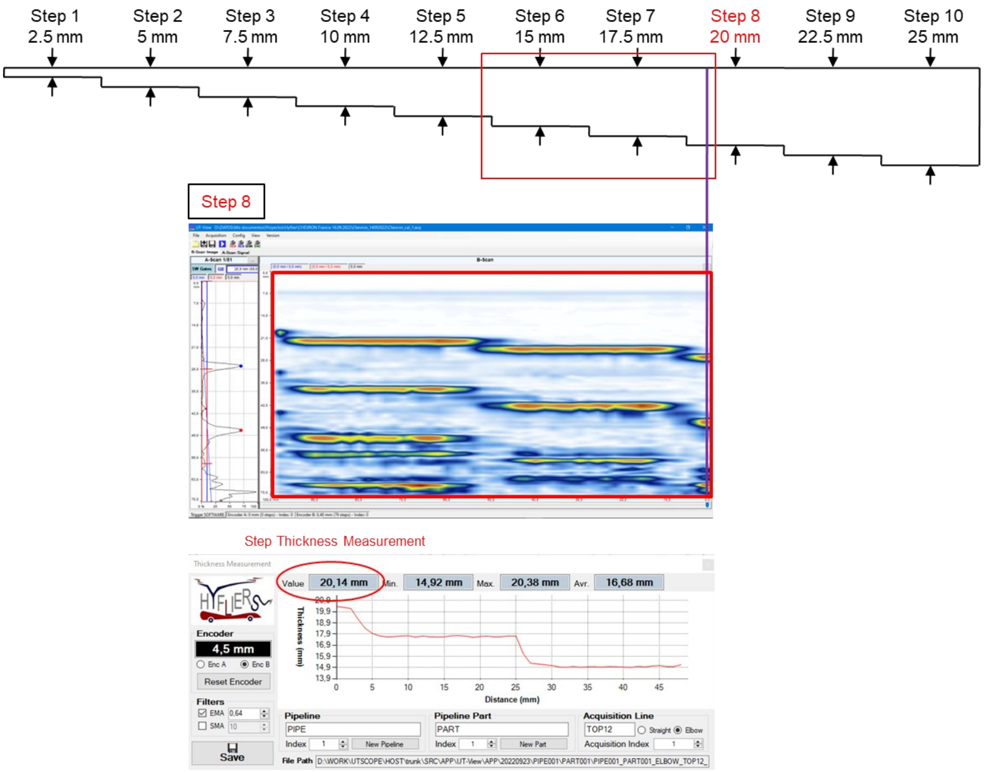



**Figure 19: UT calibration step 20.0 mm**

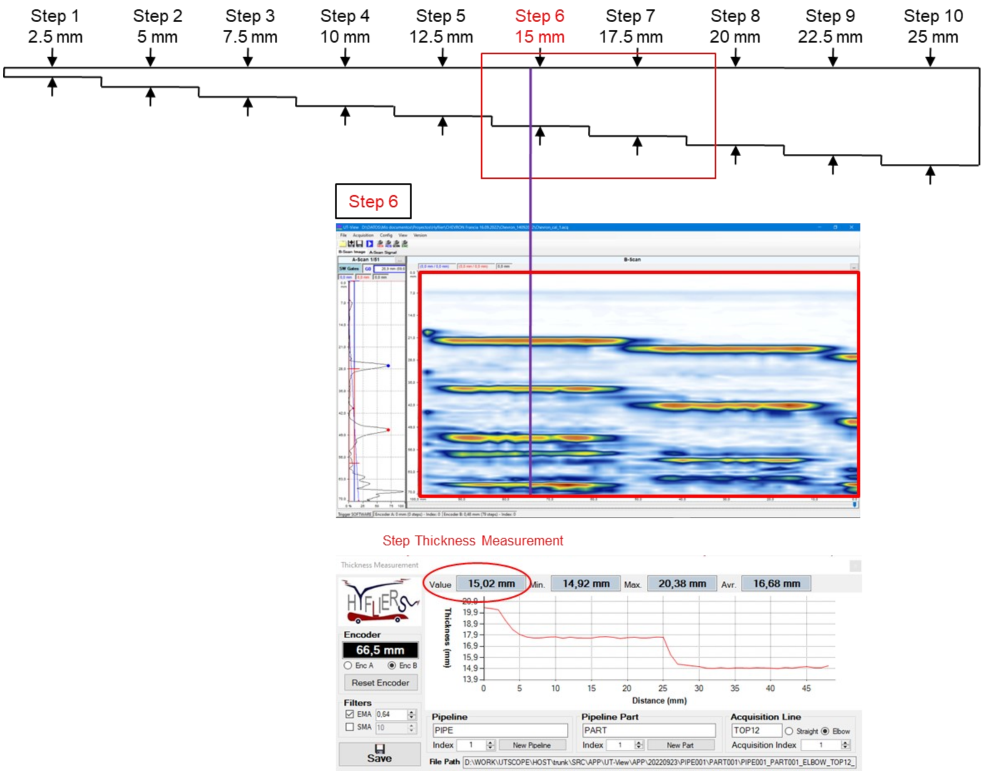



**Figure 20: UT calibration step 15.0 mm**

***Spot measurement parkour***

With a diagrammatic image showing the 10 UT inspection points taken on the raised pipe rack.

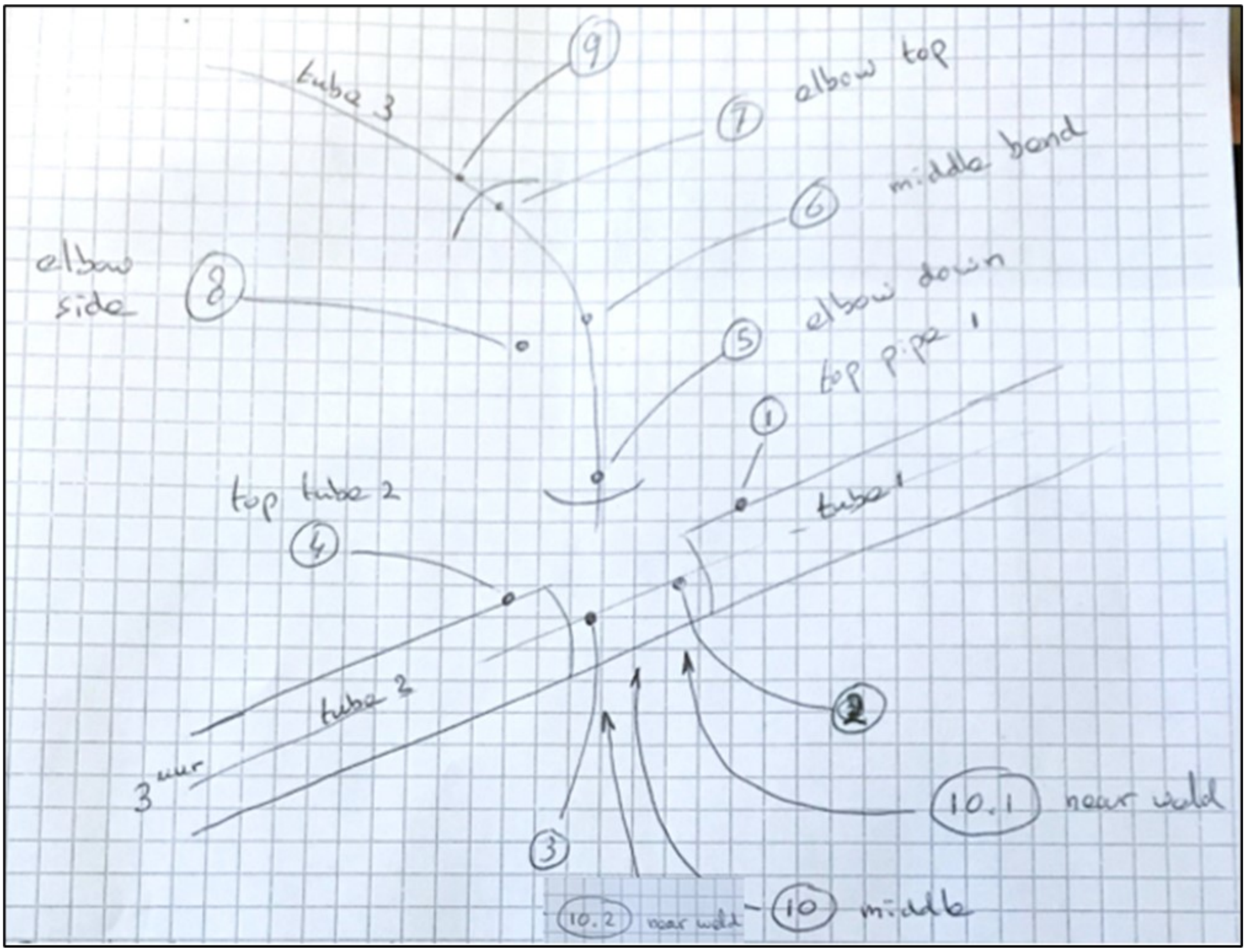



**Figure 21 Sketch diagram depicting the 10 UT inspection points acquired using the UT crawler on the 8 Inch piping.**

### 5.2.7. UT Measurement Results

Experiments were run based on a calibration block supplied by the Oronite facility. Hand UT measurements were also acquired by a certified inspection crew at the same 10 points as the HMR's UT crawler for direct comparison and validation.

The table below shows the results of the crawler UT measurements versus the UT measurements taken manually by the qualified inspector using conventional UT measurement tools.

The UT measurements were performed blindly, with no previous knowledge of nominal pipe thickness, corrosion allowance, pipe coating specification or previous inspection records.

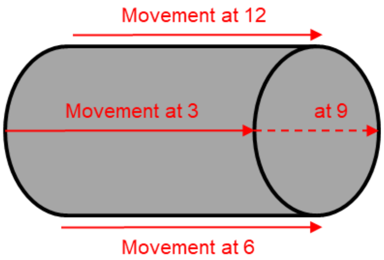
It can be clearly seen that there is correlation between the two sets of results, thus confirming that the UT crawler performed exceptionally well in the industrial site tests with an 83% correlation success rate.

Two minor discrepancies; location 1 and 10.2 appear in the table where the crawler UT measurement is lower than the manual UT measurement. As the measurements were performed blindly and correlation was done after the fact, there was no opportunity to revisit these two measurement points and perform additional UT scans in order to remedy these discrepancies.

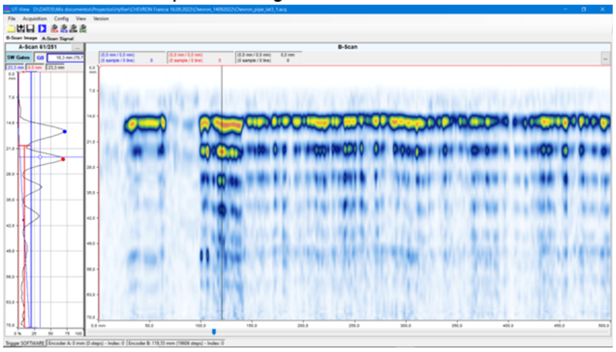
| | | UT Crawler Measurement (mm) | UT Hand Tool measurement (mm) |
|---|---|---|---|
| 1 | Top Tube 1 | 6.6 | 7.5 |
| 2 | Side T | 9.3 | 9.2 |
| 3 | Side T | 8.9 | 8.7 |
| 4 | Top Tube 2 | 7.6 | 7.8 |
| 5 | Elbow Down | 8.6 | 8.6 |
| 6 | Elbow Middle | 8.8 | 8.6 |
| 7 | Elbow Top | 8.7 | 8.6 |
| 8 | Elbow Side | 8.1 / 8.0 / 8.3 | 8.0 |
| 9 | Tube 3 Top | 7.4 | 7.9 |
| 10 | Bottom T | 10.3 / 10.1 | 10.3 |
| 10.1 | Bottom T | 10.9 | 10.7 |
| 10.2 | Bottom | 10 | 10.7 |

**Table 2: Results of UT crawler measurements against hand tool measurements**

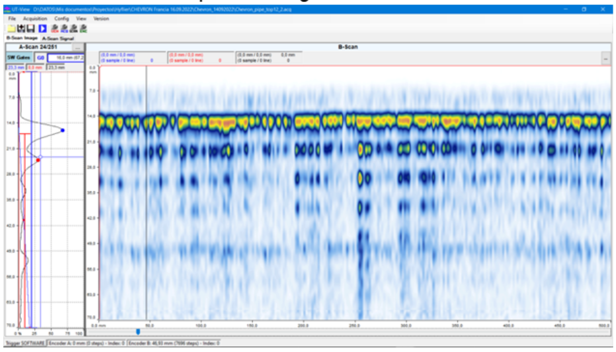
### *Straight pipe line scan*



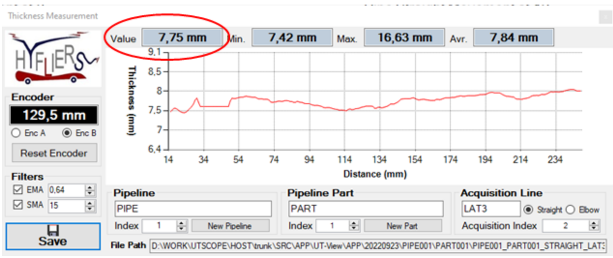

Pipeline Straight Movement at 3



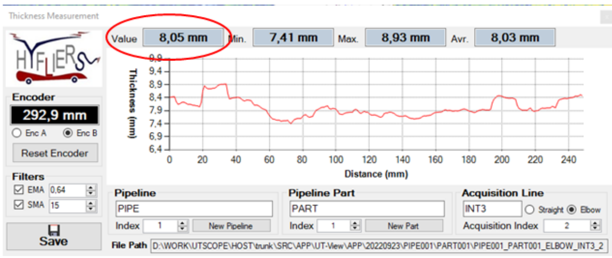
Pipeline Straight Movement at 12



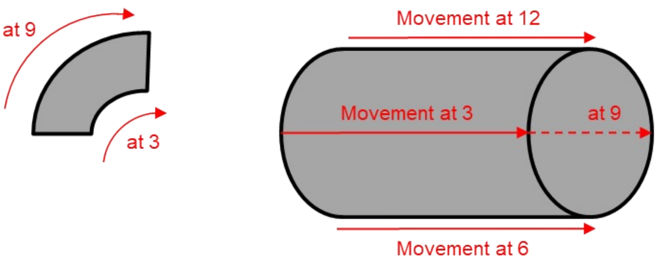
Step Thickness Measurement



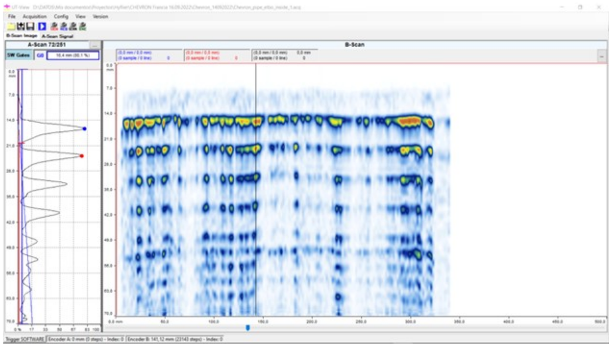

Step Thickness Measurement



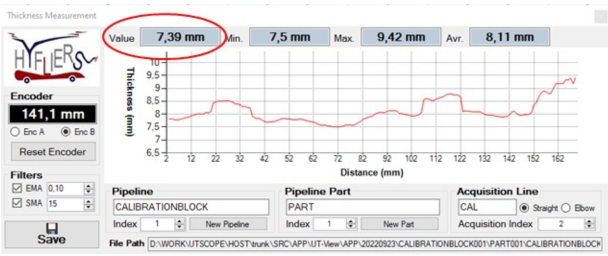
***Elbow line scan***




Pipeline Elbow Movement at 3



Step Thickness Measurement



# 6. Overall HMR end-user report

The UT satellite crawler has been a success and has proven to be a useful and novel approach to dealing with pipe inspection at height. As a standalone piece of technology without the drone it still holds up as an interesting proposition and can be run independently from the drone solution, and still allow access to areas at height by using telescopic rod for placement.

The drone transport system is a novel approach and while it does work and can function as intended, was found to be unsafe for use due to landing mechanism employed for HYFLIERS project. With further refinements such as being able to land on pipes without the need for cutting power to the rotors or by enhancing the landing clamp system to ensure the system cannot fall off the pipework resulting in a crash, both end users are in agreement that this solution shows promise and could be a viable solution/product that would have a place in inspection work scopes for facilities inspection purposes.

# 7. Conclusions

The concept of a flight capable system which can deploy a UT inspection crawler onto pipework at height, do an inspection and move off to other areas has great potential to fill a major use case in pipe inspection at height. The end users feel this technology and concept could be viable with further development to the landing procedure of the aerial system.

The HMR project was a unique and novel concept, pushing the boundaries of what is possible and viable for facilities plant inspection at height. Despite some reduced scope in testing due to issues with landing of the system, the end users see the HMR as an overall success case. The project has delivered a system which can fulfil the use case as intended but needs further work to improve the safety and reliability performance in order to be considered a viable solution for use in a live industrial setting.

The end users in HYFLIERS are in agreement that if the HMR landing mechanism can be made safe for use in a live environment and validated in an outdoor testing scenario in Seville, they would be willing to take the fully integrated solution back to their industrial sites in 2023 for further extensive testing.

# 8. Annex 1 – End User Requirements

For Importance (C, M, S), see definitions at the bottom of the table.

| ID | Description | Rationale | Importance | Success criteria & Validation method | Validation results Seville | Validation results Chevron |
|---|---|---|---|---|---|---|
| UR-01 | The system must be small enough to be transported by van or pallet | The system needs to be transported to the refinery | M | The system can be transported in a regular van | Yes | Yes |
| UR-02 | System could be small enough to be transported by helicopter | In case the system is used in an offshore facility | C | The system can be transported in regular helicopter boxes that can fit inside a helicopter The system will have the dimensions required to be transported in a regular helicopter | Yes | Yes |
| UR-03 | The system must be small enough to be transported by airfreight cargo | It is envisioned that the system will be transported by cargo to different refineries all over the world | M | The system will be able to be packed in a pallet | Yes | Yes |
| UR-04 | Recharging and maintenance must be done within a safe area | These activities could be dangerous in an explosive atmosphere area | M | The system is designed to have a separate recharging and maintenance | Yes | Yes |

| ID | Description | Rationale | Importance | Success criteria & Validation method | Validation results Seville | Validation results Chevron |
|---|---|---|---|---|---|---|
| | | | | station than the operational one | | |
| UR-05 | A gas detection system must be installed on-board the robotic vehicle | It is one of the safety mitigations measurements already identified by TotalEnergies and Chevron | M | A gas detection system is installed and operational on the robotic vehicle. The alarm needs to be transmitted to the ground control station | Yes | Yes |
| UR-06 | If gas is detected, the aerial robot must start a getaway operation in less than two seconds | As the aerial robot is not going to be ATEX, it has to fly away from the hazardous area | M | The operator is able to command the getaway operation in less than 2 seconds | Yes | Not tested – HMR was not allowed to fly in the refinery |
| UR-07 | Batteries must be protected against impacts | For safety reasons, in case of a fall, the batteries are required to be protected so they are not exposed to the atmosphere | M | Batteries protections bear impacts of 100N | Yes | Yes |
| UR-08 | Maximum weight of transporting box 30 kg | So, it can be transported by a single person (due to Health and Safety regulations from | S | Once the transporting box is fully loaded, it is weighted, and the result is less than 30 kg | Yes | Yes |

| ID | Description | Rationale | Importance | Success criteria & Validation method | Validation results Seville | Validation results Chevron |
|---|---|---|---|---|---|---|
| | | TotalEnergies and Chevron) | | | | |
| UR-09 | Flight plan including emergency paths must be approved before the operation | Required to get the permit to perform the inspections on the refinery | M | Flight plans following the established format will be designed before each operation | Yes | Not tested |
| UR-10 | The risk assessment must consider safety mitigations plan ahead and approved taking into consideration the possibility of loss of communication | Required to get the permit to perform the inspections on the refinery | M | The system has integrated a Return To Home (RTH) function, and it is automatically activated when the communications are lost | Yes | Not tested |
| UR-11 | The risk assessment must consider safety mitigations plan ahead and approved taking into consideration the possibility of collision with obstacles | Required to get the permit to perform the inspections on the refinery | M | The system has integrated a Collision Avoidance System | Yes | Not tested |
| UR-12 | The risk assessment must consider safety mitigations plan | Required to get the permit to perform | M | The cable stops when it detects that it is an abnormal | Yes | Not tested |

| ID | Description | Rationale | Importance | Success criteria & Validation method | Validation results Seville | Validation results Chevron |
|---|---|---|---|---|---|---|
| | ahead and approved taking into consideration the possibility of the drop of the robotic vehicle while flying | the inspections on the refinery | | deployment not controlled | | |
| UR-13 | The risk assessment must consider safety mitigations plan ahead and approved taking into consideration the possibility of gas detected (explosion). | Required to get the permit to perform the inspections on the refinery | M | The system has a gas sensor on-board | Yes | Not tested |
| UR-14 | In ATEX areas it is needed to follow standard procedures | Required to get the permit to perform the inspections on the refinery | M | During the experiments, TotalEnergies and Chevron will apply the standard procedures to perform the experiments | Yes | Yes |

| ID | Description | Rationale | Importance | Success criteria & Validation method | Validation results Seville | Validation results Chevron |
|---|---|---|---|---|---|---|
| UR-15 | The system should be designed taking into consideration major restrictions to be able to extend its capabilities to operate in ATEX zone 2 areas in the future | Although the project experiments will be performed in real refineries but in controlled areas, it is important for the future exploitation of the system to take into consideration the requirements to operate in ATEX zone 2 areas | C | The experiments are performed as if the system was in an ATEX zone 2 area, so the same requirements will be applied | No | No |
| UR-16 | Only brushless motors must be used | Non-brushless motors are not safe to operate in ATEX environments | M | The robotic system only incorporates brushless motors | Yes | Yes |
| UR-17 | Robotic vehicle must be collision-proof (for example mechanical protection around propellers) | In case of contact with the structure of pipes, the robotic vehicle has to be able to continue operating, and also no damage has to be generated | M | The robotic vehicle will incorporate mechanical protection mechanisms | Yes | Yes |
| UR-18 | The flight envelope and clearance requirements around the aerial vehicle | The end-user requires this information to plan and decide which pipes can the robotic system | M | This information is incorporated into the specifications of | Yes | Yes |

| ID | Description | Rationale | Importance | Success criteria & Validation method | Validation results Seville | Validation results Chevron |
|---|---|---|---|---|---|---|
| | must be provided for flying and landing | inspects, and which ones not. | | the robotic system | | |
| UR-19 | The system must incorporate sensors to determine if the landing area is clear of obstacles or not | Before landing, it is important to confirm if the landed area is clear of obstacles | M | The system can decide and distinguish between a clear and a not clear landing area | Yes | Not tested – HMR was not allowed to fly in the refinery |
| UR-20 | The combination of both robotic systems must be able to operate on pipes from 8 to 20 inches of diameter | The first priority is to be able to operate on pipes from 8 to 20 inches of diameter | M | The robotic system lands on pipes from 8 to 20 inches and can operate on it | Yes | Yes |
| UR-21 | The combination of both robotic systems must be able to operate on 6 inches diameter pipes | The second priority is to be also able to operate on pipes with 6 inches of diameter. It will be explored the impact in the design of being able to operate on 6 inches diameter pipes | S | The robotic system lands on 6 inches diameter pipes | NO. 8" was minimum possible on HMR Landing assembly | No |

| ID | Description | Rationale | Importance | Success criteria & Validation method | Validation results Seville | Validation results Chevron |
|---|---|---|---|---|---|---|
| UR-22 | The combination of both robotic systems must be able to operate on pipes from 20 to 24 inches of diameter | It would be nice to also be able to inspect pipes from 20 to 24 inches of diameter | C | The robotic system lands on pipes from 20 to 24 inches and can operate on it | Not Tested | Not Tested |
| UR-23.a | The HMR Aerial Platform must be able to land by means of a magnetic landing platform | HMR must be directly attach to the pipe once it has landed on the pipe.<br>All the pipes considered in the project will be magnetic /carbon steel since these are the ones that TotalEnergies and Chevron are most interested in | M | The force created by the HMR landing platform is at least the 15% of its weight. | Yes | Yes |
| UR-24 | The system must operate only on non-insulated pipes | All the pipes considered in the project will not have insulation since these are the ones that TotalEnergies and Chevron are most interested in | M | The considered pipes within the ConOps are only non-insulated pipes | Yes | Yes |
| UR-25 | The system magnets must operate on a | Important information for the design of the | M | The force created by the landing gear is | Yes - | Yes - |

| ID | Description | Rationale | Importance | Success criteria & Validation method | Validation results Seville | Validation results Chevron |
|---|---|---|---|---|---|---|
| | surface with a non-magnetic layer of 1 mm or less | magnetic elements of the robotic system<br>Maximum non-magnetic layer thickness, less than 1 mm | | at least the 15% of its weight on a pipe with a non-magnetic layer of 1 mm | Tested on typical initial paint layer | Tested on typical initial paint layer |
| UR-26 | The system magnetics should operate with a non-magnetic layer of 2 mm or less | Important information for the design of the magnetic elements of the robotic system<br>Maximum non-magnetic layer thickness, less than 2 mm | S | The force created by the landing gear is at least the 15% of its weight on a pipe with a non-magnetic layer of 2 mm | No | No |
| UR-27 | The system magnetics could operate with a non-magnetic layer of 3 mm or less | Important information for the design of the magnetic elements of the robotic system<br>Maximum non-magnetic layer thickness, less than 3 mm | C | The force created by the landing gear is at least the 15% of its weight on a pipe with a non-magnetic layer of 3 mm | No | No |
| UR-28 | The robotic system should be able to cross 5 mm high welds | Welds are usually max. 5 mm high and it is required to cross them to | S | The robotic system crosses welds during an operation | Partially – 3 mm welds tested | Yes |

| ID | Description | Rationale | Importance | Success criteria & Validation method | Validation results Seville | Validation results Chevron |
|---|---|---|---|---|---|---|
| | | complete the inspection | | | | |
| UR-29 | The robotic system should be able to cross horizontal elbows of OD>12” | Required to complete elbow inspections | S | The robotic system crosses horizontal elbows during an operation | Yes | Yes |
| UR-30.a | The satellite installed on the HMR aerial robot must be able to move along the pipe | Required to get to the inspection area from the landing point | M | The robotic system moves along a pipe a minimum of 1 m | Yes | Yes |
| UR-31 | The system must incorporate sensors to allow the pilot or automatically the system to assess the condition of the pipe | Before starting the inspection, it is important to assess the surface condition of the top of the pipe | M | The system allows the assessment of the condition of the top of the pipe by using a video camera visualized by the operator | Yes | Yes |
| UR-32 | The system must incorporate sensors to allow the pilot or automatically the system to assess the | Before starting the inspection, it is important to assess the surface condition of the pipe | C | The system allows the assessment of the condition of the whole of the pipe | Yes | Yes |

| ID | Description | Rationale | Importance | Success criteria & Validation method | Validation results Seville | Validation results Chevron |
|---|---|---|---|---|---|---|
| | condition of the whole pipe | | | | | |
| UR-33 | The system will incorporate the sensors to allow the pilot or automatically the system to locate the weld of the pipe | After landing it is important to locate the weld | M | Once landed, the system can localize the weld on the pipe. | Yes | Not tested |
| UR-34.a | The system must allow positioning relative to a feature (e.g. weld) with an accuracy of 2 cm at 3, 6, 9 and 12 positions. | | M | The system can be positioned relative to a feature, e.g. a weld, with an accuracy of 2 cm with at 3, 6, 9, 12 positions | Yes, except for line scans on elbow sides | Yes, except for line scans on elbow sides |
| UR-34.b | The system should locate itself, autonomously, with respect to the weld in 3, 6, 9 and 12 positions with less than 2 cm of accuracy | | S | The system locates itself automatically with respect to the weld in 3, 6, 9 and 12 positions with less than 2 cm of accuracy | Not tested | Not tested |

| ID | Description | Rationale | Importance | Success criteria & Validation method | Validation results Seville | Validation results Chevron |
|---|---|---|---|---|---|---|
| UR-35 | The system must allow positioning relative to a feature (e.g. weld) with an accuracy of 1 cm at 3, 6, 9 and 12 positions. | | S | The system must be positioned relative to a feature (e.g. weld) with an accuracy of 1 cm at 3, 6, 9, 12 positions. | Spot measurements: Yes<br>Line measurements: No | Spot measurements: Yes<br>Line measurements: No |
| UR-36.a | The system must perform an ultrasonic inspection for wall thickness from 3 mm to nominal | The ultrasonic inspection needs to have good quality in order to complete the inspection | M | The quality of the inspection will be assessed by a qualified ultrasonic operator provided by TotalEnergies and/or Chevron | Yes | Partially -<br>On assets with 7 to 11 mm remaining thickness tested. |
| UR-36.b | The system must perform an ultrasonic inspection for wall thickness from <2.5 mm to nominal | The ultrasonic inspection needs to have good quality in order to complete the inspection | S | The quality of the inspection will be assessed by a qualified ultrasonic operator provided by TotalEnergies and/or Chevron | Yes | Not tested |
| UR-37 | The system must be able to save and display in real-time A-SCAN data on the ground | Required to assess in real-time or acceptable low delay time the quality of the inspection | M | The system allows to save and display real-time A-SCAN data | Yes | Yes |

| ID | Description | Rationale | Importance | Success criteria & Validation method | Validation results Seville | Validation results Chevron |
|---|---|---|---|---|---|---|
| UR-38 | The system must allow the operator to control the ultrasonic sensor from the ground | Required to be able to perform good quality inspections during the operation | M | The operator has similar control and configuration capabilities as in regular inspections without the robotic system | Yes | Yes |
| UR-39 | The system must be able to operate on surfaces at 60ºC | This is the most usual temperature range on pipes | M | Components of the system which will be in contact with the pipes have an operative temperature of more than 60ºC | Yes – Components with surface contact accordingly rated | Not tested |
| UR-40 | The system must be able to operate on surfaces at 100ºC | This temperature is also possible, but it is the second priority for Chevron and TotalEnergies | C | Components of the system which will be in contact with the pipes have an operative temperature of more than 100ºC | No – Satellite components rated up to maximum 80°C | No |
| UR-41 | Robotic system MTOW must be less than 15 kg | Maximum weight that TotalEnergies and Chevron safety departments allow to operate in their facilities | M | The system is weighed just before the take off and it weighs less than 15 kg | Yes | Yes |

| ID | Description | Rationale | Importance | Success criteria & Validation method | Validation results Seville | Validation results Chevron |
|---|---|---|---|---|---|---|
| UR-42 | Robotic system MTOW should be less than 12 kg | Maximum weight that TotalEnergies and Chevron estimate as safe even in case of an accident during operations | S | The system is weighed just before the take off and it weighs less than 12 kg | Yes | Yes |
| UR-43 | Robotic system MTOW could be less than 8 kg | Maximum weight that TotalEnergies and Chevron estimate as safe even in case of an accident during operations | C | The system is weighed just before the take off and it weighs less than 8 kg | No | No |
| UR-44 | The system could be able to measure height of corrosion deposit or depth (at least with 0.5 mm relative accuracy) | It would be a nice feature in order to add value to the robotic system | C | The system incorporates the sensors that allow the pilot or automatically the system to measure height of corrosion deposit or depth | Yes | Yes |
| UR-45 | The system must be able to perform ultrasonic inspection at 3, 6, 9 and 12 positions in the first, middle and second welds in horizontal elbows | Required to complete an elbow inspection. First priority for TotalEnergies and Chevron | M | The system performs a quadrant horizontal elbow inspection: 4 points (3, 6, 9 and 12 positions) close to first weld, 4 points close in | Yes | Yes |

| ID | Description | Rationale | Importance | Success criteria & Validation method | Validation results Seville | Validation results Chevron |
|---|---|---|---|---|---|---|
| | | | | the middle and 4 points close to second weld | | |
| UR-46 | The system must be able to perform ultrasonic inspection at 3, 6, 9 and 12 positions in the first, middle and second welds in vertical elbows | Required to complete an elbow inspection. First priority for TotalEnergies and Chevron | M | The system performs a quadrant vertical elbow inspection: 4 points (3, 6, 9 and 12 positions) close to first weld, 4 points in the middle and 4 points close to second weld. | Yes | Yes |
| UR-47 | The system must be able to perform ultrasonic grid inspections on elbows following TotalEnergies and Chevron inspection procedures | Required to complete an elbow inspection. First priority for TotalEnergies and Chevron | M | The system performs grid inspection on elbows. | Yes | Yes |
| UR-48 | The system should be able to perform ultrasonic grid inspections on horizontal T | Second priority of required inspections for TotalEnergies and Chevron | S | The system performs grid inspections on horizontal T joint in 1 and 3 areas (including impact area). | Yes | Not tested |

| ID | Description | Rationale | Importance | Success criteria & Validation method | Validation results Seville | Validation results Chevron |
|---|---|---|---|---|---|---|
| | joints (in 1 and 3 areas) | | | | | |
| UR-49 | The system should be able to perform ultrasonic quadrant inspections on horizontal T joints (in 1 and 3 areas) | Second priority of required inspections for TotalEnergies and Chevron | S | The system performs horizontal quadrant T joint inspection in 1 and 3 areas (including impact area) | Yes | Yes |
| UR-50 | The system could be able to perform ultrasonic grid inspections on reducers and horizontal T joints (in area 2) | Third priority of required inspections for TotalEnergies and Chevron | C | The system performs grid inspection on reducers and T joint in area 2 | Not tested – No reducer available | Not tested |
| UR-51 | The system could be able to perform ultrasonic quadrant inspections on reducers and horizontal T joints (in area 2) | Third priority of required inspections for TotalEnergies and Chevron | C | The system performs quadrant inspections on T joints in area 2 | Yes | Yes |

| ID | Description | Rationale | Importance | Success criteria & Validation method | Validation results Seville | Validation results Chevron |
|---|---|---|---|---|---|---|
| UR-52 | The system must be able to perform quadrant inspection of a horizontal pipe | This inspection must be always possible to be performed due to its importance for the end-users | M | The system performs horizontal pipe quadrant inspection until the first weld whatever the configuration | Yes | Yes |
| UR-53 | The system must be able to inspect racks of pipes of 75 cm distance between pipes | Since these pipes are already very difficult to inspect even with a human operator and regular means (scaffolding, rope access, etc.) | M | The system is able to inspect at least two pipes that are close to each other no more than 75 cm | Not tested | Yes - System can operate on pipes with minimum 10cm separation from one another |
| UR-54 | The robotic system should be able to perform A-scan type of inspection in straight pipes and in areas close to welds | Chevron and TotalEnergies are very interested in scan type of inspection | S | The system performs scan-type of ultrasonic inspections in straight pipes close to welds | Not tested | Yes |
| UR-55 | The system could be able to perform A-scan type of inspections in straight pipes with elbows | This would be ideal and very nice to have for Chevron and TotalEnergies | C | The system performs scan-type of ultrasonic inspections in straight pipes with elbows | Not Tested | Yes |

| ID | Description | Rationale | Importance | Success criteria & Validation method | Validation results Seville | Validation results Chevron |
|---|---|---|---|---|---|---|
| UR-56 | The system should incorporate similar ultrasonic sensor user interface on the ground as regular ultrasonic sensor systems | The operator should have a similar way of interaction with the ultrasonic sensor software interface even if it is on-board the robotic system | S | A qualified operator will evaluate the ultrasonic sensor user interface | Yes | Yes |
| UR-57 | In single points measurements, the system must log: identification number, and wall thickness value | Defined following TotalEnergies and Chevron inspection procedures | M | A qualified operator will evaluate the log information | Yes | Yes |
| UR-58 | In grid measurements, the system must log: identification number of the area and for each point it must log: the position (relative to the grid) and the wall thickness | Defined following TotalEnergies and Chevron inspection procedures | M | A qualified operator will evaluate the log information | Yes | Yes |

| ID | Description | Rationale | Importance | Success criteria & Validation method | Validation results Seville | Validation results Chevron |
|---|---|---|---|---|---|---|
| UR-59 | In A-scan type inspections, the system could log: identification number of the area, minimum wall thickness, and an image (using standard colour coding) that contains position (relative to the grid) and thickness for each point | Defined following TotalEnergies and Chevron inspection procedures | C | A qualified operator will evaluate the log information | Yes | Yes |
| UR-60 | The system must be able to change or recharge batteries onsite (in safe areas only) | Since it is foreseen that these types of operations will be required to continue with the operation during one day of work | M | The system allows to change or recharge batteries onsite | Yes | Yes |
| UR-61 | The system must be able to reload ultrasonic coupling onsite (if applicable) | Since it is foreseen that these types of operations will be required to continue with the operation during one day of work | M | The system allows to reload the ultrasonic coupling onsite | Yes | Yes |
| UR-62 | Gas detection alarm must be clearly | Important from the safety point of view | M | The safety personnel of TotalEnergies | Yes | Not tested |

| ID | Description | Rationale | Importance | Success criteria & Validation method | Validation results Seville | Validation results Chevron |
|---|---|---|---|---|---|---|
| | communicated to the pilot | | | and Chevron will check this requirement | | |
| UR-63 | The system must incorporate a clear and fast interface to start the emergency procedure after gas detection | Important from the safety point of view | M | The safety personnel of TotalEnergies and Chevron will check this requirement | Yes | Not tested |
| UR-64 | The operator must be able to perform small repairs and maintenance onsite (in safe areas only) | No need to send back the robotic system after minor malfunctions occur | M | The project partners must be prepared in the experiments with spare parts so that they can continue the operation even in cases of minor malfunctions | Yes | Yes |
| UR-65 | The operator must have a detailed plan for obtaining the permit to flight one year in advance of the experiments | Important for the success of getting the permits to flight in TotalEnergies and Chevron facilities | M | A detailed plan of the experiments will be completed one year in advance | Yes | Yes |
| PR-01 | The HMR must be able to land autonomously with an | This includes the automatic detection of the pipe and the | M | The HMR lands autonomously on the previously set | Yes | Not tested – HMR was not allowed to |

| ID | Description | Rationale | Importance | Success criteria & Validation method | Validation results Seville | Validation results Chevron |
|---|---|---|---|---|---|---|
| | accuracy of 5 cm with respect to the landing position | accurate relative estimation of the position of the aerial robot with respect to the pipe using on-board sensors | | landing point no farther than 5 cm from it | | fly in the refinery |
| PR-02 | The satellite robot must be able to navigate autonomously over the pipe, and within a tolerance band of 1 to 5 mm at the 12 o'clock | It is related to the construction of an exact corrosion map | M | On a representative pipeline on land, the linear advance and retraction should be repeated 10 times in 50 cm and there should be no deviation at the end greater than 2 mm. This test must be done at a 45º interval. | Not applicable to HMR with RC satellite. Addressed with Eth satellite but not integrated. | Not tested |
| PR-03 | Coupling of the ultrasonic sensor must enable continuous thickness measurement between the first and second back-wall echo | This is related to the precision of the measurement and its SNR ratio. Which must be measured at intervals of different degrees (0, 90, 180, 270º) | M | The system must keep a SNR better than 20 dB (between the backwall echo and he electronics noise). | Yes | Yes – Degraded surface condition can cause intermittent loss of signal |

| ID | Description | Rationale | Importance | Success criteria & Validation method | Validation results Seville | Validation results Chevron |
|---|---|---|---|---|---|---|
| PR-06 | The following parameters will be measured which must be in the environment of deviation of 5% (range, amplitude, bandwidth, etc.) | The results must be contrasted with the standard deviation of a commercial ultrasound equipment | | Compliance of an ultrasonic instrument to a standard means all stipulations of the standard have to be fulfilled based on EN 12668 standards | Yes | Yes |
| PR-06 | Calibration velocity with a UT block must result in a thickness measurement with no more than an error of 3% | A calibration block will be used to allow: 1) Verifying the overall functioning of the unit of measurement 2) Obtaining the two main calibration parameters a) Sound path inside the transducer 2) Calibration of the ultrasound speed in the material | M | The measurements taken by the UT sensors, once it is calibrated, have an error less than 3% of the thickness wall | Yes | Yes |

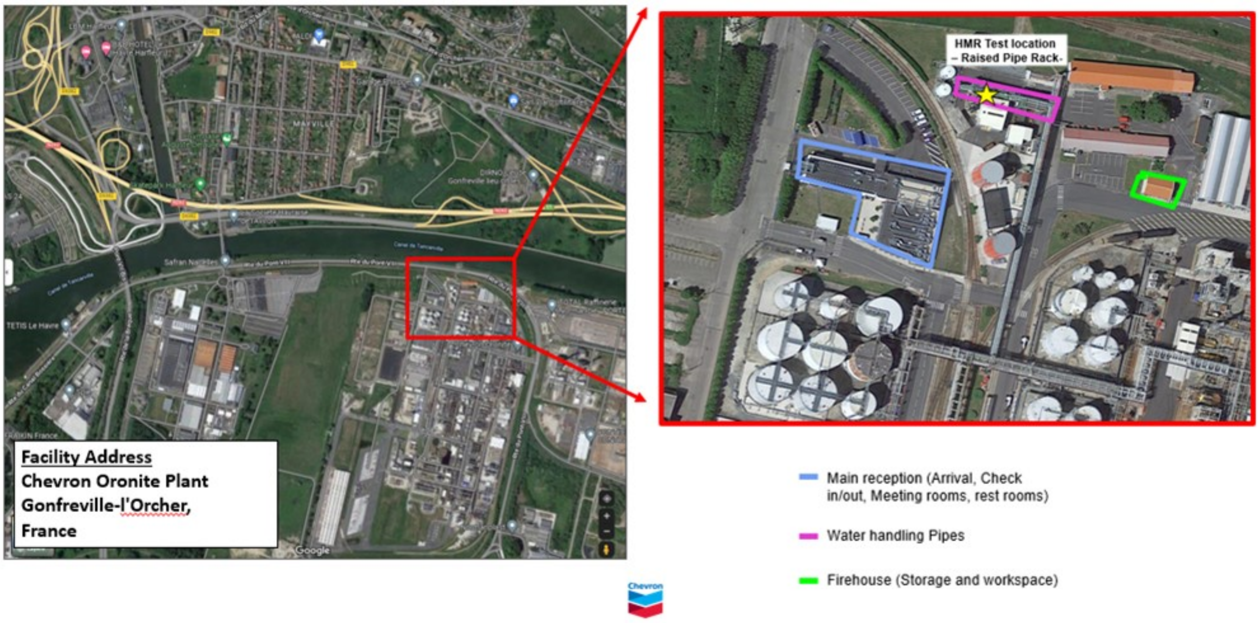
**Convention for the end user requirements**

| | |
|---|---|
| Must (M): | Must be fulfilled: Defines a requirement that has to be satisfied for the final solution to be acceptable. |
| Should (S): | Should be achieved: This is a medium-priority requirement that should be included, if possible, within the agreed delivery time. To be targeted at, shall be reviewed at each milestone. It needs justification if included or discarded, and |

| | |
|---|---|
| | there is a strong incentive to include it in a (later) industrialization, but not a Must for HYFLIERS. |
| Could (C): | This is a nice-to-have requirement (time and resources permitting), but the solution will still be accepted if the functionality is not included. |

# 9. Annex 2 – Tests locations at Chevron Oronite Facility

Testing for the HMR was conducted in the Northern part of the Oronite plant at the water pumping facility. Here we had accessible pipe work of sufficient size to test the HMR and UT Crawler robot.



# 10. Annex 3 – Risk assessment related to HMR operation

| No | Chronological phases | Means: material, human, products | Interference risks and/or released emissions | Assessment of gross risk | Enterprises Concerned | Preventive measures | Who | Evaluation residual risk |
|---|---|---|---|---|---|---|---|---|
| 1. | **Walking the COSAS plant** | Light vehicle<br><br>pedestrian | Traffic strike<br><br>Fall from the ground floor<br><br>H2S<br><br>Noisy area<br><br>Explosive atmosphere | M | | • Compliance with the traffic laws and the site's traffic plan: speed limit of 20 km/h<br>• It is strictly forbidden to park on pedestrian areas and protected crossings.<br>• Parking on the field is only allowed for the loading/unloading of equipment.<br>• pedestrians : use the site's pedestrian ways and pedestrian crossings.<br>• Wearing a hard hat, safety glasses, steel toed boots, covering work clothes.<br>• On manufacturing units and storage wearing covering antistatic, chemical protective and fire-retardant clothes.<br>• Mandatory safety brief before any intervention.<br>• Wearing an H2S detector and a leak mask per person throughout the site.<br>• Wearing hearing protection | ALL<br>ALL<br>ALL<br>ALL<br>ALL<br>ALL<br>ALL<br>ALL<br>ALL<br>ALL | L |

| No | Chronological phases | Means: material, human, products | Interference risks and/or released emissions | Assessment of gross risk | Enterprises Concerned | Preventive measures | Who | Evaluation residual risk |
|---|---|---|---|---|---|---|---|---|
| | | | | | | • Do not use or carry electrical devices or devices that can be sources of ignition: non-ATEX mobile phone, MP3 players, laptop, lighter, flashlight ...<br>• Immediately report any anomaly: torn cables, exposed wires, broken fasteners, broken or open housings ...<br>• **In explosive atmosphere areas delimited by an orange marking [e.g.], the use of equipment powered by a non-ATEX combustion engine is prohibited.** | ALL<br>ALL | |
| 2. | **Presence on site and respect for distancing rules** | Human | Coactivity | M | ALL | • Respect for barrier gestures<br>• Compliance with health rules according to the health situation of the COSAS site | ALL<br>ALL | L |
| 3. | **Unloading / Loading of equipment** | Manual handling | Tms | M | ALL | • Wearing the right PPE (hard hat, steel toed boots, safety glasses, covering work clothes)<br>• Wearing handling gloves<br>• Respect for good gestures and postures<br>• Two-man handling for heavy loads | ALL<br>ALL<br>ALL<br>ALL<br>ALL | L |

| No | Chronological phases | Means: material, human, products | Interference risks and/or released emissions | Assessment of gross risk | Enterprises Concerned | Preventive measures | Who | Evaluation residual risk |
|---|---|---|---|---|---|---|---|---|
| | | | | | | • Load port limited to 25 kg per person | | |
| 4. | **Preparation / Modification of the robot** | Manual and portable power tools | Shock<br>Bump<br>Pinch<br>Tms | M | ALL | • Wearing the right PPE (hard hat, steel toed boots, safety glasses, covering work clothes)<br>• Wearing handling gloves<br>• Compliant tooling in good condition<br>• Respect for good gestures and postures | ALL<br>ALL<br>ALL<br>ALL | L |
| 5. | **Electrical connection** | Extension cord | Electrification<br>Electrocution | M | ALL | • Extension cord in good condition and compliant<br>• Respect for good gestures and postures<br>• Favor the passages of the extensions in height<br>• Placing extension cords in dry places | ALL<br>ALL<br>ALL<br>ALL | L |
| 6. | **Using laptops** | PC | Fire<br>Explosion | M | ALL | • Wearing the right PPE (hard hat, steel toed boots, safety glasses, covering work clothes)<br>• Compliant PC in good condition<br>• Respect for good gestures and postures | ALL<br>ALL<br>ALL | L |
| 7. | **Visual inspection** | Visual | Fall on one level<br>Tms | M | ALL | • Wearing the right PPE (hard hat, steel toed boots, safety glasses, covering work clothes)<br>• Vigilance when travelling<br>• Compliance with tags | ALL<br>ALL<br>ALL | L |
| 8. | **Photos and vidéos recording** | Non-ATEX camera | Fire explosion | M | ALL | • Permission from COSAS to take photos and videos | ALL<br>ALL<br>ALL | L |

| No | Chronological phases | Means: material, human, products | Interference risks and/or released emissions | Assessment of gross risk | Enterprises Concerned | Preventive measures | Who | Evaluation residual risk |
|---|---|---|---|---|---|---|---|---|
| | | Telephone | | | | • Wearing a 4 gas detector<br>• Vigilance when walking<br>• Camera and phone in good condition and compliant | ALL | |
| **Drone flight and UT thickness measurements** | | | | | | | | |
| 9. | **Preparation of the robot for take-off and calibration of the integrated UT probe (Note: No HYFLIERS drone flights were allowed)** | Manual and portable power tools<br><br>Drone<br><br>Battery<br><br>Ultrasonic Thickness probe | Shock<br><br>Blow<br><br>Bump | M | ALL | • Wearing the right PPE (hard hat, steel toed boots, safety glasses, covering work clothes)<br>• Wearing handling gloves<br>• Compliant tooling in good condition<br>• Marking the intervention area<br>• Respect for good gestures and postures<br>• Compliance with the recommendations defined in the SDS (neoprene gloves)<br>• Laptop compliant and in good condition<br>• Standards compliant UT probe | ALL<br>ALL<br>ALL<br>ALL<br>ALL<br>ALL<br>ALL<br>ALL | L |
| 10. | **Take-off, flight with UT thickness measurements and landing (Note: No HYFLIERS drone flights were allowed)** | Drone | Fall of the drone<br><br>Collision of the drone with the installations | H | ALL | • **High potential for damage to equipment and process plant. No drone flights allowed.**<br>• Wearing the right PPE (hard hat, steel toed boots, safety glasses, covering work clothes)<br>• Obtaining the take-off authorization by telephone and/or radio<br>• The pilot of the drone must be able to present all the regulatory documents | ALL<br>ALL<br>ALL<br>ALL<br>ALL<br>ALL<br>ALL<br>ALL | L |

| No | Chronological phases | Means: material, human, products | Interference risks and/or released emissions | Assessment of gross risk | Enterprises Concerned | Preventive measures | Who | Evaluation residual risk |
|---|---|---|---|---|---|---|---|---|
| | | | | | | (identity, pilot authorization, flight authorization, drone identification papers)<br>• Strict adherence to the flight plan<br>• Personnel trained and authorized to conduct a drone<br>• Drone compliant and in good condition<br>• No use of the drone in the ATEX zone<br>• No flight over people<br>• The drone pilot must keep a constant visual with his drone<br>• Vigilance when walking<br>• Predetermined take-off and landing zones | ALL<br>ALL<br>ALL | |
| 11. | **Use of scaffolding** | Scaffolding | Fall of person<br>Falling objects | M | ALL | • After the technical acceptance of the scaffolding by the manufacturer (affixing of a green sign, filled in and signed in the left part), the company wishing to use it must check that it is authorized to use it (left part) and that it complies with its needs and safety rules. (see attached sign)<br>• This verification will be carried out by a company delegate prior to first use of the scaffolding by their staff<br>• They will fill the form by indicating the name of the | ALL<br>ALL<br>ALL<br>ALL | L |

| No | Chronological phases | Means: material, human, products | Interference risks and/or released emissions | Assessment of gross risk | Enterprises Concerned | Preventive measures | Who | Evaluation residual risk |
|---|---|---|---|---|---|---|---|---|
| | | | | | | company, their name, the date and will sign;<br>• They acknowledge that the scaffolding is fit for purpose and undertake that it will not be modified by his staff.<br>• The company that wishes a modification of the scaffolding to continue its intervention will inform the applicant (responsible for COSAS or intervening company) who will act with the manufacturer.<br>• Stakeholders must have been trained in the use of scaffolding according to the CNAMTS R408 standard<br>• It is forbidden to carry out temporary work at height when weather conditions: wind, storm, frost or snow are likely to compromise the safety or health of workers (Article R4323-68 of the Labor Code)<br>• Tagging the work area | ALL<br>ALL<br>ALL<br>ALL | |
| 12. | **Preparation of the robot and calibration of the integrated UT probe** | Manual and portable power tools<br>Drone<br>Battery<br>Ultrasonic | Shock<br>Blow<br>Bump | M | ALL | • Wearing the right PPE (hard hat, steel toed boots, safety glasses, covering work clothes)<br>• Wearing handling gloves<br>• Compliant tooling in good condition | ALL<br>ALL<br>ALL<br>ALL<br>ALL | L |

| No | Chronological phases | Means: material, human, products | Interference risks and/or released emissions | Assessment of gross risk | Enterprises Concerned | Preventive measures | Who | Evaluation residual risk |
|---|---|---|---|---|---|---|---|---|
| | | Thickness probe | | | | • Marking the intervention area<br>• Respect for good gestures and postures<br>• Compliance with the recommendations defined in the SDS (neoprene gloves)<br>• Wedge compliant and in good condition<br>• Standards compliant UT probe | ALL<br>ALL<br>ALL<br>ALL | |
| 13. | **Waste generated** | Drone propeller<br><br>Neoprene gloves | Pollution | M | ALL | • Compliance with selective sorting<br>• Dumpsters D.I.D (Hazardous Industrial Waste)<br>• Taken over and evacuated by the intervening company | ALL<br>ALL<br>ALL | L |

# 11. Annex 4 – Safety Plan (Plan de Prévention)

**PREVENTION PLAN**

Pursuant to Decree No. 92-158 of 20/02/92 Order of 19 March1993

☒ **Amendment n° initial** ☐

Date of completio 12/09/2022 ement

Operation number : 2 2

**Operation** Title : Robotic Inspection Test on Sector 5

**Purpose of the amendment** :

NEW COMPANY ☐ NEW RISKS ☐ OTHER ☐

Type of work performed during the operation :

EXTENSION OF WORK DURATION ☐
(maximum duration: 12 months)

Expected start date of the works : 12/09/2022 Foreseeable date of completion of the works : 16/09/2022

**Contact details of the COSAS** person **(s) responsible for monitoring the work:**

| **Last name first name persons responsible for monitoring the work** | The Building | Tel: |
|---|---|---|
| SOUFFLET Aurore | Operational | 0616872551 |
| | | |
| | | |

**Guarantor : Environment Department:**

| **Last Name First Name of the Guarantor** | Tel: |
|---|---|
| **LEMAITRE Julie** | 0760008808 |

| **List of interlocutors** | Tel: |
|---|---|
| **Cleaning contract** | 6 5459 |
| **Pumping contract** | 6,7849 |
| **Rubbish** | 6 7941 |

**The preliminary inspection – joint inspection isregistered on form 760VIS02. It is annexed to the prevention plan.**

**Occupational Physician** : Doctor Bérengère BELLIARD ☎ 02-35-25-55-27
7014 X 76080 LE HAVRE CEDEX

| | |
|---|---|
| For any ACCIDENT or INCIDENT (fire, pollution ...), it is necessary to alert the emergency services by dialing the following number: | **5555** |
| For any thermal or chemical burn, rinse under a safety shower for at least 20 minutes and alert the emergency services | |

| Organization of the command on the construction site |
|---|
| |

| **Responsible(s) in charge of the cleanliness of the site and waste management:** |
|---|
| |

| **Opinion of the members of the CSE/CSSCTE who participated in the preliminary visit of the prevention plan** |
|---|

*For COSAS :*

| *Name* | *SIGNATURE* |
|---|---|
| | |

*For Intervening Companies:*

| *Name* | *SIGNATURE* |
|---|---|
| | |

*Opinions of the CSE or CSSCTE :*

| |
|---|
| |

| **Coordination meetings safety prevention and inspection** |
|---|

| Planned dates | Comments |
|---|---|
| | |

| **Workstations and risks requiring enhanced individual monitoring** |
|---|

**Beware of possible medical incapacity in relation to the risks of the operation.**

| **Employees employing or exposed towork and/or risks** | **Tasks concerned** | **Companies concerned** |
|---|---|---|
| asbestos | | |
| CMR agents | | |
| group 3 and 4 biological agents | | |
| ionizing radiation | | |
| the risk of falling from a height during the assembly and dismantling of scaffolding operations | | |
| workers with a driving licence (forklift operator, driving machinery) | | |
| manual handling > 55 kg for men | | |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niveau 6 m
Vous êtes ici

## Signature for agreement on the prevention plan

The meeting begins when all participants are present.

**Attached documents**

| | | |
|---|---|---|
| | | |
| | | |

<u>Note</u> : an update of the prevention plan is mandatory as soon as the operation mentioned evolves, the phases of evolution change, new risks are introduced... A new risk analysis will be carried out (see procedure760MAC02).
<u>Intervening Companies</u> : by their signature, the representatives of the companies undertake to respect the terms of the prevention plan, **to inform their staff of the risks, the preventive measures as well as the action to be taken in the event of an accident and to** send us the sheet concerning the information of their staff.

**<u>Instructions for employees</u>**: Foreword, everyone on site must have participated in Chevron's environmental safety training. In addition, before the start ofwork, during the validation of work permits at the place of intervention, the following information will be transmitted to the stakeholders:

- the nearest telephone location and emergency call number
- the location of the nearest safety shower
- the nearest containment points
- the position of the most visible air sleeve
- the risks of the area of intervention and their preventive measures

| Name | ENTERPRISE | FUNCTION | SIGNATURE |
|---|---|---|---|
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |

***<u>Responsible</u>*** for ***<u>workx COSAS:</u>***

| Name | *SERVICE* | *SIGNATURE* |
|---|---|---|
| | | |
| | | |
| | | |