PROJECT OF DECOMMISSIONING, CONTAMINATED WATER AND TREATED WATER MANAGEMENT

DEVELOPMENT OF CONTROL ROD DRIVE HOUSING CUTTING AND REMOVAL TECHNOLOGIES

PUBLIC REPORT

October 2023

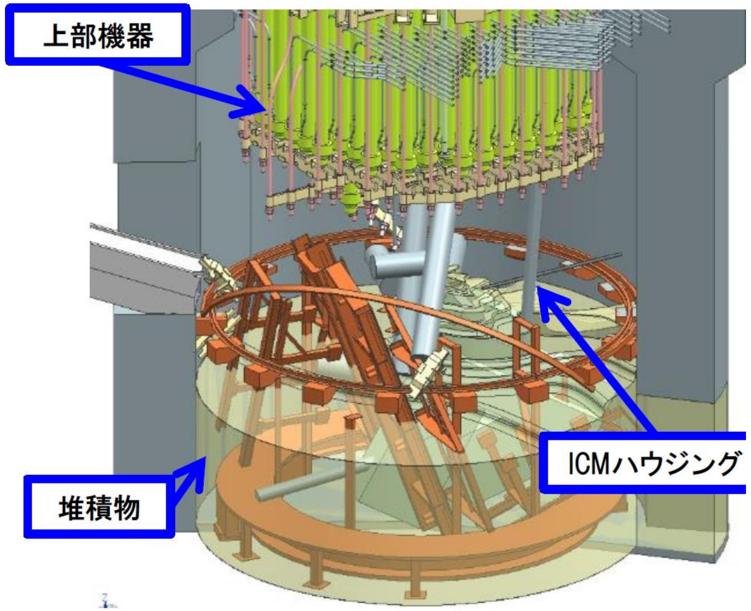
CONTENT OF THE PRESENTATION

A. BACKGROUND & PURPOSE

Why the project is needed?

CRD-H cutting and retrieval is a challenge to be addressed in the global scenario of Fukushima Daiichi damaged reactors decommissioning. Because conditions of CRD-H are deteriorated and because it is important to ensure that no fall of object can occur, these operations appear to be technically critical.

Therefore, R&D is needed to study the feasibility of a safe solution for the cutting & retrieval of CRD-H.



Irid : 平成30年度補正予算 廃炉・汚染水対策事業費補助金 技術研究組合 国際廃炉研究開発機構(IRID)「燃料デブリ・炉内構造物の取り出し規模の更なる拡大に向けた技術の開発」2020年度実施分最終報告、2021年08月

Usage of the project results:

The project results shall support the development of technologies contributing to the decommissionning of Fukushima Daiichi Nuclear Power Plant. More specifically, the results of the project shall help in the implementation of a strategy for the safe removal of the CRD-H on Units 1, 2 and 3.

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Goal of the project:

The purpose of the project is to study Control Rod Drive Housing (CRD-H) cutting and the retrieval of the cut pieces. Three different cutting techniques were already selected at the beginning of the project: disk cutter, laser cutting and Abrasive Water Jet (AWJ).

With the results of the essential tests and preliminary studies for the implementation on site, it is possible to start preliminary studies for the design of a system that can cut and retrieve the CRD-H and avoid the fall of objects and work on a complete cutting and retrieval scenario.

The goal of this project is to secure the existence of one workable scenario, as safe and efficient as possible, to remove the CRD-H.

B. GENERAL OVERVIEW OF THE PROJECT

GENERAL OVERVIEW OF THE PROJECT

Project content and progress have been determined in order to consider the whole operation of CRD-H removal. Here below the main steps (and their content) of the project are detailled:

INVESTIGATION

Content:

- Determination of the input data of the project
- Investigation of potential cutting techniques and analysis of pros and cons
- Investigation of potential solutions in order to avoid potential fall of objects

Outcomes:

- First assessment of cutting techniques capabilities
- First assessment of solutions in order to avoid the fall of objects
- Roadmap of the projects (cutting tests, operability, study of implementation)

CONFIRM THE CHALLENGES

Content:

- Essential cutting tests of CRD-H with laser technique, AWJ and disk cutter
- Essential cutting tests for the insertion of a mechanical part in order to avoid the fall of inner parts of CRD-H
- First studies of implementation on site, first scenario assessment

Outcomes:

- Confirmation of cutting tools performance
- Confirmation of performance of system to avoid the fall of inner parts of CRD-H
- Preparation of the operability tests (reachability of cutting tool on specific mock-up, operability tests on specific mock-up with remote controled robotic arm

CONFIRM THE FEASIBILITY & CONCEPTUAL STUDIES

Content:

- Reachability tests on specific mock-up in order to verify that the cutting tool can reach all the elements to be cut
- Operability tests with remote controled robotic arm in order to verify that the cuts are possible
- Complete CRD-H retrieval scenario considering results of tests and hypothesis about the situation on site

Outcomes:

- Confirmation of operability
- Performance assessment on site (time of operations, waste management, etc.)

PROGRESS OF THE PROJECT

C. ITEMS OF WORK

ITEM 1 – INVESTIGATION (INPUT DATA & FUNCTIONAL ANALYSIS)

- Verification that available input data is correclty used in the frame of the project. Functional analysis helps to determine the functions & constraints that the future system needs to comply with
- First evaluation based on operational experience to determine which tool can be efficient for the different parts that compose a CRD-H. Indeed, a CRD-H is considered to be a complex system that includes several elements such HCU, hanging rods, etc. It has been considered that several tools may be needed for the whole CRD-H decommissioning operation

ITEM 2 – ASSESSMENT OF CUTTING CAPABILITIES FOR VARIOUS CUTTING TOOLS (DISK CUTTER, ABRASIVE WATER JET, LASER CUTTING)

- Essential cutting tests in order to assess cutting capabilities of Abrasive Water Jet cutting, Disk cutting and Laser cutting

ITEM 3 – SYSTEM TO AVOID THE FALL OF OBJECTS

One of the major issues that has been highlighted is the potential fall of an object during the cutting and retrieval of CRD-H operations. Therefore, item 3 of work has been implemented so it was possible to:

- Determine and evaluate preliminary solutions to avoid the fall of object. It concerns the inner parts of the CRD-H as well as bigger parts of CRD-H
- Carry out essential tests to assess the efficiency of studied solutions (for the fall of inner parts of CRD-H only)
- Carry out preliminary studies in order to find a solution in a case of a fall of a « big » object (such as a whole CRD-H for instance)

ITEM 4 – OPERABILITY TESTS

Another major issue is the capability for the cutting tools to access the different parts to be cut. This is especially true for the external parts of the CRD-H that are close to the pedestal wall. Therefore, this item of work covered:

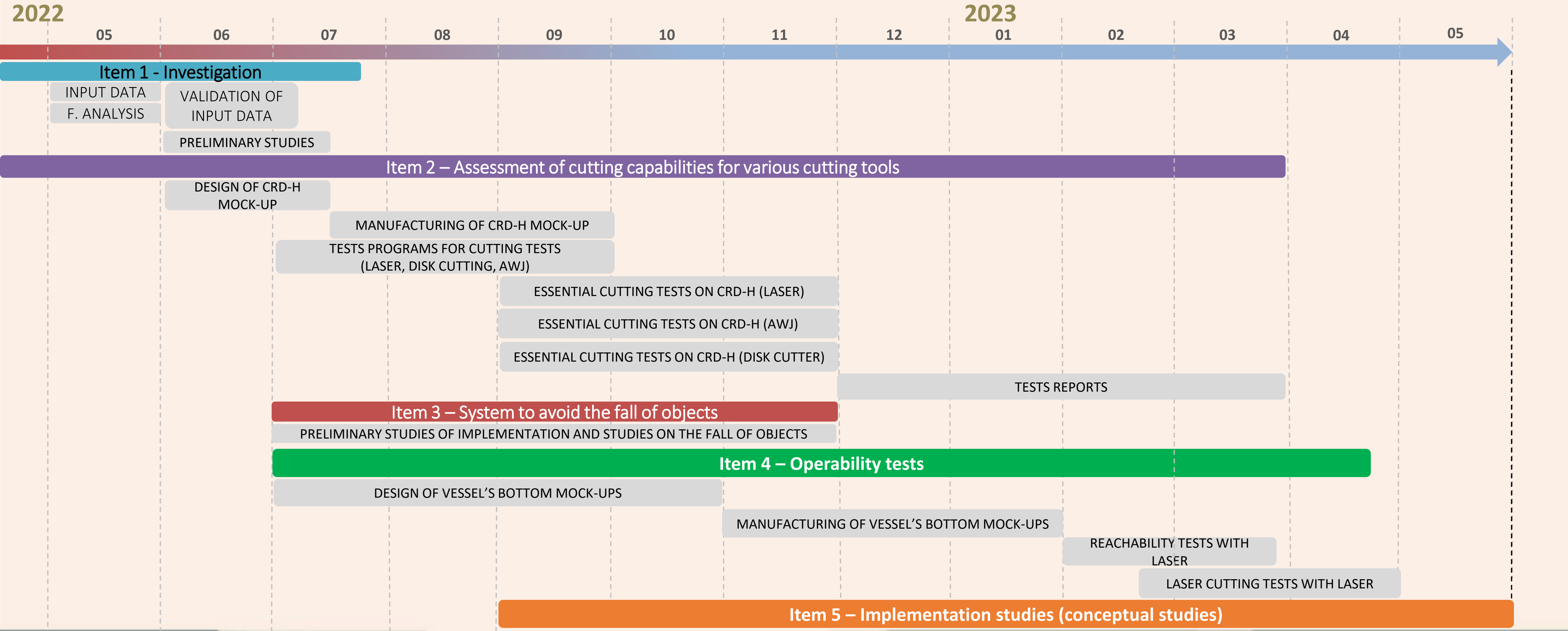
- Studies for the implementation of cutting tools in order to ensure in which conditions it is possible to implement the cutting tools
- Essential tests on a specific mock-up in order to ensure the capability of a laser cutting tool to reach every element of the CRD-H
- Operability & cutting tests in order to ensure that laser cutting is possible for every elements that compose the CRD-H with remote controled means. System to avoid the fall of inner parts has also been tested during this campaign

ITEM 5 – IMPLEMENTATION STUDIES

Following the results of the different studies and tests carried out in items 1 to 4, implementation studies have been carried out. They cover:

- Complete scenario of intervention, including downgraded situation management
- Assessment of implementation times for the whole CRD-H decommissioning scenario

D. SCHEDULE OF THE PROJECT



Item 1 - Investigation

- INPUT DATA
- F. ANALYSIS
- VALIDATION OF INPUT DATA
- PRELIMINARY STUDIES

Item 2 – Assessment of cutting capabilities for various cutting tools

- DESIGN OF CRD-H MOCK-UP
- MANUFACTURING OF CRD-H MOCK-UP
- TESTS PROGRAMS FOR CUTTING TESTS (LASER, DISK CUTTING, AWJ)
- ESSENTIAL CUTTING TESTS ON CRD-H (LASER)
- ESSENTIAL CUTTING TESTS ON CRD-H (AWJ)
- ESSENTIAL CUTTING TESTS ON CRD-H (DISK CUTTER)
- TESTS REPORTS

Item 3 – System to avoid the fall of objects

- PRELIMINARY STUDIES OF IMPLEMENTATION AND STUDIES ON THE FALL OF OBJECTS

Item 4 – Operability tests

- DESIGN OF VESSEL'S BOTTOM MOCK-UPS
- MANUFACTURING OF VESSEL'S BOTTOM MOCK-UPS
- REACHABILITY TESTS WITH LASER
- LASER CUTTING TESTS WITH LASER

Item 5 – Implementation studies (conceptual studies)

I. INVESTIGATION

1. 0. GENERALITIES

At the very beginning of the project, it is important to gather all the necessary information that will be useful for the completion of the project. Input data that are needed concern:

- CRD-H characteristics: materials, geometry (diameters (outer, inner, inner parts), list of components…)
- CRD-H area characteristics: surroundings (HCU (Hydraulic Control Unit), isolating plate, rods, bars, etc.)
- CRD-H environment: access, openings, overall geometry, pedestal conditions (water level, known state of CRD-H and vessel's bottom), etc.

These input are helpful to design a solution that could be suitable for the implementation on site. Indeed, not only it is needed to determine which cutting tool is capable of cutting a CRD-H, it is also mandatory to assess the conditions of intervention.

Following pages synthetize the input data that have been used for the completion of the project.

I. INVESTIGATION

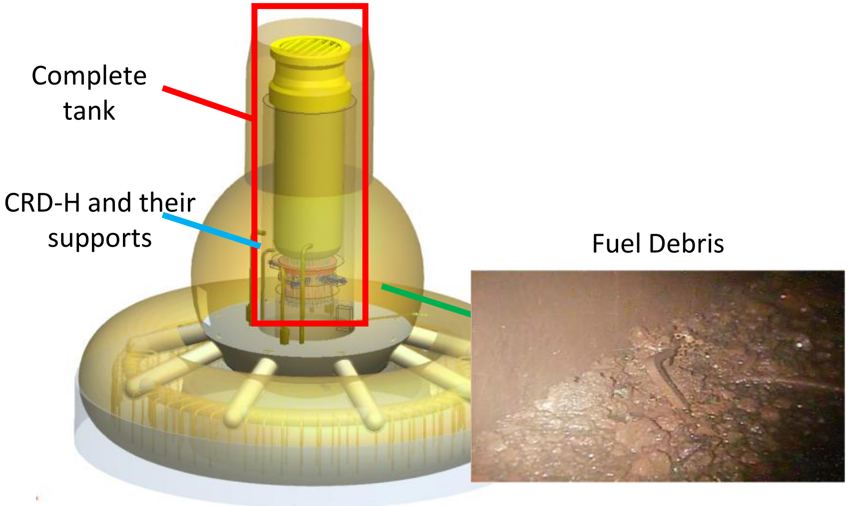
1. 1. INPUT DATA ANALYSIS

In this section of the report, we intend to synthetize the work that has been achieved in order to determine the applicable input data that have used for the whole project. Input data concern the geometry of each units, the conditions that are known on site, etc.

DATA CONCERNING THE OVERALL GEOMETRY OF PEDESTAL THAT HAVE BEEN CONSIDERED

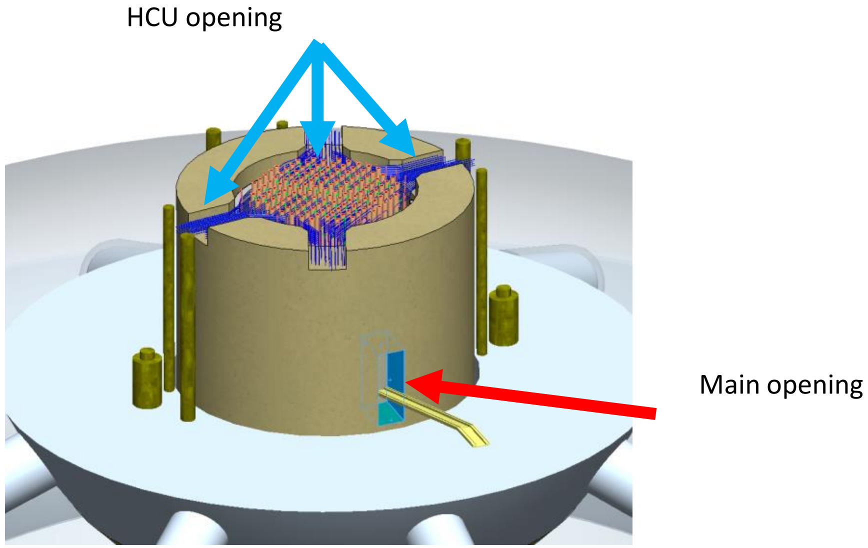
3 different units reactors

- Unit 1 is 13% smaller than Units 2 and 3
- Presence of Fuel Debris in the bottom of the pedestal
- Presence of a cooling shower system operationnal on site (water runoff from the RPV)
- The access platform to the CRD-H is destroyed and evacuated



Openings

- An opening (1 980 x 770 mm) with a ramp that lets a 1000mm opening height
- 4 openings (1 000 x 760 mm) for pipes HCU (diameter of each HCU : 25-30mm)

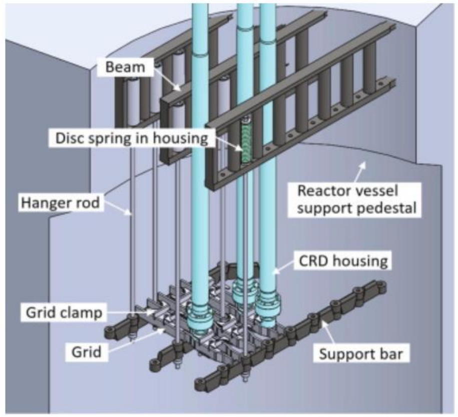


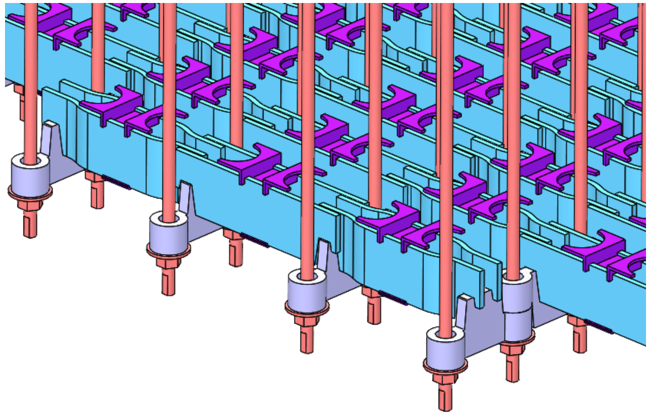
I. INVESTIGATION

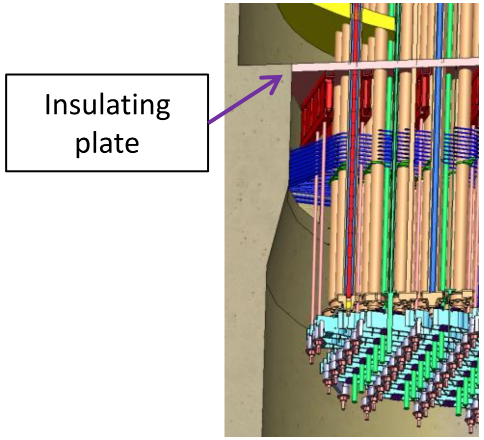
1. 1. INPUT DATA ANALYSIS

CRD-H AND NEARBY ELEMENTS

- The structure bearing CRD-H is made, from top to bottom, of : insulating plate (limit of the study scope), beam, hanger rod, a grid and support bar (each dimension has been estimated)







- 97 CRD-H for unit 1 and 137 CRD-H for units 2 and 3
- The CRD-H are welded from vessel's bottom, in suspension.
- Some CRD-H may contain Fuel Debris, and/or water but not under pressure
- Some CRD-H may have been damaged, even missing (if missing, out of study scope)
- Material housing: 304L stainless steel

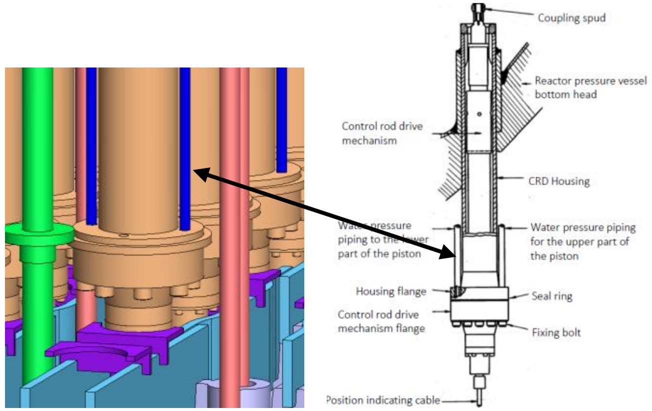
- Length from the bottom of the beam to the top of the grid: 2 500 mm
- External diameter: 152-159 mm
- Layer thickness: 13-18 mm for the most external one
- The cutting starts from the bottom

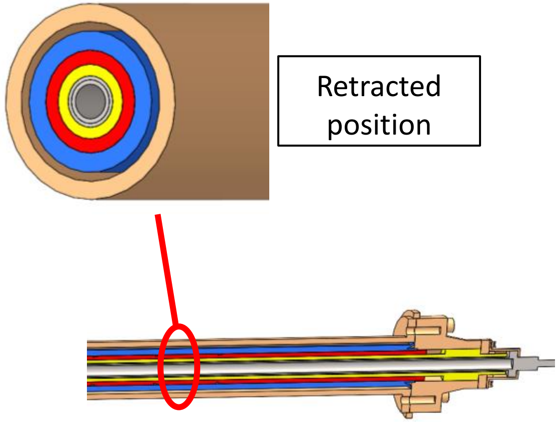
I. INVESTIGATION

1. 1. INPUT DATA ANALYSIS

CRD-H AND NEARBY ELEMENTS

- Each CRD-H has 2 HCU, probably loaded with fluids (water, contaminated water, etc.) but not under pressure
- The inner parts of the CRD-H are considered present, so the most restrictive case is considered





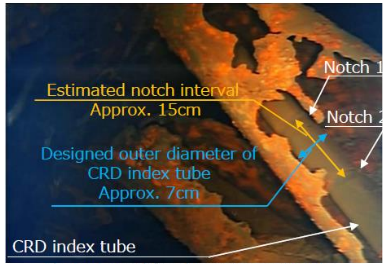


Photo 1 used for dimension estimate

Tokyo Electric Power Company Holdings, Inc.,Unit 3 Primary Containment Vessel Internal Investigatio,November 30, 2017

I. INVESTIGATION

1. 2. FUNCTIONAL ANALYSIS (SHORT SYNTHESIS)

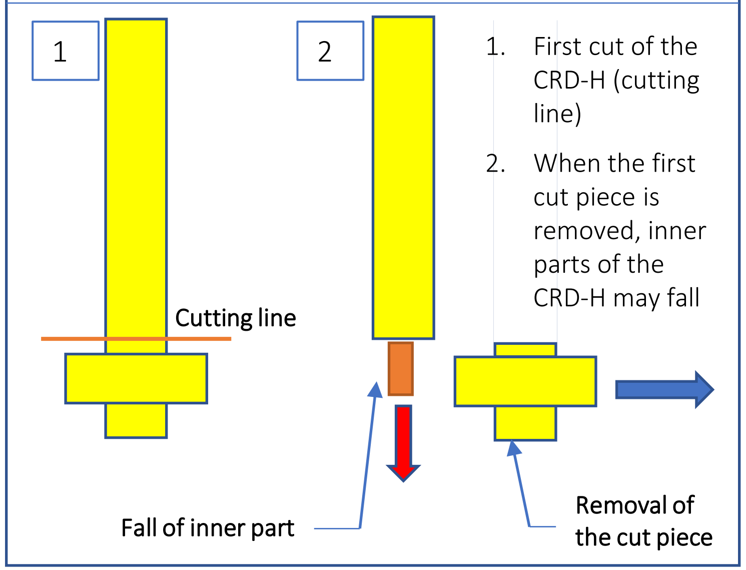
REQUIREMENTS:

- **Earthquake**: during the operations, equipment in place must not damage the pedestal barrier and the operations must stop in a safe situation
- **Fall prevention**: locally (avoiding the fall of inner parts of the CRD-H) and globally (catching up a part of a too highly damaged CRD-H, away from the CRD-H currently being dismantled)

CHALLENGES:

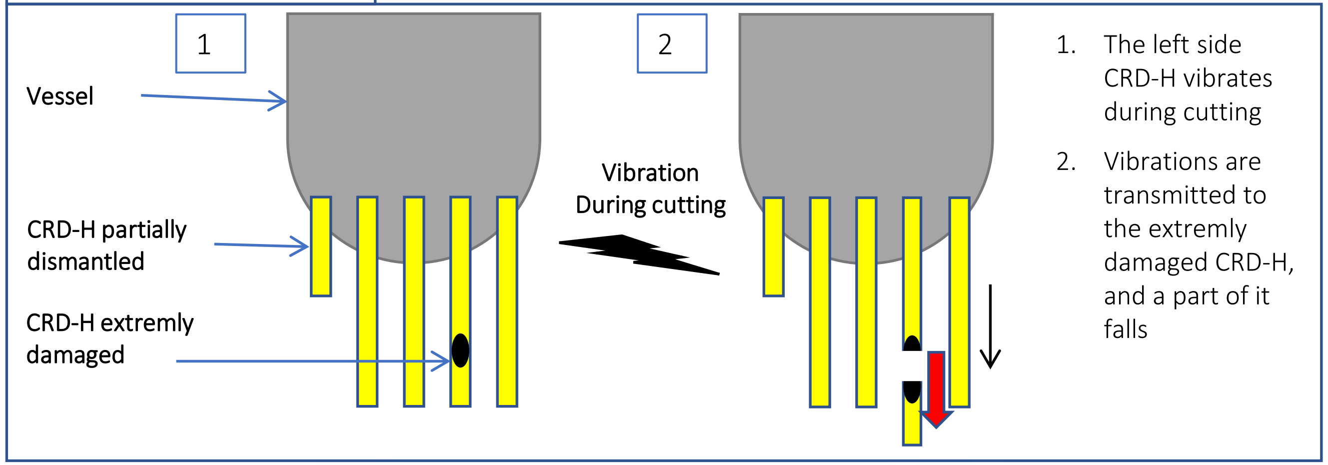
- Positioning of the cutting tool in a extremely narrow environment
- Positioning of the system for the removal of the cut piece
- Positioning of the system to avoid the fall of the inner parts of the CRD-H
- Cutting of the CRD-H, a multiple layer item, potentially filled with Fuel Debris, with a limited cutting strength
- Holding in position the inner parts of the CRD-H
- Saving a fallen part to fall at the bottom of the pedestal in the Corium
- Keeping safety barrier upstanding during an earthquake

Local fall of objects issue



1. First cut of the CRD-H (cutting line)
2. When the first cut piece is removed, inner parts of the CRD-H may fall

Global fall of object issue



1. The left side CRD-H vibrates during cutting
2. Vibrations are transmitted to the extremly damaged CRD-H, and a part of it falls

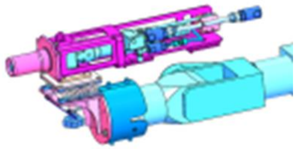
I. INVESTIGATION

1. 3. ASSESSMENT OF CUTTING CAPABILITIES FOR VARIOUS CUTTING TOOLS

Cutting a CRD-H for its retrieval not only concerns the CRD-H itself alone. In order to remove a CRD-H, it is mandatory to also consider the HCU and other surrounding elements (such as plates, grid, rod, bars, etc.).

Several cutting techniques have been considered in a first step in order to assess their capabilities depending the element to be cut that is considered. Their capabilities have been assessed considering criteria given in the next page.

LIST OF CUTTING EQUIPMENT CONSIDERED



LASER

Designed for the decommissioning of nuclear power plants, the Laser cutting head ELC-A (CEA) can withstand extremely severe working conditions.

An additional collection head under development allows the collection of airborne particles that are produced during the cutting operations.

DISK CUTTER

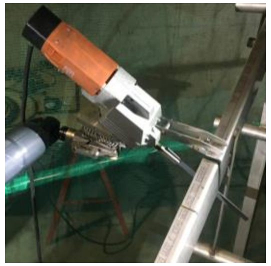
The disc cutter is a simple solution to implement. Its size depends on the disc to be used and the power to be provided. A motor creates the rotation of a disc that cuts by abrasion. The depth of cut depends on the diameter of the disc. The disc is a replaceable element.

AWJ

The abrasive water jet is a powerful tool for cutting and drilling. This process is enhanced by adding an abrasive to the working fluid to speed up the cutting of hard steels

SHEAR

A shear can be used to cut and reduce metal parts very quickly. It is a water hydraulic system. Its cutting capacity depends on its size.



SABER SAW

The sabre saw is a dismantling tool with an interchangeable straight blade. It allows a cold and slow cutting.

The control of the cutting geometry is not precise, but is sufficient for dismantling. The blade is a replaceable element (1 cut per blade).

BAND SAW

The band saw is a slow and cold continuous band cutting tool. It is a pneumatically powered tool.

For this tool developed by ONET, the cutting capacity is 100 mm x 100 mm.

I. INVESTIGATION

1. 3. ASSESSMENT OF CUTTING CAPABILITIES FOR VARIOUS CUTTING TOOLS

COMPARISON – POSSIBILITIES OF USE AND CAPABILITIES OF EACH TOOLS DEPENDING THE ELEMENT TO BE CUT THAT IS CONSIDERED

This table shows the results of the studies carried out on our different cutting equipment solutions. They are rated according to the different criteria explained in the previous page as well as their compatibility with the elements that make up the environment: CRD-Hs, HCUs and support structures.

Criteria / Solution	Ability to cut ...			Compatibility with a damaged CRD-H	Waste production	Radioactivity dispersion	Additional fire risk	Environment accessibility	Operability	Maintenance	Safety mode	OPEX (OPerating EXpense)
	CRD-H	HCU	Others structures									
Laser	Yes	Yes	Yes	○	○	△	🟩	○	○	🟩	○	○
Disk cutter	Yes	Yes	Yes	△	🟩	🟩	△	△	△	○	△	🟩
AWJ	Yes	Yes	Yes	🟩	△	△	○	🟩	○	🟩	○	△
Shear	No	Yes	Yes	❌	○	○	○	🟩	🟩	🟩	🟩	🟩
Saber saw	No	Yes	Yes	❌	○	🟩	○	○	△	○	△	🟩
Band saw	No	Yes	Yes	❌	○	🟩	○	❌	🟩	🟩	△	🟩

○ **Best fit**

🟩 **Goog fit**

△ **Medium fit**

❌ **Not Acceptable**

I. INVESTIGATION

1. 3. ASSESSMENT OF CUTTING CAPABILITIES FOR VARIOUS CUTTING TOOLS

Main conclusions of the preliminary studies for the assessment of cutting capabilities for various cutting tools are the following:

- As the table shows, it is necessary to consider not only the cutting capacity, but also various criteria such as operability, remote maintenance, waste production, etc. to fully assess the capabilities of each cutting tool
- Each tool has benefits and weak points
- Only laser cutting, AWJ and disk cutting techniques are suitable to completely dismantled a CRD-H (i.e. cutting the CRD-H itself, but also the surrounding parts)
- Other mechanical tools can be interesting for the cutting of a limited items that surround the CRD-H
- However, one major benefit of AWJ and laser cutting is precisely that they are mechanical cutting tools which ease the issues of blockage and maintenance

➡ *For the next steps of the project, only the disk cutting, the AWJ and the laser cutting techniques have been considered*

I. INVESTIGATION

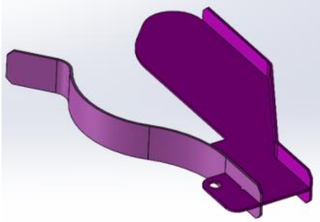
1. 4. FIRST DEVELOPMENT ABOUT THE FALL OF OBJECT ISSUE

As it is explained in §1.2 of this document, one issue of CRD-H cutting will be the fall of inner parts if there is any left. Therefore, it has been investigated several solutions to block the inner parts of the CRD-H or to mitigate the risk of fall.

LIST OF SOLUTIONS TO PREVENT THE FALL OF INNER PARTS OF THE CRD-H

PIN

The pin inserted in a hole drilled will prevent falling event of inner tubes or other large pieces inside the CRD -H.

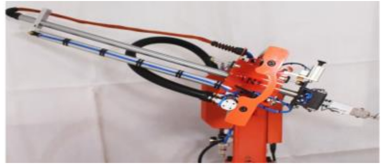


HALF-PLATE

Inserting metal plate/net in order to prevent fall off cut-out inner CRD-H elements or other inside the CRD-H foreign materials.

WELDING

This tool can be equipped directly on an arm or manipulated by a clamp. Such tools are already in use on the Marcoule nuclear research center.



RESIN INJECTION

Injection of resin or other expanding material through the opening will secure inner tubes/parts and if available any foreign material inside the CRD-H housing prior cutting procedure.

BUCKET

Placed under the CDR-H during the cutting or evacuating operations would prevent fall of cut out elements or fuel debris, internal CRD-H elements or melting compositions.

I. INVESTIGATION

1. 4. FIRST DEVELOPMENT ABOUT THE FALL OF OBJECT ISSUE

COMPARISON (SOLUTIONS TO PREVENT THE FALL OF INNER PARTS OF THE CRD-H)

This table shows the results the studies carried out on our different solutions to prevent the fall of inner parts of the CRD-H. These are rated according to different criteria as well as their installation and use requirements: whether they require cutting or drilling on the CRD-H.

Criteria / Solution	Requires an intervention …		Compatibility with a damaged CRD-H	Waste management	Risk of fall of internal elements in the CRD-H	Radioactivity dispersion	Check that the solution is effective	OPEX
	Partial cutting	Drilling						
Pin	No	Yes	🔵	🔵	🟩	🟩	🔵	🔵
Half-Plate	Yes	No	🟩	🔵	🟩	🔵	🔵	🔵
Welding	Yes	No	△	🟩	🟩	△	△	🟩
Resin injection	Yes	No	🟩	△	🔵	🔵	△	△
Bucket	No	No	△	🔵	🔵	🟩	🔵	🟩

These two solutions have been tested on later stages of the project

🔵 **Best fit** 🟩 **Goog fit** △ **Medium fit** ❌ **Not Acceptable**

I. INVESTIGATION

1. 4. FIRST DEVELOPMENT ABOUT THE FALL OF OBJECT ISSUE

Main conclusions of the preliminary studies for the assessment of preventing fall of internal parts of CRD-H are the following:

- The pin seems effective and needs to be tested
- The half-plate seems effective and needs to be tested
- These solutions can be completed by the bucket

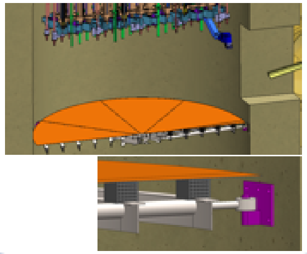
➡ *For the next steps of the project, tests have been carried out to confirm the feasibility to put in place pin or plate solution.*

I. INVESTIGATION

1. 4. FIRST DEVELOPMENT ABOUT THE FALL OF OBJECT ISSUE

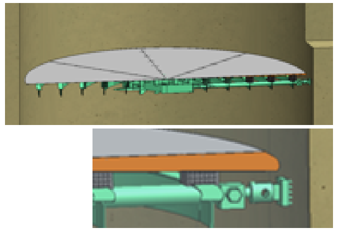
LIST OF SOLUTIONS TO PREVENT THE FALL OF GLOBAL OBJECTS

The following solutions are those selected by Onet Technologies following various studies on the global fall prevention problem.
Among these solutions, the majority are platform solutions. These platforms remain concepts, they have a similar design but are equipped with different frames.



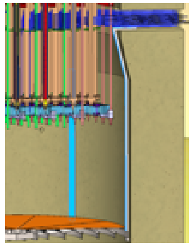
PLATFORM FIXED

Assembled on drill and spit supports previously attached to the pedestal. The frame is assembled via the robot on the supports, a damping device is fixed on it, and a set of sheet metal covers the whole.



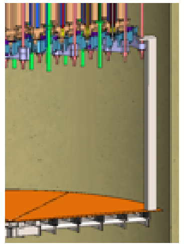
PLATFORM EXTENDED

Assembled set using actuatable extension devices on the walls of the pedestal. Brackets are placed on the pedestal beforehand. The frame is assembled by the robot using the supports.



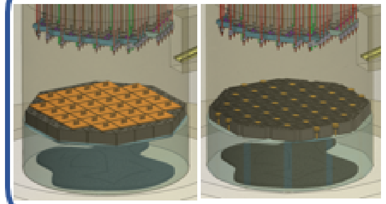
PLATFORM SUSPEND HCU

Assembled on supports placed and resting in the passage openings of the HCU. The frame is assembled via the robot on the supports, we find the damping device and the plates.



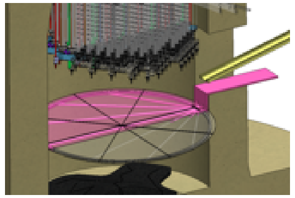
PLATFORM SUSPEND ROD

Assembled on supports placed and resting on some peripheral rod or support bar. The frame is assembled via the robot on the supports, there is the damping device and the sheets.



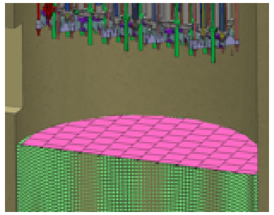
FLOATING PLATFORM

It is a platform assembled on a set of floating supports. This requires a water level above the debris. The chassis is assembled via the robot on the supports, we find the damping device and the plates.



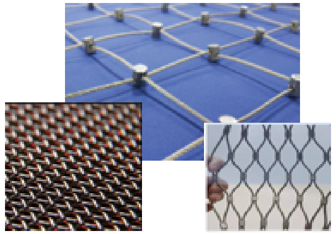
PLATFORM HELD AT PCV

Assembly fixed from the PCV using a plate linking the inside of the pedestal to the PCV. The frame is assembled via the robot onto the supports. A damping device is attached to it and a set of sheets covers it.



SHOCK-ABSORBING LAYER

Filling the bottom of the pedestal with particles (for example boron carbide balls) combined with a shock absorber system (assembly of tiles on top). The whole system absorbs all shocks and is easily maintained.



FISHNET

Flexible steel net, hung on supports previously fixed on the pedestal, via shock absorbers.

I. INVESTIGATION

1. 4. FIRST DEVELOPMENT ABOUT THE FALL OF OBJECT ISSUE

COMPARISON BETWEEN SOLUTIONS TO PREVENT THE FALL OF OBJECTS (GLOBAL)

As for the local solution for the prevention of the fall of the inner parts of the CRD-H, the table gives the notation of the different solutions listed in the previous page.

Criteria / Solution	Size of retained elements	Resistance to falling elements	Complexity of installation	Impact on the pedestal	Clutter	Complexity of dismantling	Permissible additional load
Platform fixed	○	○	□	△	○	□	○
Platform extended	○	□	□	□	○	△	○
Platform suspend HCU	○	○	△	□	△	□	○
Platform suspend ROD	○	△	△	○	△	□	□
Floating platform	□	□	○	□	○	○	□
Platform held at PCV	○	□	△	□	□	□	□
Shock-absorbing layer	○	○	○	□	○	○	○
Fishnet	□	△	○	△	○	○	△

Floating platform: Concept to be studied
In a further step

Shock-absorbing layer: Concept to be studied
In a further step

○ Best fit
□ Goog fit
△ Medium fit
✗ Not Acceptable

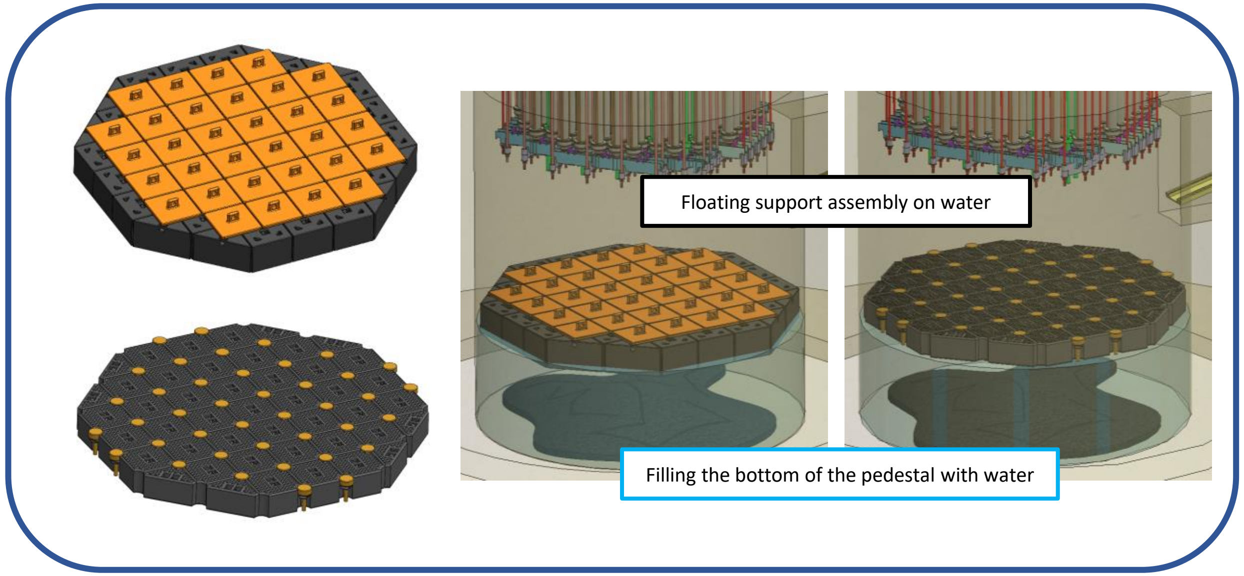
I. INVESTIGATION

1. 4. FIRST DEVELOPMENT ABOUT THE FALL OF OBJECT ISSUE

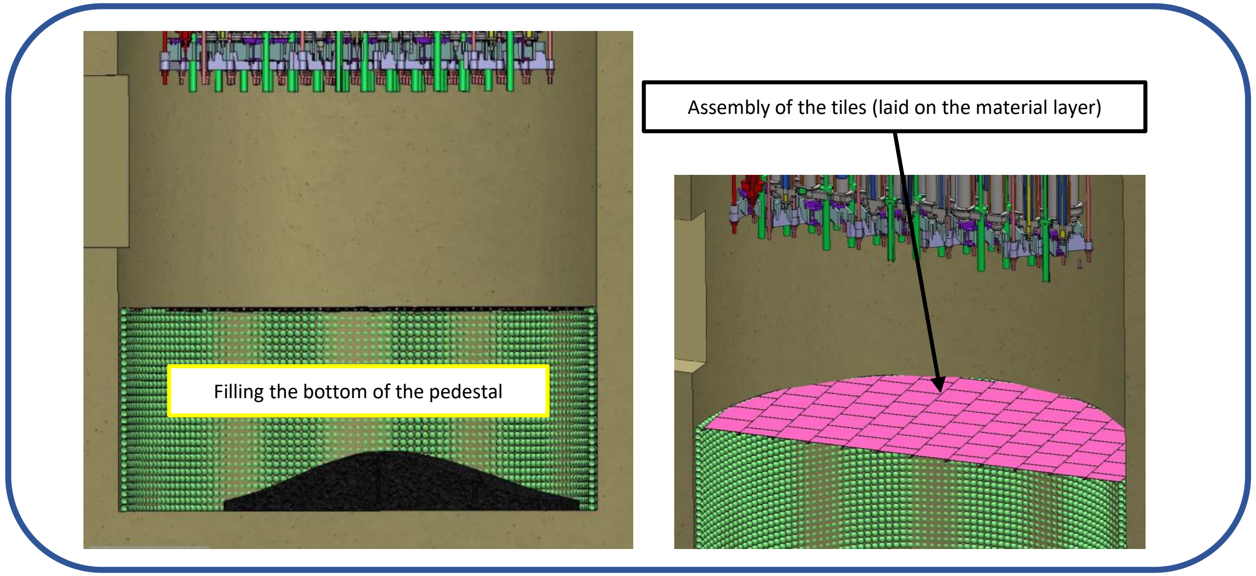
SYNTHESIS OF THE ANALYSIS: SOLUTIONS TO PREVENT GLOBAL FALL

The various studies have led to various solutions for the fall of global objects. The recommended fall arrest systems, those with the best results in the comparative analysis, are the floating platform and the shock absorption layer.

FLOATING PLATFORM



SHOCK-ABSORBING LAYER



These solutions are the most suitable according to Onet Technologies CN. They can hold elements of all sizes, resist repeated dropping of elements, are easily installed and maintained/dismantled, have little impact on the pedestal and will not interfere with the dismantling system.

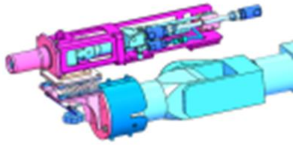
I. INVESTIGATION

1. 5. SYNTHESIS OF INVESTIGATIONS PHASE

Our different studies have led to different conclusions regarding the use of cutting tools and solutions to prevent the cut objects from falling. Each solution requires associated tests, such as cutting or drilling a CRD-H mock-up.

CUTTING EQUIPMENT COMPARISON : TEST PROGRAM

LASER



DISK CUTTER

AWJ

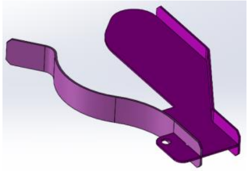
The three tools initially identified (laser, disk cutter and abrasive water jet) got no inadmissibility rating and can be compared on the 4 criteria "compatibility with a damaged CRD-H, waste management, environment accessibility, and OPEX", by the intermediary of a first series of tests, as identical as possible, on an elementary model.

Depending on the results, they may possibly be supplemented by overall tests to better estimate criteria such as accessibility, operability and degraded modes.

SOLUTIONS TO PREVENT THE FALL OF INNER PARTS OF THE CRD-H : TEST PROGRAM

PIN

HALF-PLATE



BUCKET

The prevent fall systems chosen at this stage are the pin and the half-plate.

These two systems require a preliminary operation of drilling or half-cutting before their installation.

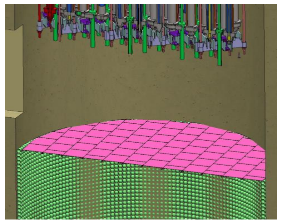
These operations will be tested on basic CRD-H models, to check their operability.

The bucket is an additional prevent fall system, that will be implemented in different phases of the scenario, to improve the efficiency

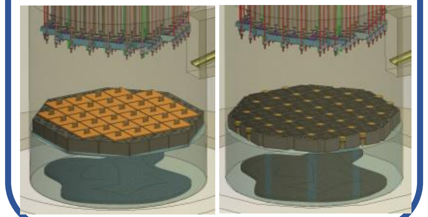
SOLUTIONS TO PREVENT THE FALL OF GLOBAL OBJETCS

Given the damaged state of several CRD-H, to guarantee the absence of falling parts on to the Fuel Debris, in addition to a local solution, it is necessary to consider a global solution of the platform type.

SHOCK-ABSORBING LAYER



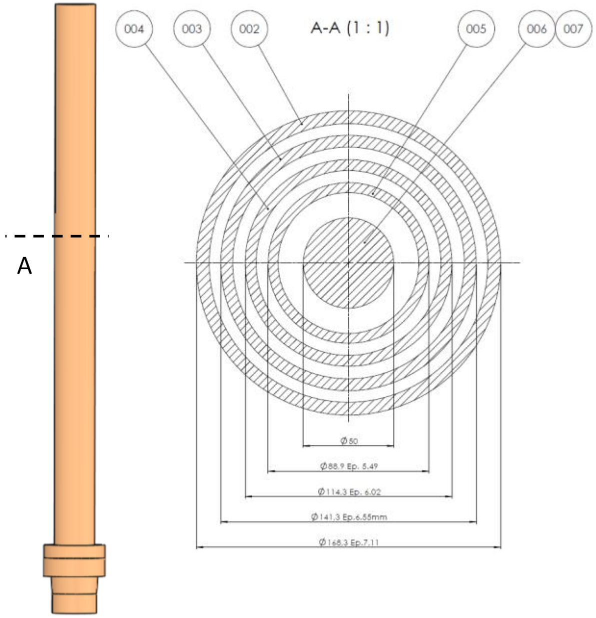
FLOATING PLATFORM



II. ASSESSMENT OF CUTTING CAPABILITIES FOR VARIOUS CUTTING TOOLS (DISK CUTTER, AWJ, LASER CUTTING)

2. 0. GENERALITIES

This phase of the project aimed at assessing the capabilities of the three identified cutting tools. More specifically, cutting performances (cutting efficiency in various conditions, cutting time, etc.) have been monitored. Cutting tests have been carried out on a simplified mock-up of CRD-H.

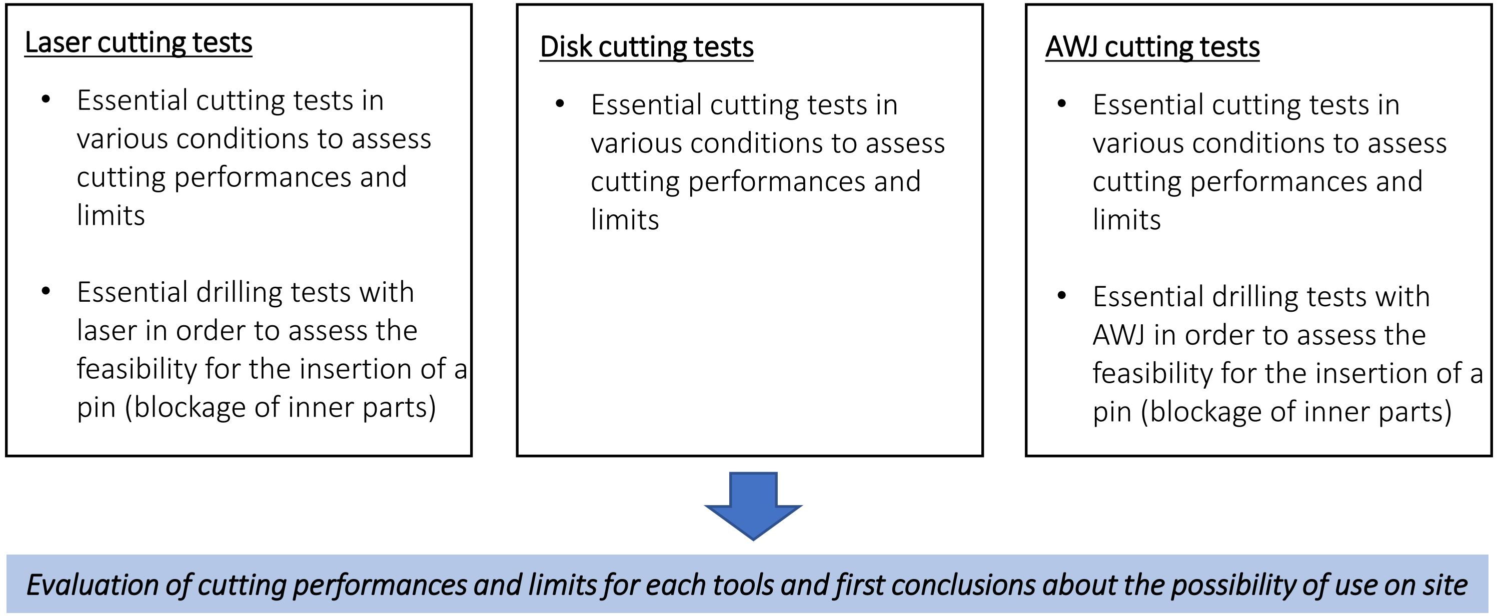


Control Rod Drive Housing and inside parts mock-up (A-A cut)

Picture of the mock-up of CRD-H for performance assessment of cutting tools

Cutting tests have been carried out on industrial cutting tools with optimized cutting parameters: it is then possible to determine the capability of a cutting tool. If the cutting test is not conclusive in lab conditions, then it is possible to conclude that the cutting tool will not be suitable for an implementation on site.

In this phase of tests, solutions for the blockage of inner parts have also been tested.



Laser cutting tests

- Essential cutting tests in various conditions to assess cutting performances and limits
- Essential drilling tests with laser in order to assess the feasibility for the insertion of a pin (blockage of inner parts)

Disk cutting tests

- Essential cutting tests in various conditions to assess cutting performances and limits

AWJ cutting tests

- Essential cutting tests in various conditions to assess cutting performances and limits
- Essential drilling tests with AWJ in order to assess the feasibility for the insertion of a pin (blockage of inner parts)

Evaluation of cutting performances and limits for each tools and first conclusions about the possibility of use on site

II. ASSESSMENT OF CUTTING CAPABILITIES FOR VARIOUS CUTTING TOOLS (DISK CUTTER, AWJ, LASER CUTTING)

2. 1. LASER CUTTING TESTS

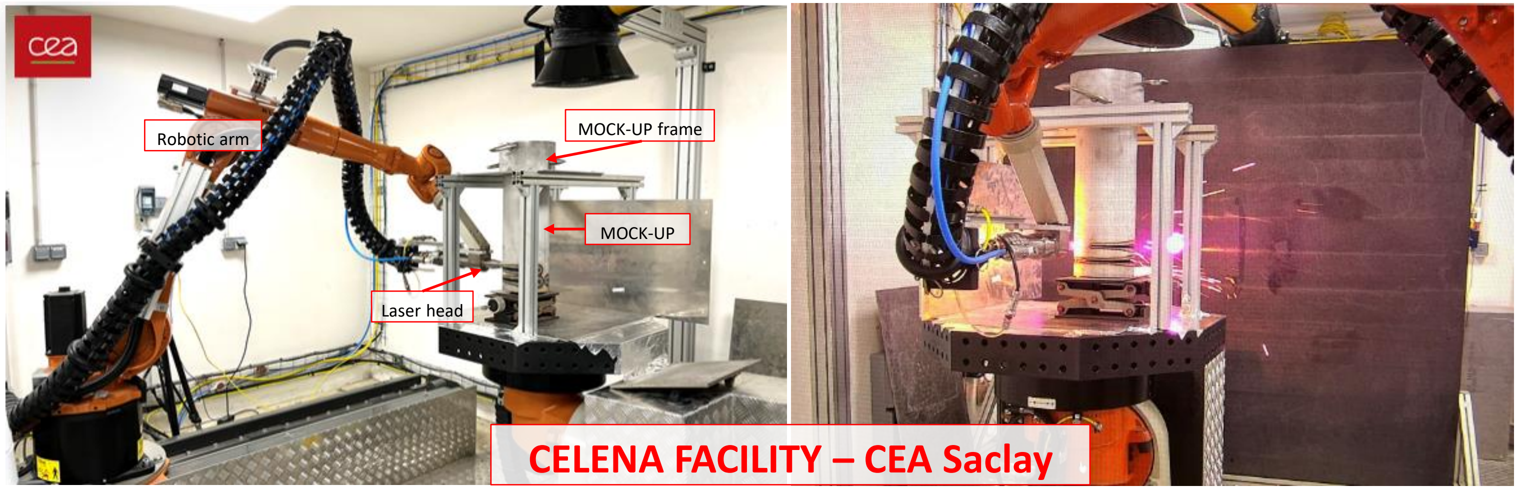
Tests carried out in **CELENA Facility** in CEA's premises at Saclay from September to October 2022

Objectives of the tests:

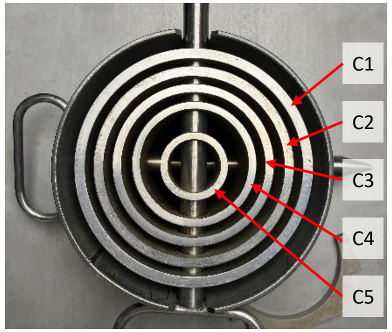
- Confirm the feasibility of CRD-H cutting with laser cutting
- Confirm the feasibility of drilling a tube with laser for the insertion of a pin (to avoid fall of inner parts of CRD-H)

Experimental Means:

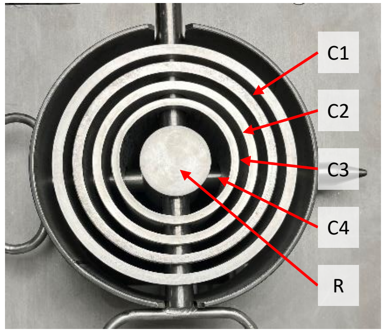
- Laser source with a maximum output power of 8 kW
- A linear motion table XYZ: BALTHAZAR
- A robotic arm: KUKA
- Cutting head: straight air-cooled head
- Pressurized air – 6 bar
- Four Mock-ups :
  - M1: 5 concentric cylinders (from C1 to C5)
  - M2: 4 concentric cylinders + a central rod (from C1 to C4 + R)
  - M3: 2 cylinders C1 + C5
  - M4: cylinder C1 + central rod R + fused cast zirconia (ZrO_2) gravel
- Mock-up mounted on a frame



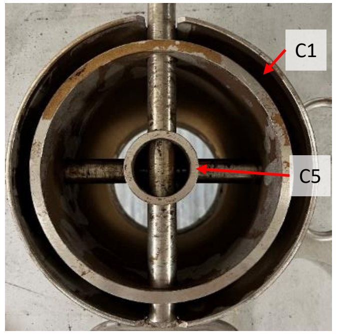
CELENA FACILITY – CEA Saclay



Mock-up M1



Mock-up M2



Mock-up M3

Mock-up M4

II. ASSESSMENT OF CUTTING CAPABILITIES FOR VARIOUS CUTTING TOOLS (DISK CUTTER, AWJ, LASER CUTTING)

2. 1. LASER CUTTING TESTS

Test program – divided in 4 steps

1.1 Feasibility tests with 8 kW laser power

- Objective : cut through a maximum diameter of a mock-up
- Tests were carried out on four mock-ups having the following characteristics:
  - M1: 5 concentric cylinders (Diameter (D) ~ 168 mm and effective thickness (T) ~ 60 mm))
  - M2: 4 concentric cylinders + a central rod, D ~ 168 mm and T ~ 100 mm)
  - M3: 2 cylinders C1 + C5 (D ~ 168 mm and T ~ 64 mm)
  - M4: cylinder C1 + central rod R + pieces of fused cast zirconia (D ~ 168 mm and T < 168 mm)

1.2 Tolerance assessment

- Parameter: only the variation of laser head – mock-up position was tested. Angle cut was not possible for the maximum available output power.
- Tests were performed on mock-up M1 with the robotic arm

1.3 Essential tests for preventing the fall of objects (pin or plate insertion to block the CRD-H’s inner parts)

I. Laser piercing

Goal : pierce a hole of 1 cm diameter for the full diameter of the mock-up

- Tests performed on mock-ups : M1 and M2
- Three configurations were tested – variable laser head – mock-up position, multi point piercing and spiral trajectory cutting

II. Cut through the half diameter

Goal : widen the laser kerf’s width to insert a plate

- Tests performed on mock-ups : M1 and M2
- Two configurations were tested

1.4 Laser cutting tests on mock-up which simulates a damaged CRD-H

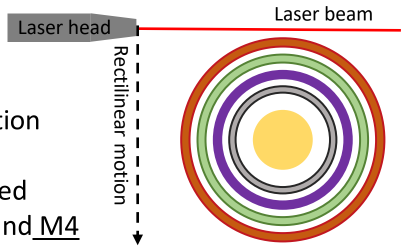
II. ASSESSMENT OF CUTTING CAPABILITIES FOR VARIOUS CUTTING TOOLS (DISK CUTTER, AWJ, LASER CUTTING)

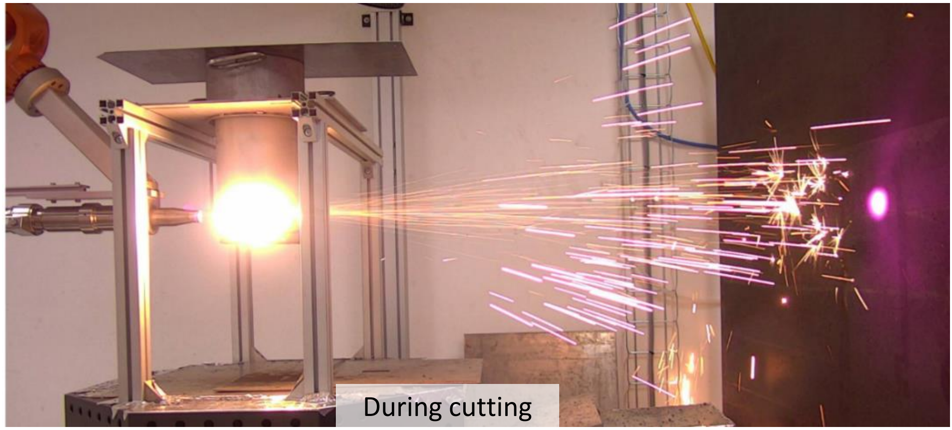
2. 1. LASER CUTTING TESTS

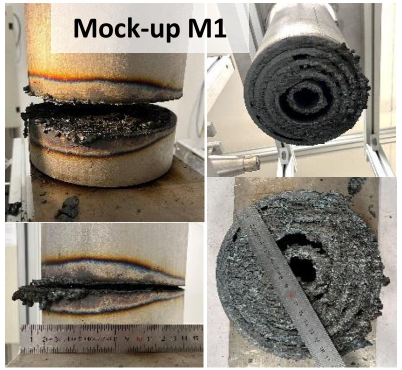
Steps 1&2: Feasibility tests with 8 kW laser power and tolerance assessment

Test conditions :

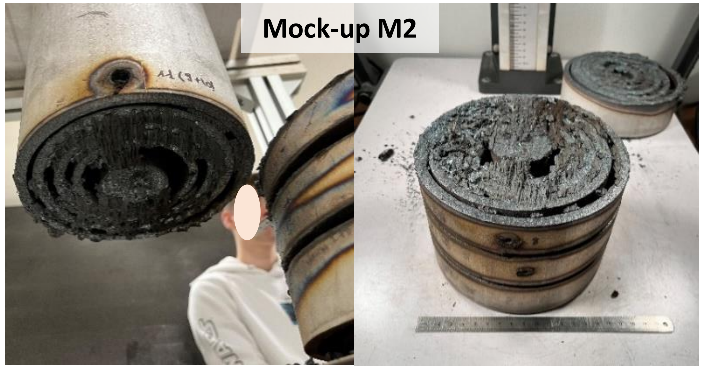
- Laser output power: 8 kW
- Variable cutting speed
- The cutting head was moved following a rectilinear motion using a KUKA robotic arm
- The cut was stop once the mock-up completely separated
- Test were carried out on four mock-ups : M1, M2, M3 and M4





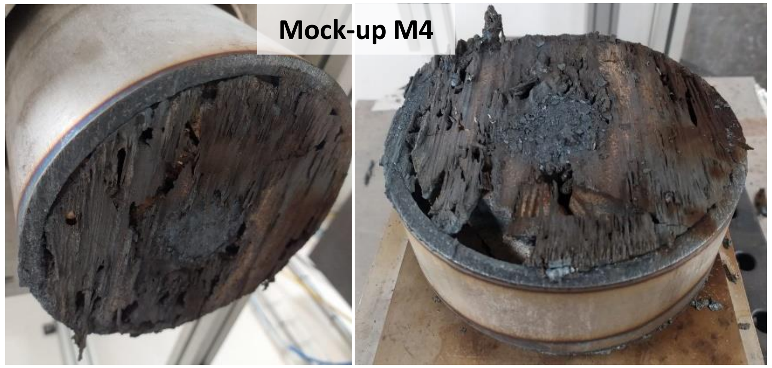


Effective thickness: **60 mm**
Cutting : **succeed**



Effective thickness: **100 mm**
Cutting : **succeed**

Effective thickness: **64.2 mm**
Cutting : **succeed**



Effective thickness: **168 mm**
Cutting : **succeed**

- All four **mock-ups were successfully cut with 8kW laser power**. There was no need to test smaller diameter mock-ups, as laser cutting was successful for the mock-ups full diameter.
- For M1, the cutting process was assessed for laser head – mock-up position. Slightly different values of the cutting speed were obtained for 10 and 20 mm positions.

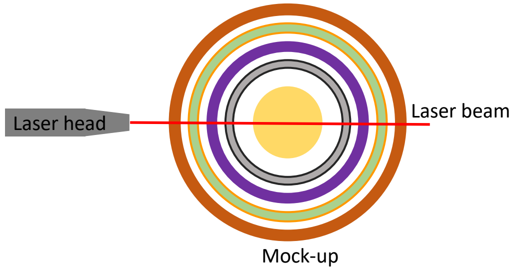
II. ASSESSMENT OF CUTTING CAPABILITIES FOR VARIOUS CUTTING TOOLS (DISK CUTTER, AWJ, LASER CUTTING)

2. 1. LASER CUTTING TESTS

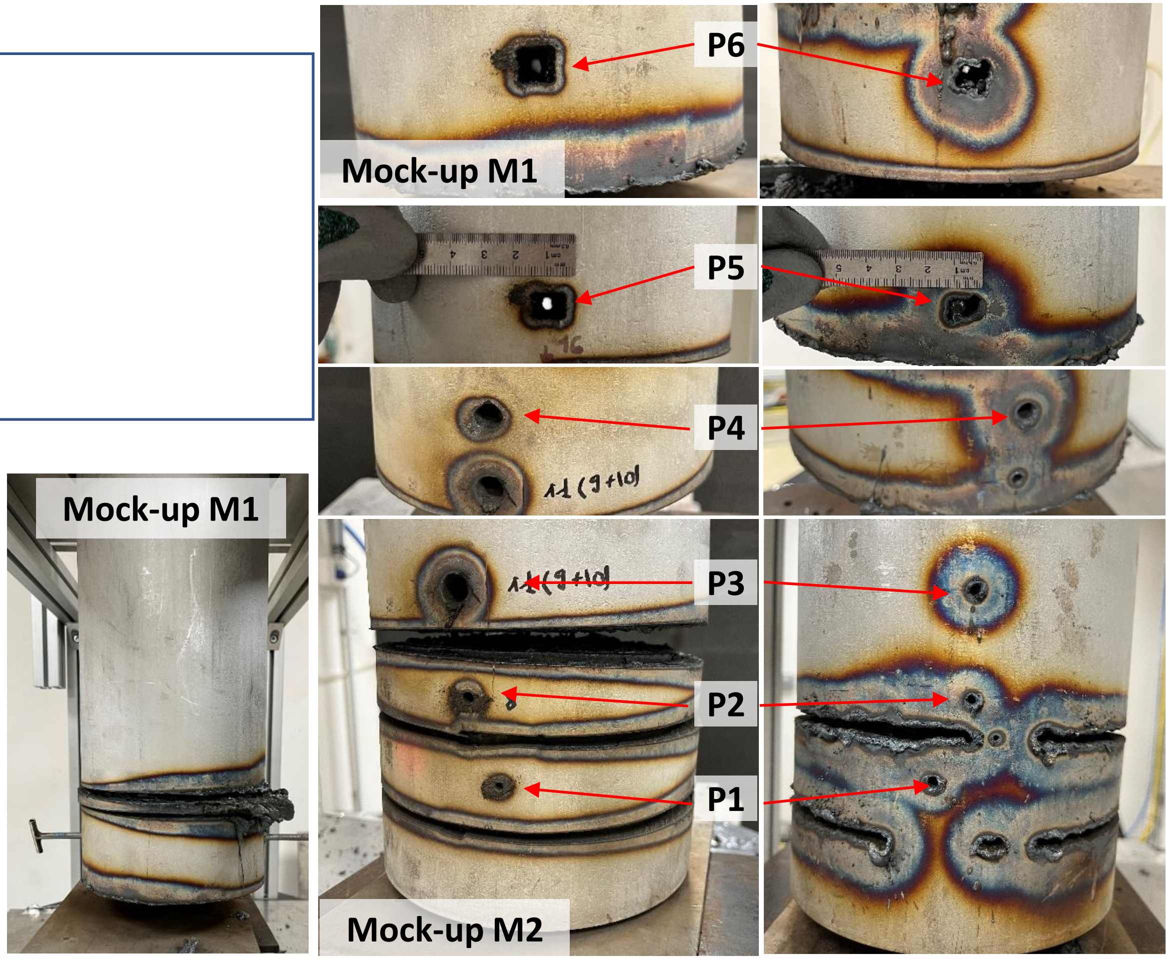
Step 3: Essential tests for preventing the fall of objects (pin insertion to block the CRD-H's inner parts)

Test conditions :

- Laser output power: 8 kW
- Pressurized air: 6 bar
- The cutting head was moved using a KUKA robotic arm following either a rectilinear or a circular trajectory
- Five kind of tests were performed on two mock-ups : M1 and M2

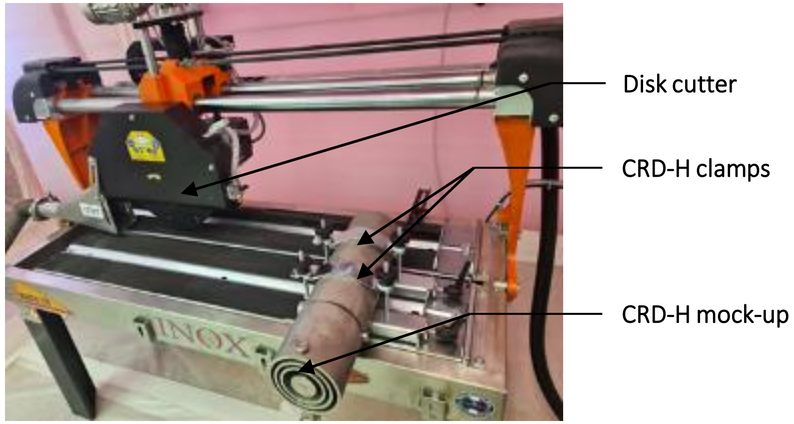


Test	Motion	D_{IN} (mm)
P1	Static piercing	3
P2	Static piercing	4
P3	Piercing - rectilinear step back of the laser head	9
P4	Cutting using circular trajectories	8
	+ rectilinear step back of the laser head + static piercing	8
P5	Multi-point piercing	~ 10
P6	Multi-point piercing	~ 10



II. ASSESSMENT OF CUTTING CAPABILITIES FOR VARIOUS CUTTING TOOLS (DISK CUTTER, AWJ, LASER CUTTING)

2. 2. DISK CUTTING TESTS



- Set-up:

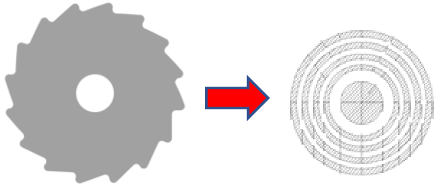
  A mock-up of CRD-H with 5 tubes of different diameter and thickness was designed for laser/disk cutter/AWJ cutting tests. For the disc tests, the largest diameter tube (168.3 mm) is not used because the equipment does not allow it. The feasibility of cutting by disc cutter is tested on a simpler configuration.

  The cutting of the CRD-H is done with an automatic disc cutter installed in a containment airlock. The machine allows to adapt the rotation speed of the disc, the cutting speed and the cutting angle.
  The CRD-H mock-up will be clamped onto the cutting table. The cutting movement will be mainly linear but tests with an angle can be done.

- Test program:

  The test program is divided in 2 steps, a first step which will allow to define the optimal cutting conditions for a simple configuration and a second step where the CRD-H will be cut in several observable configurations on site (2 fixations, 1 fixation or with an angle).

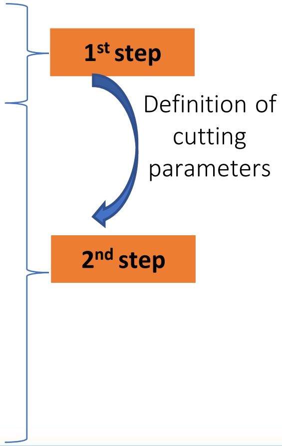
  For each cutting, the criteria analyzed are the following:
  - ☐ Possibility of cutting
  - ☐ Status of the disk (wear, breakage...)
  - ☐ Observation of a vibration on the disc and on the CRD-H



Disk 350 mm or 450 mm

Parameters of cutting:
- Disk cutter: up to 1380 rpm
- Cutting speed: 60 to 1100 cm/min
- Cutting angle: 0 to 45°

Type of tests	Objectives	Disk configuration	Number of clamps	Cutting parameters	Number of cutting
Definition of the settings	Definition of the most accurate cutting parameters	Linear	2	Variable cutting and rotation speeds (2 to 3 speeds tested)	6 (depending on the results)
Linear cutting with double fixation	Check the cut with a linear approach on a fixed CRD-H (1st cut)	**Linear**	2	Fixed cutting and rotation speeds	1
Linear cutting with simple fixation	**Check the cut with a linear approach on a CRD-H already cut or incorrectly fixed**	**Linear**	1	Fixed cutting and rotation speeds	**1**
Linear cutting half a diameter	Check the cut with a linear approach on a CRD-H partially cut	Linear	1	**Fixed cutting and rotation speeds**	1
Angular cutting with double fixation	**Check the cut with an angular approach on a fixed CRD-H**	Angular (30°)	2	Fixed cutting and rotation speeds	**1**



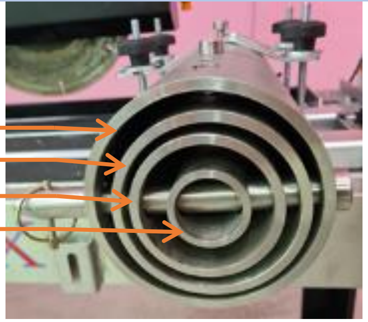
II. ASSESSMENT OF CUTTING CAPABILITIES FOR VARIOUS CUTTING TOOLS (DISK CUTTER, AWJ, LASER CUTTING)

2. 2. DISK CUTTING TESTS

BEHAVIOR OF THE INTERNAL TUBES AND ROLE OF THE HOLDING PINS WITH A KNOWN 350MM METAL DISK

The test conditions were:

- ✓ Linear cutting angle (0°)
- ✓ Use of a CRD-H mock-up with a maximum outside diameter of 141.3mm
- ✓ Use of a metal diamond disk 350 mm (because we have experience with this disk)

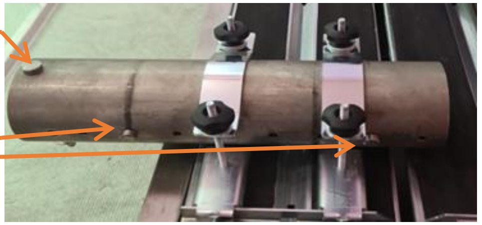


Ø141.3mm – thickness 6.55mm
Ø114.3mm – thickness 6.02mm
Ø88.9mm – thickness 5.49mm
Ø48.3mm – thickness 5.08mm

1. Impact of the means of fixation

These tests are performed with a fixed rotation speed (1380 rpm) and a fixed cutting speed (90 cm/min).

Test 1: 2 clamps + 1 vertical pin + 2 horizontal pins

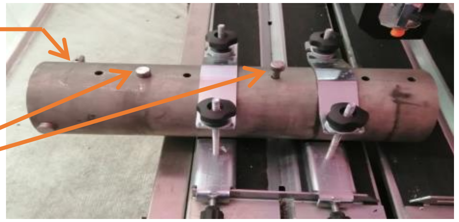


Vertical pin

Horizontal pins

➡ High vibration and blocking the disk at the end of the cutting process

Test 2: 2 clamps + 2 vertical pins + 1 horizontal pin

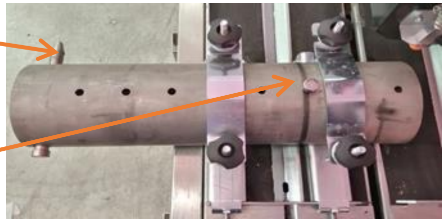


Horizontal pin

Vertical pins

➡ Successful cutting

Test 3: 2 clamps + 1 vertical pin (near) + 1 horizontal pin

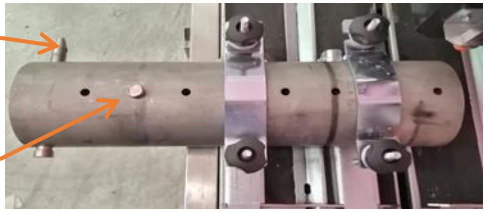


Horizontal pin

Vertical pin **near** the cutting zone

➡ Successful cutting

Test 4: 2 clamps + 1 vertical pin (far) + 1 horizontal pin

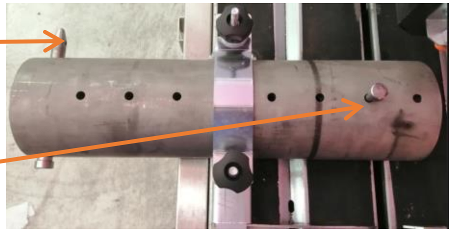


Horizontal pin

Vertical pin **far** the cutting zone

➡ High vibration and blocking the disk at the end of the cutting process

Test 5: 1 clamp + 1 vertical pin (near) + 1 horizontal pin



Horizontal pin

Vertical pin **near** the cutting zone

➡ Successful cutting

➡ In order to ensure that the disk is cut without blocking, the following fixing parameters should be used:

- mounting of **1 or 2 clamps** to hold the CRD-H in position
- Positioning of a pin **near the cut and perpendicula**r to the cutting direction to avoid displacement of the internal tubes

II. ASSESSMENT OF CUTTING CAPABILITIES FOR VARIOUS CUTTING TOOLS (DISK CUTTER, AWJ, LASER CUTTING)

2. 2. DISK CUTTING TESTS

BEHAVIOR OF INTERNAL TUBES AND ROLE OF CUTTING SPEED AND ROTATION SPEED

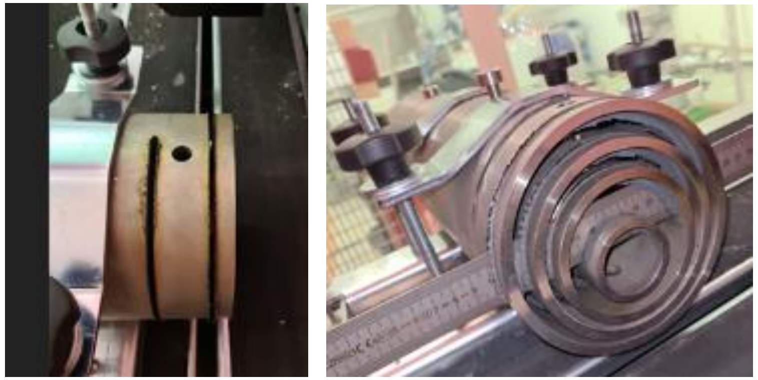
2. Impact of the cutting speed

These tests are performed with the optimal fixation means defined in step 1 (2 clamps + 2 vertical pins + 1 horizontal pin) and a fixed rotation speed (1380 rpm).

→ 2 cutting speeds are tested: 90 cm/min (minimal speed of the grinder) and 170 cm/min

Test	Speed cutting (cm/min)	Results
6	90	Successful cutting
7	170	Blocking of the disk after 7s → disk cutter stops automatically to protect the motorization

Final status - speed cutting (test 6)



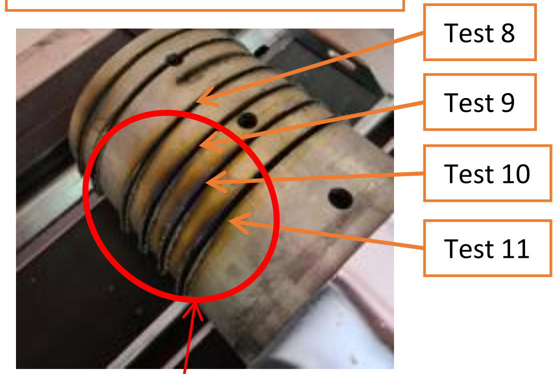
3. Impact of the rotation speed

These tests are performed with the optimal fixation means defined in step 1 (2 clamps + 2 vertical pins + 1 horizontal pin) and the speed cutting defined in step 2 (90 cm/min).

→ 4 rotation speeds are tested: 1380 rpm(maximal speed of the grinder) / 1200 rpm / 1000 rpm / 800 rpm

Test	Rotation speed	Results
8	1380 rpm	Successful cutting
9	1200 rpm	Successful cutting
10	1000 rpm	Successful cutting
11	800 rpm	Successful cutting

Final status - rotation cutting



The cutting slots show higher temperature marks as the rotation speed decreases.

➡ The decrease in speed increases the duration of the cutting time which implies a higher heating of the disk and a faster wear. It is preferable to use the speed of 1380 rpm.

II. ASSESSMENT OF CUTTING CAPABILITIES FOR VARIOUS CUTTING TOOLS (DISK CUTTER, AWJ, LASER CUTTING)

2. 2. DISK CUTTING TESTS

BEHAVIOR OF THE INTERNAL PARTS WITH A DIAMOND DISK OF 450MM

Cutting test of tubular CRD-H in the optimal condition

These tests are performed with the optimal parameters defined previously:

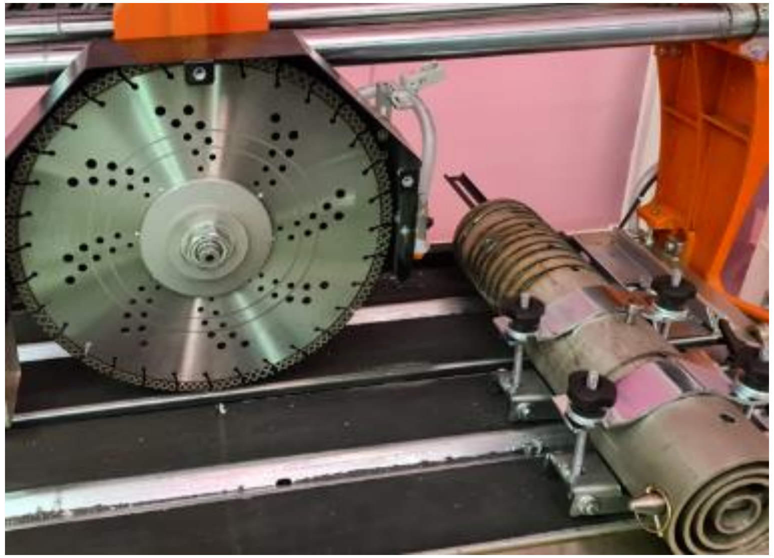
- Fixation with 2 clamps and 2 vertical pins + 1 horizontal pin
- Cutting speed: 90 cm/min
- Rotation speed: 1380 rpm

The test conditions were identical to the parameter test conditions. Only the cutting disk is different with a 450 mm diameter disk being used to allow the cutting of the CRD-H in one pass:

- ✓ Linear cutting angle (0°)
- ✓ Use of a CRD-H mock-up with 3 pipes (141.3 mm / 114.3 mm / 88.9 mm) and a bar (48.3 mm)
- ✓ Use of a disk D 450 mm with diamond teeth

Test	Conditions	Cutting speed	Rotation speed	Cutting length	Results
1	Air	90 cm/min	1380 rpm	141.3 mm	Successful cutting
2	Water cooling	90 cm/min	1380 rpm	70 mm	Cutting half of the CRD-H in 21 min → Fast wear of the disk
3	Air	90 cm/min	1380 rpm	10 mm	Very slow cutting --> the disk is damaged

Diamond disk DSL MAXX D 450 mm



The CRD-H can be cut in one pass with a secure fixation but the disk seems to degrade quickly.

The CRD-H cuttings in tests 2 and 3 could not be completed because the disk was too damaged. The disk allows only one complete cut.

II. ASSESSMENT OF CUTTING CAPABILITIES FOR VARIOUS CUTTING TOOLS (DISK CUTTER, AWJ, LASER CUTTING)

2. 2. DISK CUTTING TESTS

BEHAVIOR OF THE INTERNAL PARTS WITH A SAW BLADES OF 355MM

Cutting test of tubular CRD-H in the optimal condition

These tests are performed with the following parameters:

- Fixation with 2 clamps and 2 vertical pins + 1 horizontal pin
- Cutting speed: 90 cm/min
- Rotation speed: 1380 rpm

The test conditions were identical to the parameter test conditions. Only the cutting disk is different with a 450 mm diameter disk being used to allow the cutting of the CRD-H in one pass:

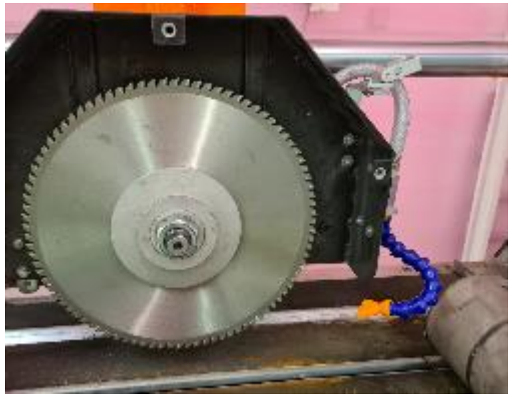
- ✓ Linear cutting angle (0°)
- ✓ Use of a CRD-H mock-up with 4 pipes (141.3 mm / 114.3 mm / 88.9 mm) and a bar (48.3 mm)
- ✓ Use of a saw blades D 355 mm with tungsten carbide teeth

Test	Conditions	Cutting speed	Rotation speed	Cutting length	Results
1	Air	90 cm/min	1380 rpm	141.3 mm	Successful cutting
2	Air	90 cm/min	1380 rpm	85 mm	Cutting half of the CRD-H → Fast wear of the disk

The CRD-H can be cut in one pass with a secure fixation but the disk seems to degrade quickly:

- **increased cutting time** on the 2nd cutting
- **early wear of the disc** with the breakage of several teeth

With the saw blade, there seems to be a higher stress on the CRD-H mock-up. This stress slightly displaces the CRD-H during the cutting process, which leads to a blocking of the disc and a wear of the teeth.


DRYTECH Saw Blades 355/90T


Complete cutting in test 1


Early wear of the disc

II. ASSESSMENT OF CUTTING CAPABILITIES FOR VARIOUS CUTTING TOOLS (DISK CUTTER, AWJ, LASER CUTTING)

2. 2. DISK CUTTING TESTS

INFLUENCE OF A CENTRAL ROD ON THE CUTTING

Cutting test of CRD-H with a central rod

These tests are performed with the following parameters:

- Fixation with 1 clamp and 1 vertical pin far the cutting zone + 1 horizontal pin
- Cutting speed: 90 cm/min
- Rotation speed: 1380 rpm
- Linear cutting angle (0°)
- Use of the Diamond disk D 450 mm

The CRD-H mock-up includes 3 tubes (141.3 mm / 114.3 mm / 88.9 mm) and a central bar of 48.3 mm.

Initial status

Test	Conditions	Cutting speed	Rotation speed	Cutting length	Results
4	Water cooling	90 cm/min	1380 rpm	141.3 mm	2 blockages of the disk: • 1 after cutting the central rod • 1 after cutting the 114.3 mm tube

A disk cutter will not cut assemblies that include moving components.

In order to allow a cutting without blocking, it is necessary to position pins and clamps near the cutting zone.

Blocking at the central bar

Blocking at pipe 114.3 mm

II. ASSESSMENT OF CUTTING CAPABILITIES FOR VARIOUS CUTTING TOOLS (DISK CUTTER, AWJ, LASER CUTTING)

2. 2. DISK CUTTING TESTS

CUTTING FEASIBILITY IN CASE OF DIFFICULTY IN POSITIONING THE CUTTING TOOL

Angular cutting test of CRD-H

These tests are performed with the following parameters:

- Cutting speed: 90 cm/min
- Rotation speed: 1380 rpm
- Linear cutting angle (30°)
- Use of a metal diamond disk 350 mm

The CRD-H mock-up includes 4 tubes (141.3 mm / 114.3 mm / 88.9 mm / 48.3 mm).

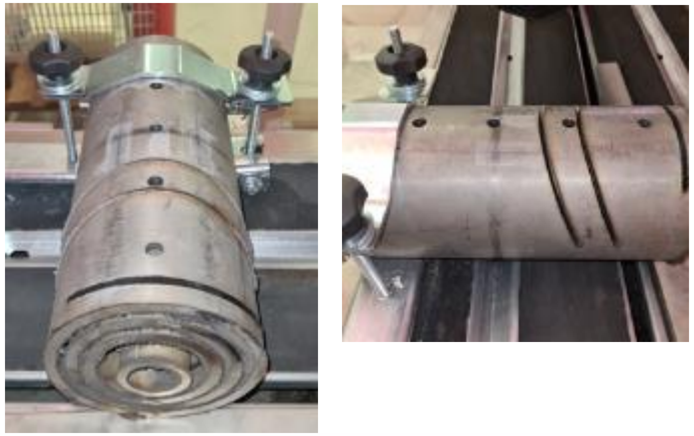
Test	Fixations	Cutting speed	Rotation speed	Cutting length	Results
1	1 clamp + 1 vertical pin (near the cutting zone) 1 horizontal pin	90 cm/min	1380 rpm	141.3 mm	Successful cutting
2	1 clamp + 1 horizontal pin	90 cm/min	1380 rpm	141.3 mm	Successful cutting

Cutting the CRD-H at an angle is possible with cutting results similar to linear cutting test.

The cutting forces are identical for linear and angular cutting.

Initial status

Final status



II. ASSESSMENT OF CUTTING CAPABILITIES FOR VARIOUS CUTTING TOOLS (DISK CUTTER, AWJ, LASER CUTTING)

2. 2. DISK CUTTING TESTS

SYNTHESIS - DISK CUTTING TEST

CRD-H CONFIGURATION:

The cutting results obtained depending on the configuration of the CRD-H are:

- Cutting achieved
  - ☐ CRD-H mock-up includes 4 stainless steel pipes (141.3 mm / 114.3 mm / 88.9 mm / 48.3 mm)
- Cutting not achieved (blockage of the disk)
  - ☐ CRD-H mock-up includes 3 stainless steel pipes (141.3 mm / 114.3 mm / 88.9 mm) and a central rod (48.3 mm)

FIXATION:

To achieve optimal cutting without blocking the disk, it is necessary to have a good clamping of the CRD-H which limits the displacement of the internal elements (clamps and pin near the cutting zone).

CUTTING PARAMETERS:

- **Limitation of the cutting speed** to prevent the disk from blocking.
- The speed of rotation has no significant impact on the cutting process. A higher speed decreases the cutting time and the temperature rise.

DISK TYPE:

Three types of disks were tested:

- Metal diamond disk 350 mm → **Cutting completed** without blocking for all configurations but only on half of the mock-up (h=80mm) / Normal wear of the disk
- Disk D 450 mm with diamond teeth
  - ☐ **Cutting completed** without blocking for configuration with 4 pipes (Full height cutting) / Fast disk wear
  - ☐ **Blocking of the disk** with the configuration 3 pipes and a central rod
- Special stainless steel saw blade of 350 mm → **Cutting completed** but a fast wear of the blade and an important stress on the CRD-H with a risk of blocking if an element is moved (CRD-H fixation to be adapted)

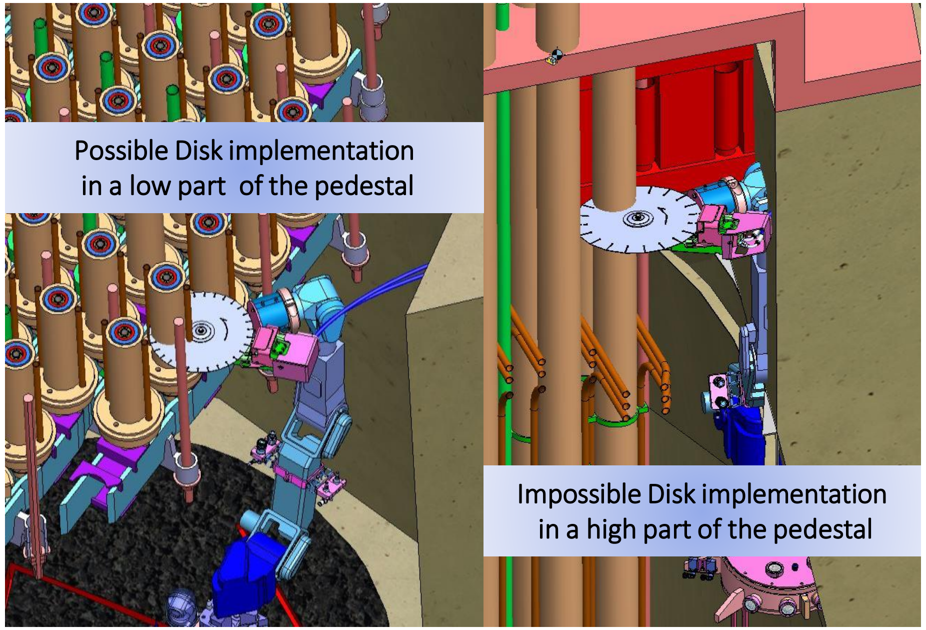
II. ASSESSMENT OF CUTTING CAPABILITIES FOR VARIOUS CUTTING TOOLS (DISK CUTTER, AWJ, LASER CUTTING)

2. 3. ADDITIONAL CUTTING TESTS WITH DISK CUTTER

CUTTING TEST WITH A SPECIFIC TREATMENT BLADE (in order to improve cutting performances):

This test leads to the same conclusion as previous tests :

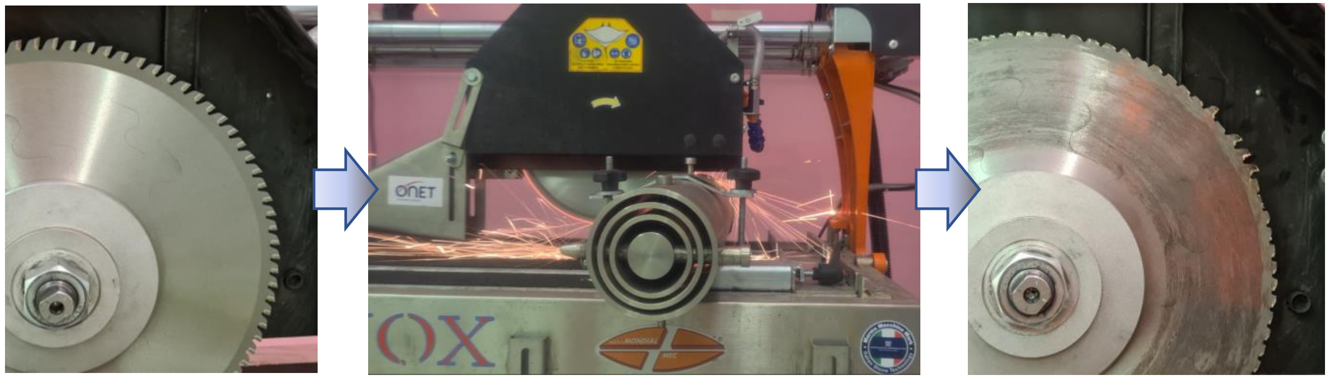
- Blockage during cutting
- Fast wear of the disk



Disk implementation along the CRD-H

Conclusion :

Disk system 450mm is too big to be set in place in many cutting configurations. Blockage risk is too high to keep disk cutting technology for CRD-H. There is no need to perform more tests. This is why only laser test will be carried done in CEA Marcoule.



Disk before cutting

Disk after cutting

DRILLING TEST WITH MECHANICAL DRILL :

Drilling was successful, but with Important vibrations during drilling. Regarding the strenght applied on the CRD-H cylinder, it seems impossible to use this technology on a damaged CRD-H

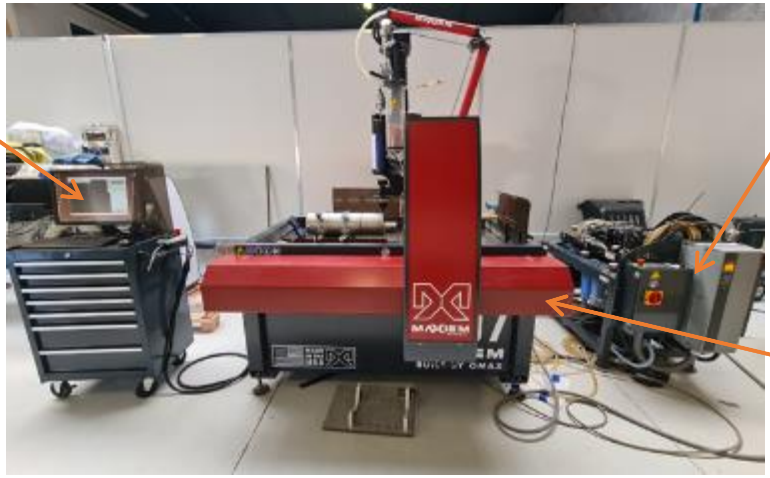
II. ASSESSMENT OF CUTTING CAPABILITIES FOR VARIOUS CUTTING TOOLS (DISK CUTTER, AWJ, LASER CUTTING)

2. 4. ABRASIVE WATER JET CUTTING TESTS

- Set-up:

The cutting tests are carried out in the OMAX facilities (specialist in water jet cutting) on a MAXIEM industrial machine.

The tests are performed on CRD-H mock-ups composed of 5 pipes (168.3 mm / 141.3 mm / 114.3 mm / 88.9 mm / 48.3 mm) or 4 pipes (168.3 mm / 141.3 mm / 114.3 mm / 88.9 mm) and 1 central rod 48.3 mm.

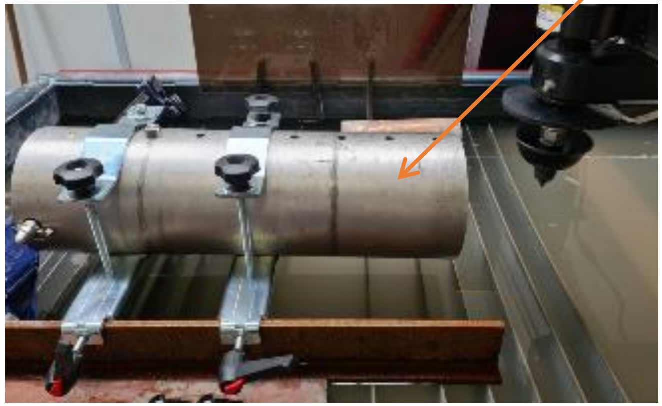


Control panel

Water pressure pump

Cutting machine MAXIEM

CRD-H mock-up



- Test program:

Test	Type of tests	Parameters to be observed
1	Linear cutting of 4 concentric stainless steel tubes	• Speed cutting • Abrasive consumption • Concentric tubes behaviour during cutting, • Pin behaviour during cutting, • Cut quality/feasibility
2	Linear cutting of 1 concentric stainless steel tubes + central rod	
3	Angular Cutting of 4 concentric stainless steel tubes	
4	Drilling of 4 concentric stainless steel + central rod	

II. ASSESSMENT OF CUTTING CAPABILITIES FOR VARIOUS CUTTING TOOLS (DISK CUTTER, AWJ, LASER CUTTING)

2. 4. ABRASIVE WATER JET CUTTING TESTS

SET CUTTING PARAMETERS

The test conditions were:

- Linear cutting angle (0°)
- Use of a CRD-H mock-up with 5 pipes (168.3 mm / 141.3 mm / 114.3 mm / 88.9 mm / 48.3 mm)
- Fixation with 2 clamps and 1 vertical pin + 1 horizontal pin

➢ Definition of the cutting speed

The variable parameter to enable waterjet cutting is the cutting speed. The water pressure and abrasive flow rate are defined by the supplier based on the equipment and feedback:

- Water pressure: 3000 bar
- Water flow rate: 3.2 L/min
- Abrasive flow rate: 320 g/min (abrasive GMA Garnet – mesh 120)

Results:

Test	Speed cutting (mm/min)	Results
1	23	Impossible to cut → non-emerging jet
2	7.75	Impossible to cut → non-emerging jet
3	4.40	Successful cutting

The optimal cutting speed is below **4.40 mm/min**.

Note: The placement of the holding pins and clamps had no effect on the cut.
Also, the waterjet near the pin did not degrade the fixation, only a slight sanding of the pin is visible.

Non-emerging cutting

Emerging cutting

II. ASSESSMENT OF CUTTING CAPABILITIES FOR VARIOUS CUTTING TOOLS (DISK CUTTER, AWJ, LASER CUTTING)

2. 4. ABRASIVE WATER JET CUTTING TESTS

CUTTING TESTS IN DIFFERENT CONFIGURATION

The test conditions were:

- Fixation with 2 clamps and 1 vertical pin + 1 horizontal pin
- Water flow rate: 3.2 L/min
- Abrasive flow rate: 320 g/min (abrasive GMA Garnet – mesh 120)

Results:

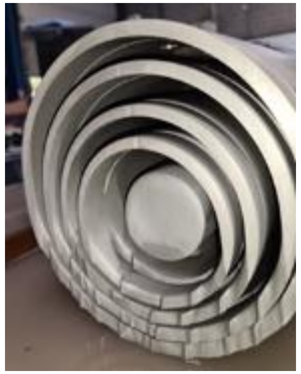
Test	CRD-H mock-up	Cutting angle	Speed cutting (mm/min)	Abrasive quantity (kg)	Results
1	5 pipes (168.3/141.3/114.3/88.9/48.3mm)	Linear (0°)	4.40	12.24	Successful cutting
2	4 pipes (168.3/141.3/114.3/88.9mm) 1 central rod 48.3mm	Linear (0°)	4.40	12.24	Partial cutting in the central zone
3	4 pipes (168.3/141.3/114.3/88.9mm) 1 central rod 48.3mm	Linear (0°)	2.75	19.58	Successful cutting
4	1 pipe 168.3mm 1 central rod 48.3mm	Linear (0°)	2.75	19.58	Successful cutting
5	4 pipes (168.3/141.3/114.3/88.9mm) 1 central rod 48.3mm	Angular (30°)	2.70	24.30	Partial cutting in the central zone

Speed reduction

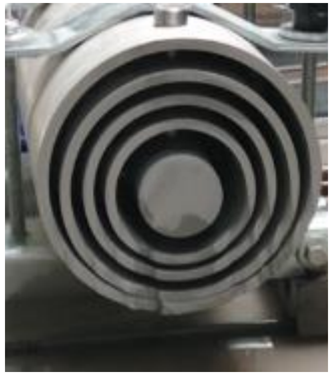
In all the cases studied, the cuts are completed or partially completed. For the partial cuts, the decrease of the cutting speed allows to realize a complete cut. CRD-H cutting is allowed but with a slow cutting speed and a high consumption of abrasive (≈ **20kg per cut**).

Note: Waterjet cutting without abrasive is not possible.

Partial cutting
Test 2

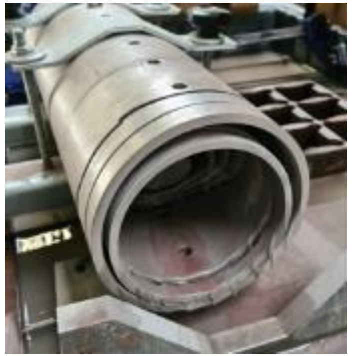


Emerging cutting
Test 3



Emerging cutting
Test 4

Partial cutting
Test 5



II. ASSESSMENT OF CUTTING CAPABILITIES FOR VARIOUS CUTTING TOOLS (DISK CUTTER, AWJ, LASER CUTTING)

2. 4. ABRASIVE WATER JET CUTTING TESTS

HOLE CUTTING TESTS

Objective:
Drill a 15 mm diameter hole to allow the insertion of a pin.

With a fixed position, the high-pressure water jet can make a hole with a diameter of 0.8 mm. To make a 15 mm diameter hole, the nozzle must be rotated (see figure on the right, position 1: starting point / position 2: end point).

The test conditions were:

- Fixation with 2 clamps and 1 vertical pin + 1 horizontal pin
- Water flow rate: 3.2 L/min
- Abrasive flow rate: 320 g/min (abrasive GMA Garnet – mesh 120)

Results:

Test	CRD-H mock-up	Cutting angle	Abrasive quantity (kg)	Results
1	4 pipes (168.3/141.3/114.3/88.9mm) 1 central rod 48.3mm	Linear (0°)	17.15	Successful cutting

The drilling of a hole by waterjet is possible but requires a precise remote operation to allow the rotation in a circle of 15 mm of the cutting nozzle.
On the front side, the cut is precise but at the exit, slight deformation appears because of the dispersion of the waterjet.
In addition, as with cutting, drilling requires a large quantity of abrasive (≈ 17kg per hole).

Initial status

Intermediate status

Final status (Top view)

Final status (Bottom view)

II. ASSESSMENT OF CUTTING CAPABILITIES FOR VARIOUS CUTTING TOOLS (DISK CUTTER, AWJ, LASER CUTTING)

2. 5. SYNTHESIS OF ESSENTIAL CUTTING TESTS

CRITERIA : test result	LASER 8 kW	DISK CUTTER 450 mm	ABRASIVE WATER JET
OPEX : cutting duration	Cutting : **succeed** On a 5 cylinders mock-up	Cutting : **succeed** On a 4 cylinders mock-up	Cutting : **succeed** On a 5 cylinders mock-up
Environment accessibility : feasibility of angular cut	Not feasible due to lack of power of laser source Will be tested again during operability tests with 14 kW laser source	Feasible	Feasible
Waste management : mass of induced waste per cut	Non significant	Wear of disk even with carbide treatment	~20 kg of abrasive/cut
Prevent fall : drilling duration	Cutting : **succeed** To be tested with 14kW	Cutting : **succeed** But with huge vibrations	Cutting : **succeed**

Main conclusions of the essential cutting tests can be summarized as following:

- The cutting of a CRD-H with disk cutter is possible only if the inner parts are blocked. If they are not, the cutting is barely possible because of the disk blockage. In any case, disks wear out very quickly which will lead to frequent disk changes on site. Furthermore, it shall be to implement a 450 mm diameter disk on site
  - ⇒ *The disk cutter solution is abandoned at this point for the next steps of the project*

- It is possible to cut efficiently a complete CRD-H with a laser cutting head. However, complete feasibility needs to be proven with the 14 kW laser head
- AWJ tests are conclusive, even if the cutting time is higher than the laser cutting time. However, AWJ produces a lot a secondary waste and presents a difficulty of implementation in some cases

III. TESTS FOR OPERABILITY ASSESSMENT

3. 0. GENERALITIES

Following the essential cutting tests, it is mandatory to evaluate the capacity of the chosen tools to be implemented on site and perform the cutting operation. Two main items need to be covered:

- The capacity of a given tool to reach the cutting positions => “Reachability tests” with representative mock-up of cutting tool, pedestal & CRD-H environment and robotic arm are needed
- The capacity of a given tool to be used with a robotic arm and perform the actual cutting operations => “Operability tests” with representative mock-up of CRD-H environment are needed. Entire cutting scenario can be tested

➡ *Tests have been carried out with laser cutting technique only*

PHASE 1 – REACHABILITY TESTS

Tests are carried out with a mock-up of a laser cutting head mounted on a robotic arm. A representative mock-up (in terms of geometry) of CRD-H environment is used

What is evaluated during this phase of tests?

✓ Ability for the laser cutting head to reach every cutting area with the help of a robotic arm in a representative environment

✗ Actual cutting operations

✗ Operability assessment with remote controled operations

PHASE 2 – OPERABILITY TESTS

Tests are carried out with a 14 kW laser source + laser cutting head mounted onto a robotic arm. Representative mock-up of CRD-H environment is used (geometry + materials)

What is evaluated during this phase of tests?

✗ Ability for the laser cutting head to reach every cutting area with the help of a robotic arm in a representative environment. (Robotic arm does not allow it in this configuration)

✓ Actual cutting operations: whole cutting scenario is carried out

✓ Operability assessment with remote controled operations

➡ *These two phases of tests cover the entire verification of the possibility of operation on site*

III. TESTS FOR OPERABILITY ASSESSMENT

3. 1. REACHABILITY TESTS

Objective:

To verify in remote operation the accessibilities and possibilities of cutting of all the components of the CRD-H. The tests were carried out on a full scale with a KUKA KR16 remote-controlled arm.

The test conditions were:

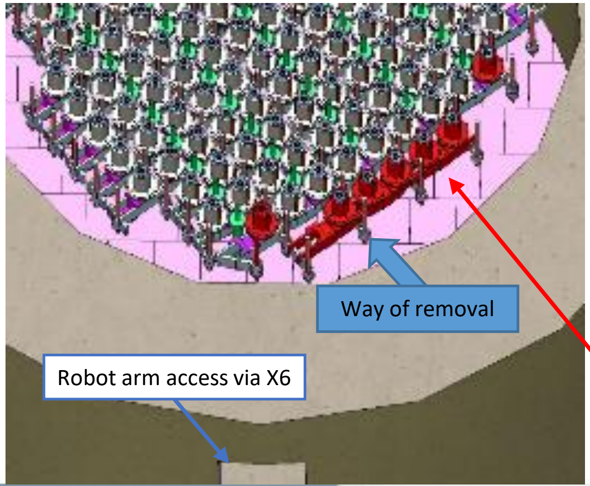
- Full scale mock-up of the CRD-H
- KUKA KR16 robotic arm
- 3D printing laser head (curved head 8 kW and linear head 14 kW)

Results:

Accessibilities were carried out according to the dismantling scenario

The remote operation tests have shown that:

- **All operations are achievable with the curved head**
- The removal of the elements close to the wall of the enclosure and the access X6 **are not achievable with the linear head** but the **other elements are then accessible with the linear head.**



Way of removal

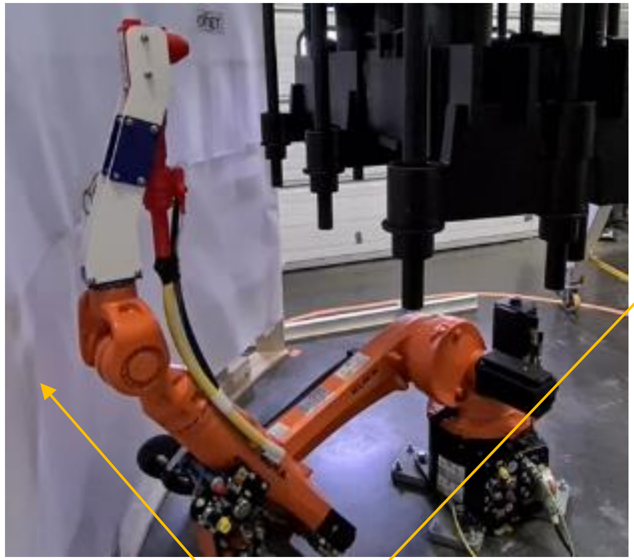
Robot arm access via X6

Curved laser head OK

Linear laser head / wall contact

In red are presented the elements not accessible with the linear laser head

Robotic arm KUKA with curved head



Robotic arm KUKA with linear head

Enclosure wall

Full scale mock-up CRD-H

Robotic arm KUKA

III. TESTS FOR OPERABILITY ASSESSMENT

3. 2. LASER CUTTING TESTS WITH REMOTE CONTROLED AUTOMATED MODES

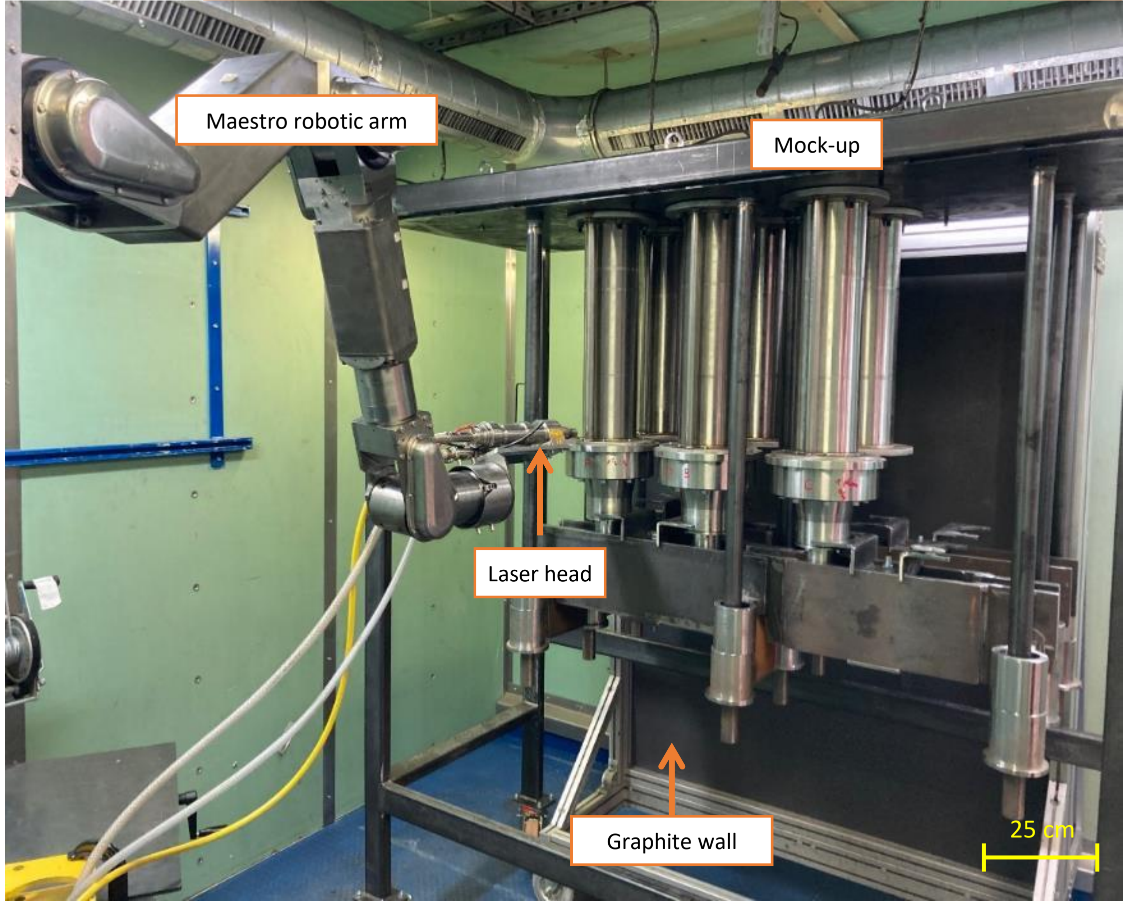
- BOTTOM VESSEL LASER CUTTING – EXPERIMENTAL SETUP

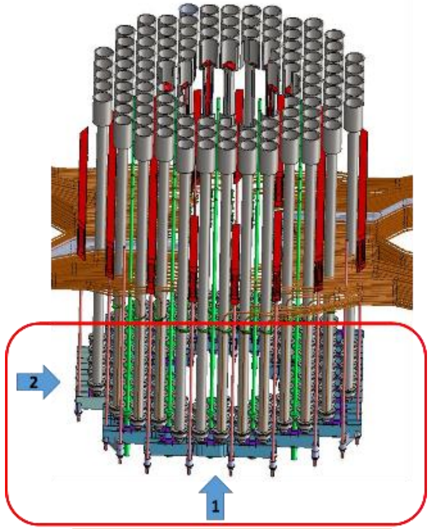
Tests carried out in HERA facility at CEA Marcoule from January to April 2023,

Experimental means:

- ✓ Laser source with a maximum power of 14 kW
- ✓ Laser cutting head : straight air-cooled head
- ✓ Pressurized air : 6 bar
- ✓ 2 PTZ camera
- ✓ Maestro robotic arm:
    - ▪ 6-axis robotic arm
    - ▪ Max payload: 60 kg / Max reach: ~1.5 m
    - ▪ 2 control modes: remote controlled with force feedback and Robotic/automatic

Cutting cell set-up (Configuration 1 of the bottom vessel CRD-H mock-up)





VESSEL BOTTOM PART

2 mock-up configuration:

Configuration 1

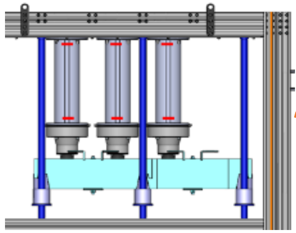
Configuration 2

III. TESTS FOR OPERABILITY ASSESSMENT

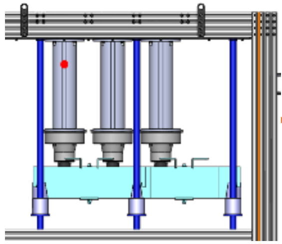
3. 2. LASER CUTTING TESTS WITH REMOTE CONTROLED AUTOMATED MODES

- BOTTOM VESSEL LASER CUTTING – TEST PROGRAM (1/2)

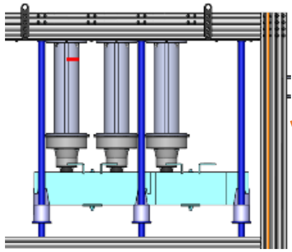
✓ Test ID 1 : Cut the HCU in front of the CRD-H



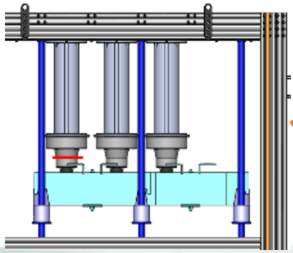
✓ Test ID 2 : Pierce a 10 mm diameter hole in a CRD-H and insert the pin-type fall prevention system in teleportation



✓ Test ID 3 : Partial cut of CRD-H (half diameter) and set up the plate-type fall prevention system in teleportation.

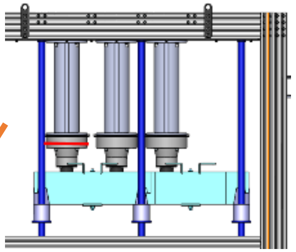


✓ Test ID 4 : Cutting of the CRD-H bottom flange

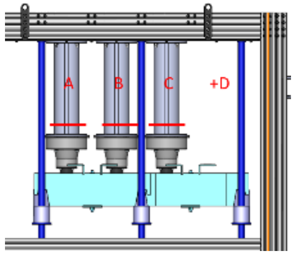


Configuration 1 of the bottom vessel CRD-H mock-up

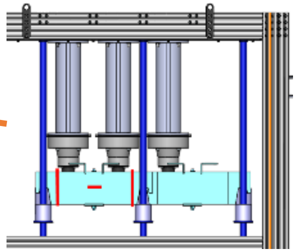
✓ Test ID 5 : Cutting of the CRD-H just above the top of the flange



✓ Test ID 6 : Cutting out the different configurations of CRD-H: A, B, C, D
✓ High thickness up to 141 mm



✓ Test ID 7 : Cutting of the grid and grid clamp and gripping test of elements in remote operation.

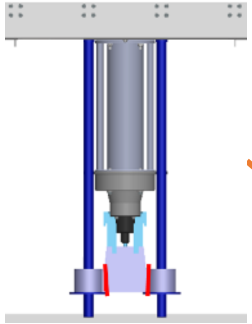


III. TESTS FOR OPERABILITY ASSESSMENT

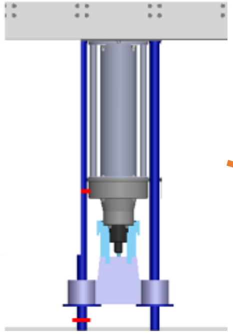
3. 2. LASER CUTTING TESTS WITH REMOTE CONTROLED AUTOMATED MODES

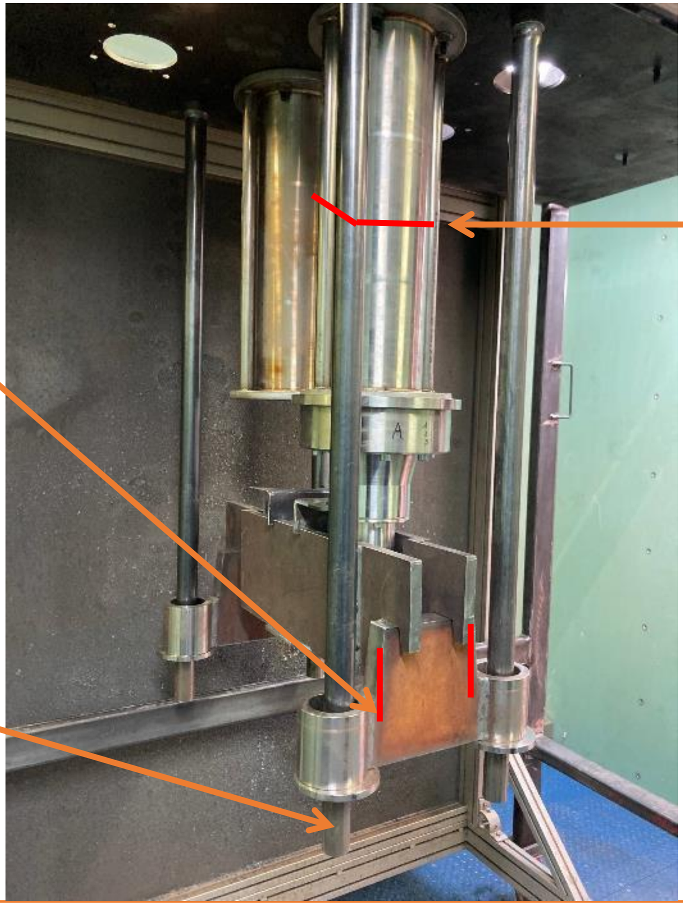
- BOTTOM VESSEL LASER CUTTING – TEST PROGRAM (2/2)

✓ Test ID 8 : Cutting of a support bar.



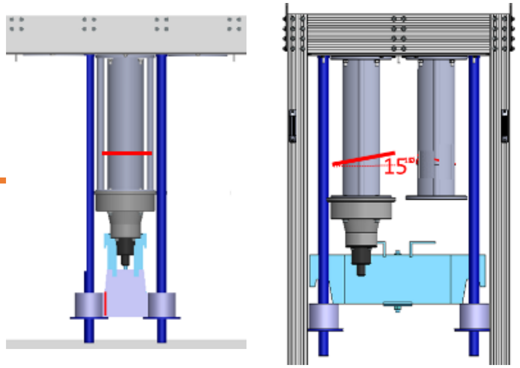
✓ Test ID 9 : Cutting of hanger rod.



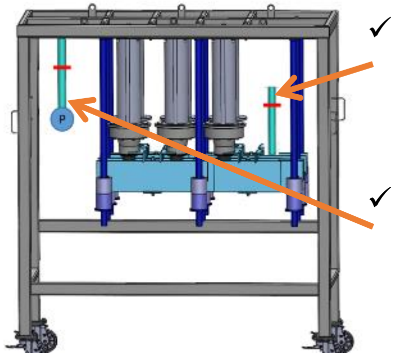


Configuration 2 of the bottom vessel CRD-H mock-up

Specific tests:



✓ Test ID 10 : Cutting with a 15° angle a CRD-H (configuration A)
✓ Thickness of 143 mm



✓ Test ID 11 : Cutting of an ICM (In Core Monitor) tube (Solid rod, 56 mm diameter) with laser at 150 mm distance.
✓ Test ID 12 : Cutting of a HCU tube filled with water. The pressure in the tube is measured with a manometer.

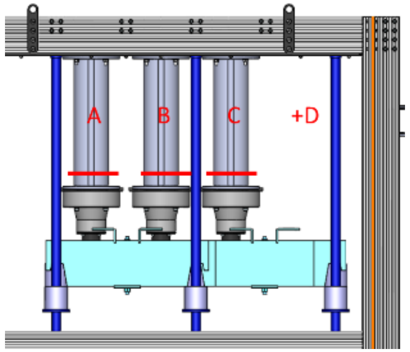
✓ Test ID 13 : Cutting of 35 mm steel plate at distances up to 500 mm.

III. TESTS FOR OPERABILITY ASSESSMENT

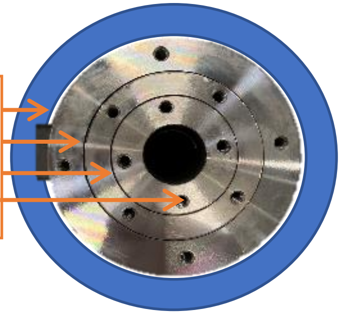
3. 2. LASER CUTTING TESTS WITH REMOTE CONTROLED AUTOMATED MODES

- BOTTOM VESSEL LASER CUTTING – RESULTS OF THE CRD-H CUTS

  - ✓ 4 configurations of CRD-H according to the presence or not of internal components.
  - ✓ All CRD-H configurations could be cut with a 14 kW laser.



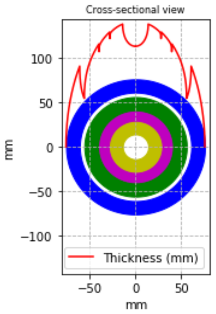
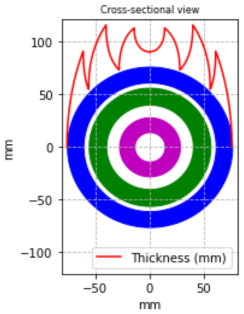
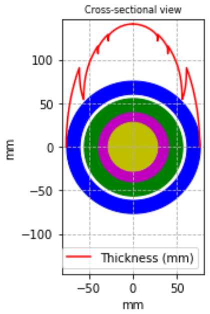
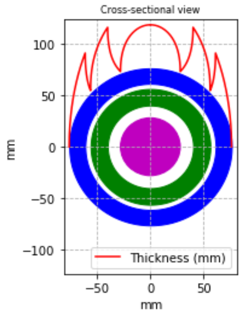
Ø152 mm – thickness 15 mm
Ø112 mm – thickness 16 mm
Ø79,5 mm – thickness 11,5 mm
Ø56 mm – thickness 14 mm



CRD-H configuration A

Cutting of CRD-H configuration A with flange

Cutting a section of the CRD-H configuration B

CRD-H configuration	A	B	C	D
Representation of the cutting profile overlaid on the corresponding CRD-H tube assembly				
Max thickness (mm)	138	115	141	118

III. TECHNICAL PROGRESS

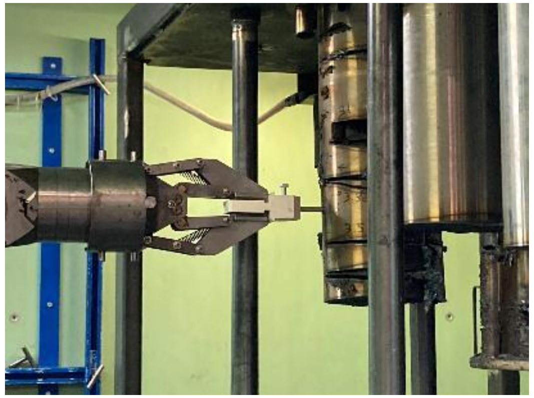
- BOTTOM VESSEL LASER CUTTING – FALL PREVENTION SYSTEM TEST RESULTS

Pierce and PIN insertion method

- ✓ Obj. : Laser drilling of a hole in the middle of CRD-H ; insert a PIN device into the hole
- ✓ Piercing Drilling : succeed
- ✓ Hole profile : Ø 13 mm at the entrance, Ø 9 mm at the exit
- ✓ PIN (Ø 8 mm) implementation in teleportation validated

Create a slot and PLATE insertion method

- ✓ Obj. : create a slot on half of the CRD-H; insert a PLATE device into the slot
- ✓ cutting (at 14 kW) : several round trips to remove adherent slag into the kerf
- ✓ Slot thickness : 3 mm
- ✓ PLATE (2 mm thick) implementation in teleportation validated

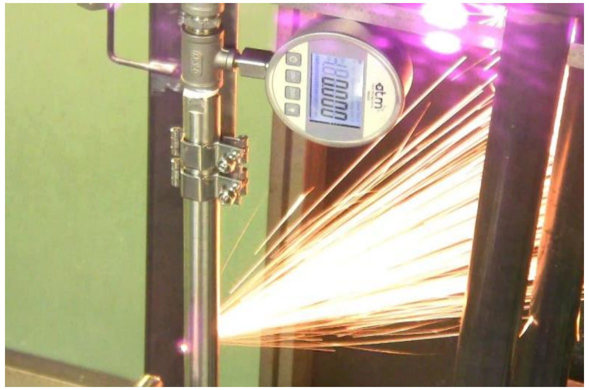


Setting up the pin-type fall prevention system in teleportation

Plate fall prevention system in place in the CRD-H

- HCU CUTTING RESULTS

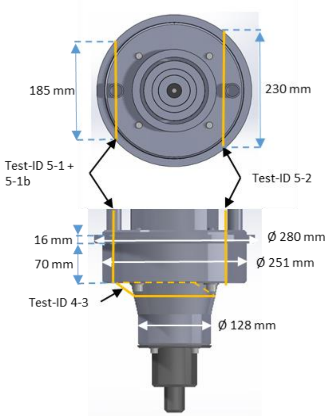
- ✓ Obj1 : remove the HCU to allow access to the CRD-H
- ✓ at normal distance (30 mm, 4 kW) / conf. 1 of the mockup : succeed
- ✓ at longer distance (100 mm, 4 kW) / conf. 2 of the mockup : succeed
- ✓ at the maximum distance tested (830 mm, 14 kW) : succeed
- ✓ Obj2 : Draining the CRD-H if water is present -> Cutting of HCU filled with water
- ✓ Measure the pressure inside the tube during cutting -> max 423 mbar at 4 kW



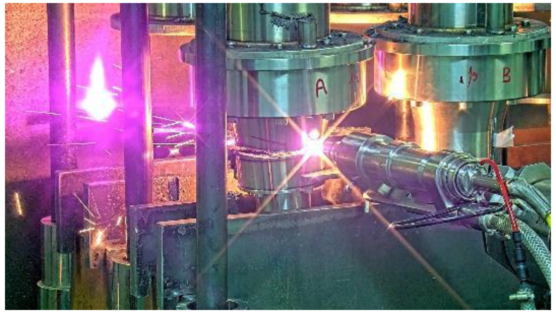
HCU filled with water and instrumented during cutting

III. TECHNICAL PROGRESS

- <u>BOTTOM VESSEL LASER CUTTING – FLANGE CUTTING TEST RESULTS</u>
  - ✓ <u>Obj</u>.: lighten the flange before separating it from the CRD-H
  - ✓ Cutting as close as possible to the top part of the flange -> Ø150 mm at 14 kW / ~ 11 kg removed
  - ✓ The cut in the upper flange diameter is too thick (Ø250 mm) to be done with a 14 kW laser
  - ✓ Lateral cutting of the upper part of the flange (185 mm max. thickness) at 14 kW / ~ 2 kg removed
  - ✓ After separating the flange from the CRD-H, the lightened flange assembly weighs ~ 39 kg



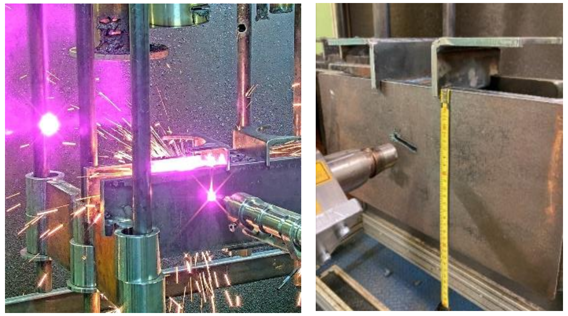
Flange cutting plan



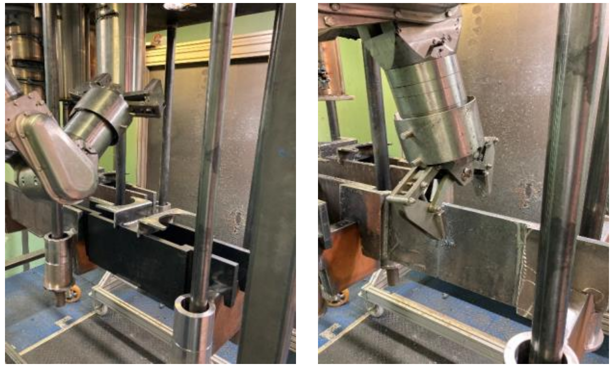
Cutting of the bottom flange part

Long distance cutting test

- <u>GRID CUTTING RESULTS</u>
  - ✓ <u>Obj</u>.: remove the grid
  - ✓ Several strategies tested:
  - Cut the grid in 2 parts at once (2 plates at the same time) at 8 kW : succeed
  - Recover the whole grid assembly without cutting it
  - Separate the 2 grid plates by cutting the holding screw through the first plate : drill and cut at 14 kW : succeed
  - ✓ The different elements of the last 2 strategies were recovered with a teleoperated clamp

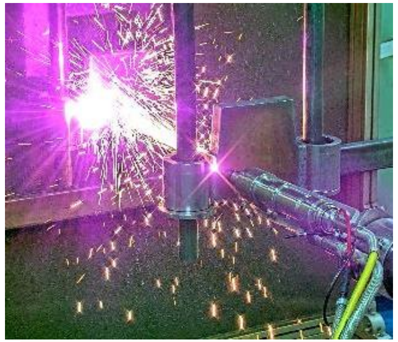


Cutting of the grid part
Left: cut in 2 part
Right: release the grid clamp

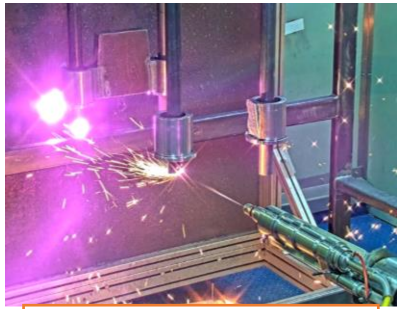


Remote gripping operation on the grid

- <u>SUPPORT BAR AND HANGER ROD CUTTING RESULTS</u>
  - ✓ Support bar cut at 14 kW for a thickness ~ 50 mm : succeed
  - ✓ Hanger rod cut at a distance of 300 mm (accessibility constraint) at 14 kW: succeed



Cutting of the support bar



Cutting of the hanger rod

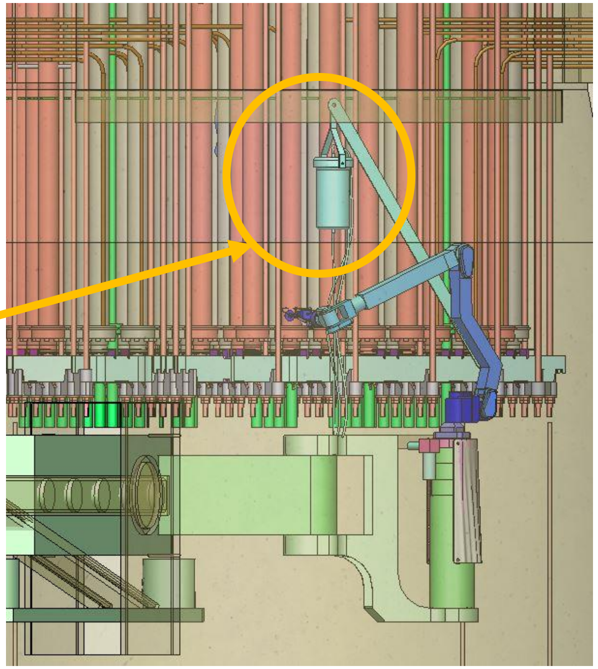
III. TESTS FOR OPERABILITY ASSESSMENT

3.3. SYNTHESIS OF CUTTING TESTS : UPDATE with operability tests results

CRITERIA : test result	**LASER 14 kW**	LASER 8 kW	DISK CUTTER 450 mm	ABRASIVE WATER JET
OPEX : cutting duration	Cutting time : **7-15 min**	Cutting time : 17 min	Cutting time : 11 min	Cutting time : 38 min
Environment accessibility : feasibility of angular cut	Feasible	Not feasible due to lack of power of laser source	Feasible	Feasible But many difficulties to manage the abrasive jar
Waste management : mass of induced waste per cut	Non significant	Non significant	Wear of disk	~20 kg of abrasive/cut
Prevent fall : drilling duration	Cutting time : **6,5 min/hole**	Cutting time : 16 min/hole	Cutting time with a drill : 6 min/hole But with huge vibrations	Cutting time : 17 min/hole

New

New



Main conclusions of the operational cutting tests can be summarized as following:

- AWJ tests are conclusive, even if the cutting time is higher than the laser cutting time. However, AWJ produces a lot a secondary waste, and presents a huge difficulty to manage the abrasive jar, that has to be fulfilled approximately after each cut
- The laser 14 kW reaches every requirements of the cutting functions and thus, is the tool proposed in the cutting scenario.

IV. IMPLEMENTATION STUDIES

4. 0. GENERALITIES

Implementation studies are carried out with regards of the tests results, operational experience, available input data and assumptions about the conditions of site. The goal of these studies is to determine in which conditions, under which scenario, it will be possible to dismantle the entire CRD-H elements.

Implementation studies cover:

- Feasibility of a cutting & removal of CRD-H scenario: the idea is to determine, step by step, how it is possible to implement the cutting tools, how it is possible to retrieve every cut pieces while ensuring that the risk of a fall of object is minimized. The scenario considers the different cutting operations, the change of tool if needed, the operations of retrieval, etc.
- Determination of operational time: according to the tests results (cutting performances) and with consideration for the determined scenario, it is then possible to evaluate the operational times on site (implementation time, cutting time, retrieval time, maintenance, etc.)

IV. IMPLEMENTATION STUDIES

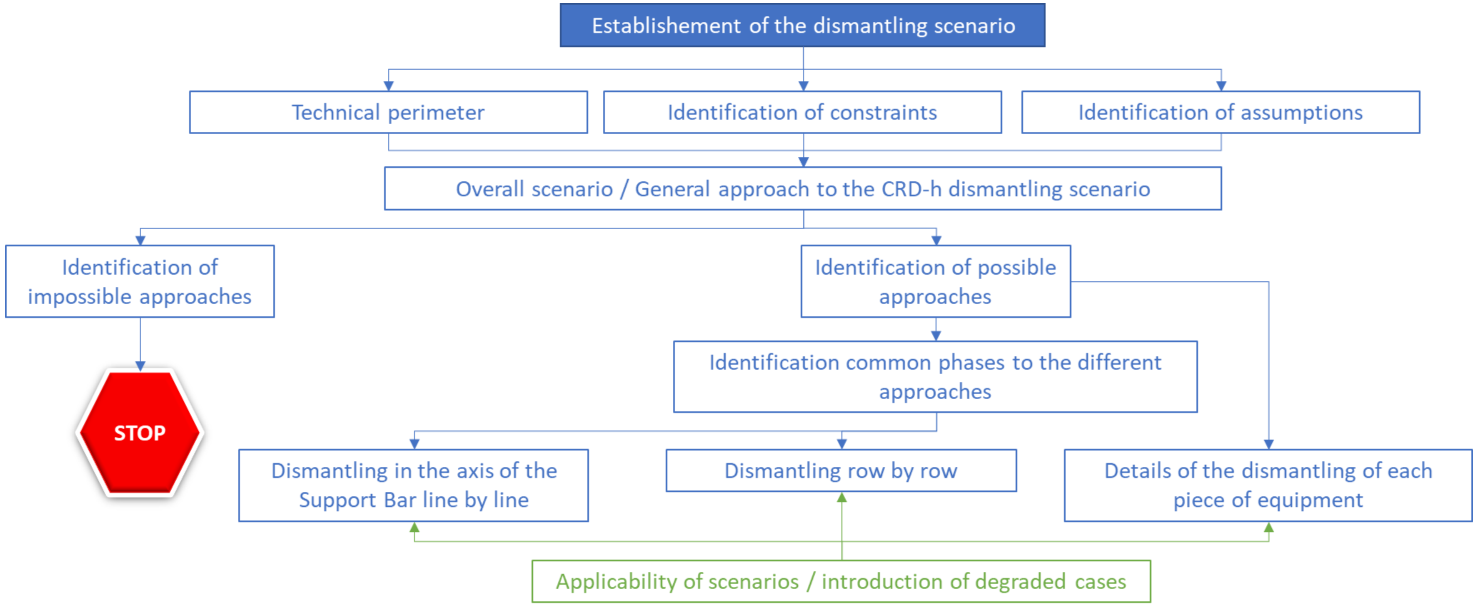
4.1 DISMANTLING OF CRD-H: METHODOLOGY AND BASIS

The dismantling scenario of CRD-H is based on these principles:

Analysis of constraints and assumptions:

- Prioritizing the removal of CRD-H before the GRID support structure
- Dismantling equipment must be able to enter through access X-6
- Minimizing the presence of dismantled equipment above the remotely operated tools in order to limit the risk of the tool jamming in the pedestal
- Limiting the risk of equipment falling for each of the elements being dismantled
- Implementing the laser aspiration head as soon as possible to limit the risk of spreading contamination
- Dismantling of CRD-H will start with CRD-H closest to X-6 in order to get better acces
- The maximum amount of space must be freed up as soon as possible near X-6 in order to limit the presence of equipment to be dismantled above the remotely operated tools

Methodology:



Establishement of the dismantling scenario

Technical perimeter

Identification of constraints

Identification of assumptions

Overall scenario / General approach to the CRD-h dismantling scenario

Identification of impossible approaches

STOP

Identification of possible approaches

Identification common phases to the different approaches

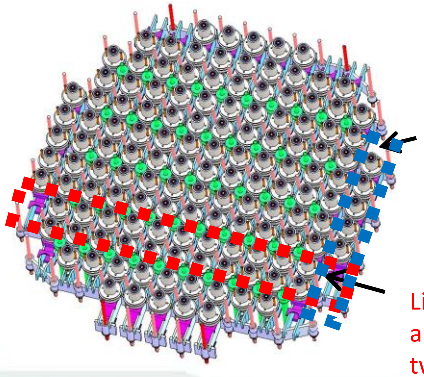
Dismantling in the axis of the Support Bar line by line

Dismantling row by row

Details of the dismantling of each piece of equipment

Applicability of scenarios / introduction of degraded cases

Lexical definition for a good understanting of the scenario : CRD-H LINE and CRD-H ROW:



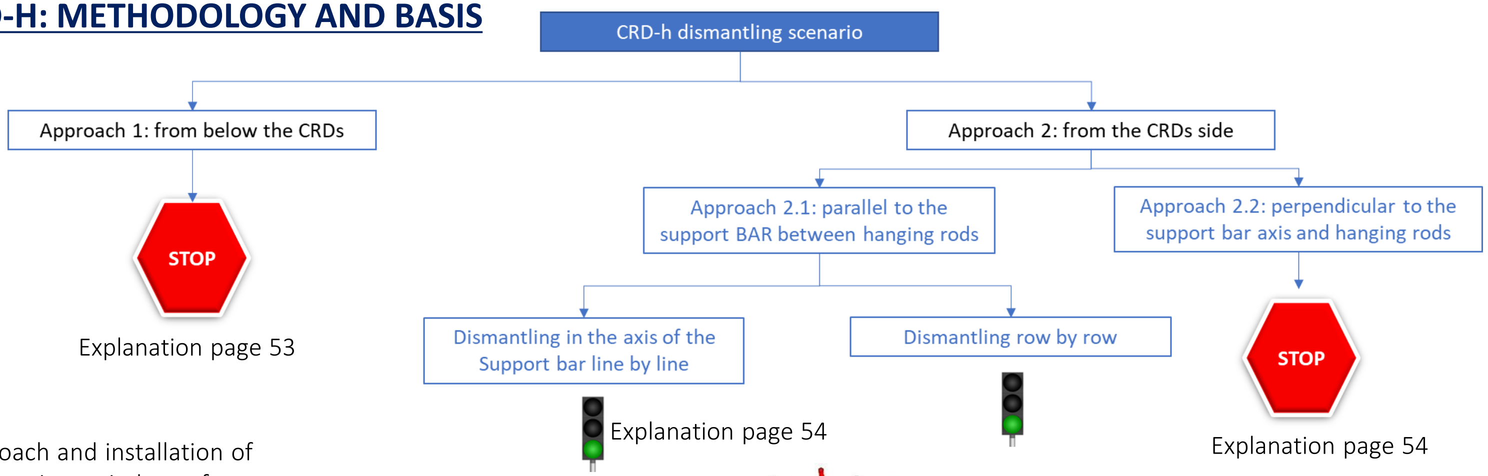
Row: set of CRD-H located perpendicular to the GRID supports between two rows of tie rods,

Line: GRID supports and located between two of them.

IV. IMPLEMENTATION STUDIES

4.1 DISMANTLING OF CRD-H: METHODOLOGY AND BASIS

Definition of possible attack zones for CRD-H dismantling



CRD-h dismantling scenario

Approach 1: from below the CRDs

STOP

Explanation page 53

Approach 2: from the CRDs side

Approach 2.1: parallel to the support BAR between hanging rods

Dismantling in the axis of the Support bar line by line

Explanation page 54

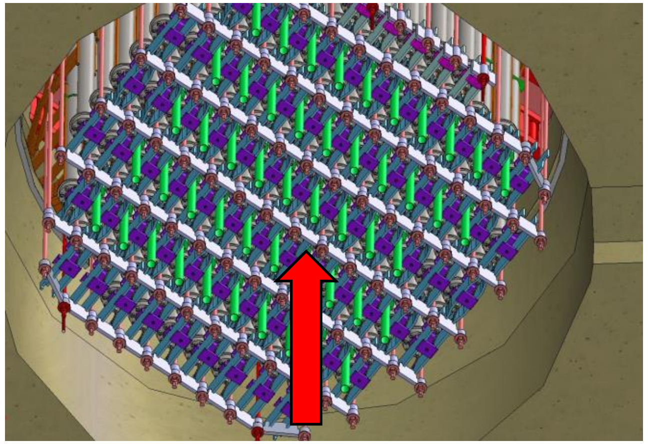
Dismantling row by row

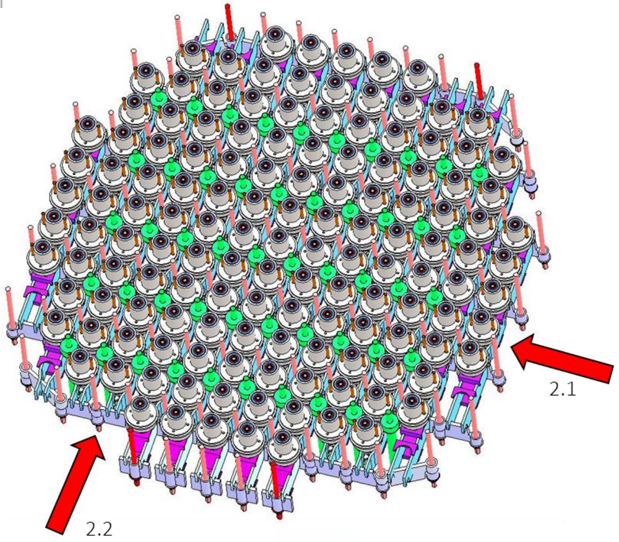
Approach 2.2: perpendicular to the support bar axis and hanging rods

STOP

Explanation page 54

Approach 1: from below: The approach and installation of the tools as well as the dismantling is carried out from below the CRD-H.

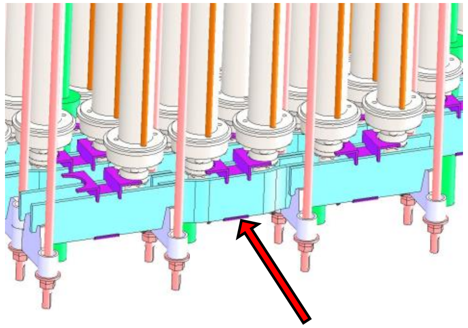




Legend : Starting aera for the dismantling of CRD-H

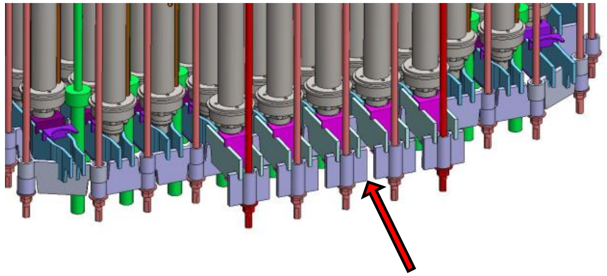
Approach 2: from one side

2.1 : on one side between the GRID supports and hanging rods



Approach 2: from one side

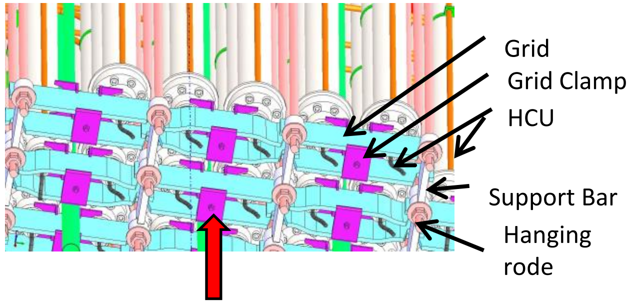
2.2 : by one side facing the GRID support and hanging rods



IV. IMPLEMENTATION STUDIES

4.1 DISMANTLING OF CRD-H: METHODOLOGY AND BASIS

Justification for keeping or not an approach : Approach 1 from below the grid and CRD-H



By considering a dismantling approach from below the CRD-H, the first equipment encountered is in the order of the plans:

- Plan 1: the support structure: support bar, GRID, lower part of the hanging rods
- Plan 2: lower end of the ICMs, end of the HCUs, flange of the CRD-H.

Findings:

- The CRDs are not directly accessible and are located above the support elements
- The support elements are the first elements accessible for removal by starting the dismantling from below.
- The space available between the various components of the CRDs and in particular between the GRIDs and the support bar is restrictive for the installation of tools and robotic arms.

With the aim of meeting the need to maintain the support structure for as long as possible :

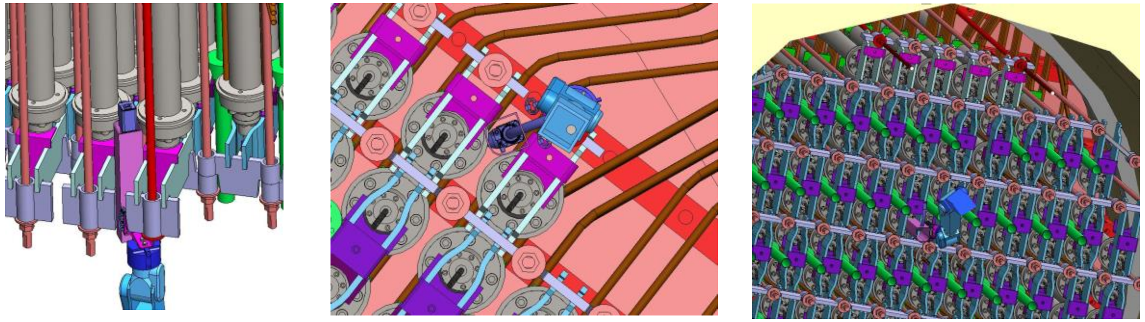
- The objective is to dismantle CRDs and other items such as ICMs in the first place
- Remove the elements of the support structure in a second step.

→ The placement of the removal tools is compromised given the space available. The same goes for the evacuation of the cut elements, it is not possible to evacuate them through the support structure.

STOP

Major drawback identified: poor accessibility of the CRDs without removing the support elements beforehand. It is impossible to maintain the support structure before removing the CRD-H as part of approach 1.

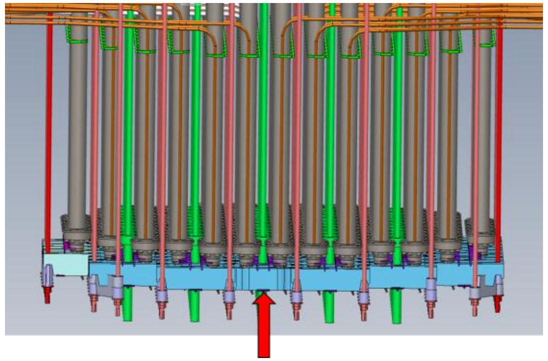
Considering the need to prioritize the dismantling of the CRDs before the support elements, here is an example of the scenario of the laser cutting tool:



IV. IMPLEMENTATION STUDIES

4.1 DISMANTLING OF CRD-H: METHODOLOGY AND BASIS

Justification for keeping or not an approach : Approach 2.1 and 2.2



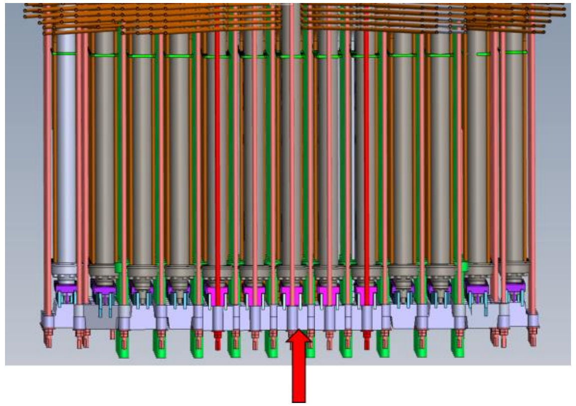
View in the axis of the support bars

Approach 2.1 : **Parallel to the support BARS and between the hanging rods**

- Maximum space available between support bars and hanging rods to reach CRD-H
- Access to the CRD-H for cutting without prior access to support bars, hanging rods or GRID is possible
- Different axes of progress are identified for the dismantling of CRD-H:
  - Row/row
  - Line/line

The approach by the axis parallel to the support BAR is retained and developed according to two approaches:

- CRD-H dismantling row by row
- CRD-H dismantling line by line



Perpendicular view to support bars

Approach 2.2: Dismantling of CRD-Hs perpendicular to the support bar

- Presence of SUPPORT BARS and hanging rods in the axis of progression
- Impossibility of progressing without removing the supports bars as dismantling progresses

STOP

Major drawback identified: poor accessibility of the CRDs without removing the support elements beforehand. It is impossible to maintain the support structure before removing the CRD-Hs as part of approach 2.2.

IV. IMPLEMENTATION STUDIES

4.2 ASSUMPTIONS ABOUT THE CARRIER

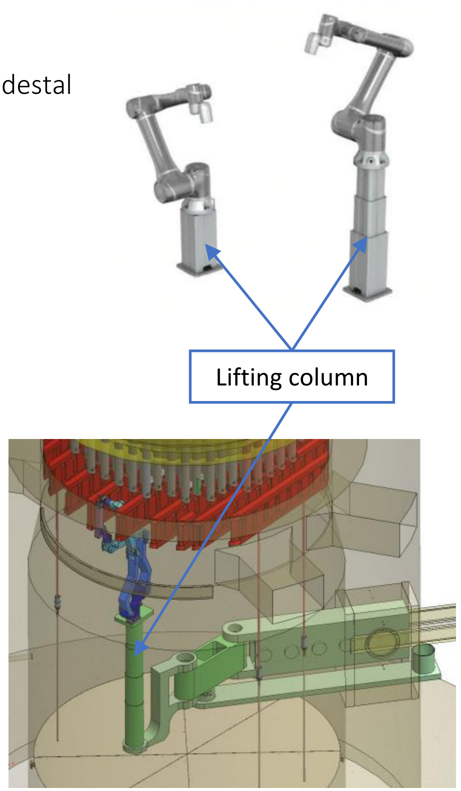
Hypothesis

The scenario needs a carrier that answers to specific hypothesis:

- Able to go in and out of the pedestal
- Able to reach every elements inside the pedestal
- Resistance to falling objects
- Includes into the structure the storage

of MUC (Mitigating Unit Can)

- Able to carry arm + tool + weight
- Accurate and stable
- Needs to be horizontal

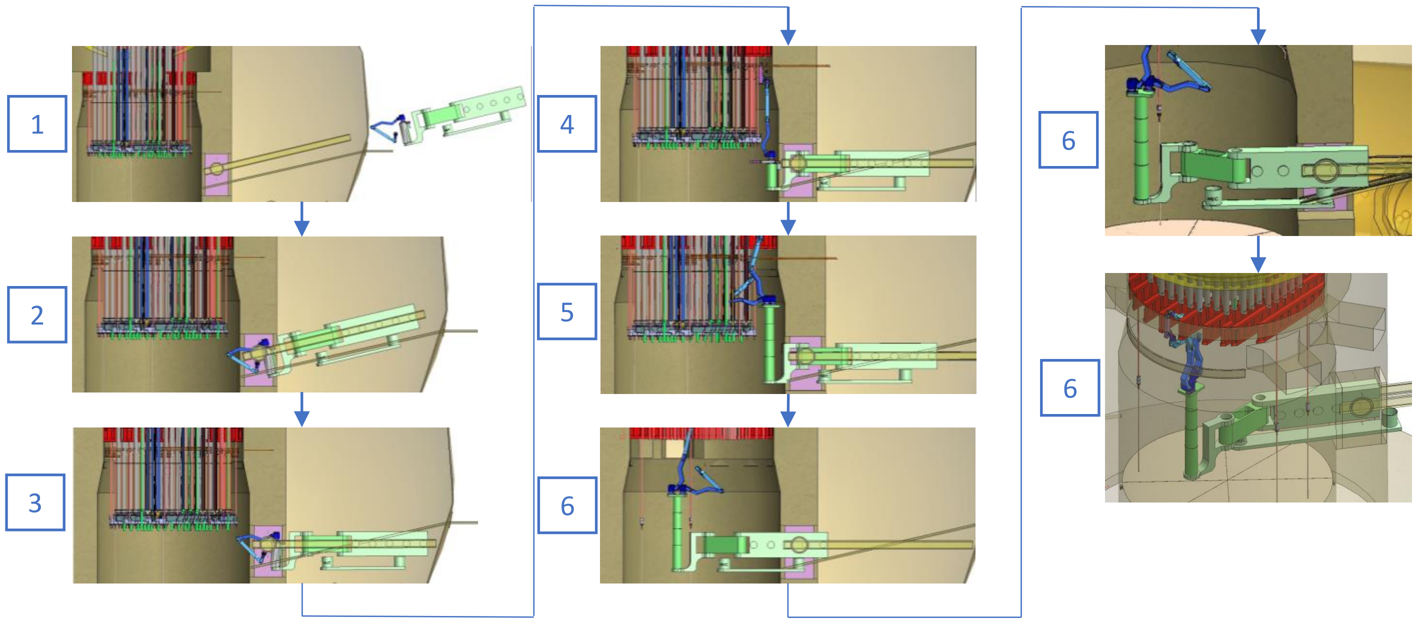


In order to reach the top elements of the pedestal, a lifting column is necessary on the carrier.

This system needs the carrier to be perfectly horizontal in order to rise the column vertically.

Entrance in the pedestal

In order to operate into the pedestal, the carrier needs to follow some steps priorly. (The number of arms on the carrier is not relevant in the example below)



[1] The carrier enters into the PCV

[2] The carrier is totally set in the runners

[3] The carrier is moved to be set horizontally

[4] The carrier moves inside the pedestal, it is now possible to spread the arm

[5] The lifting column can rise vertically

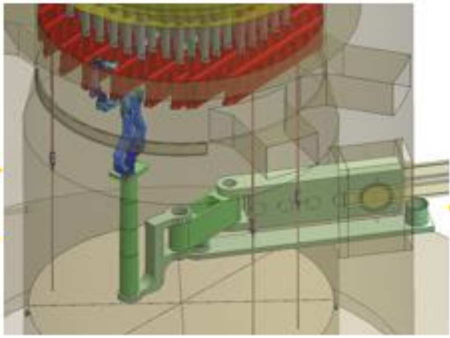
[6] The carrier can go deeper inside the pedestal to reach elements

IV. IMPLEMENTATION STUDIES

4.3 GENERAL ARRANGEMENT OF THE CRD-H DISMANTLING SCENARIO

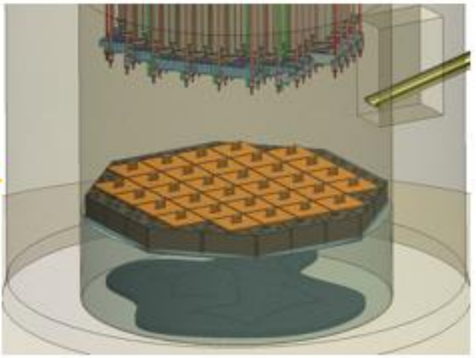
General arrangement

- General dismantling CRD-h scenario
- Installation of remotely operated equipment
- Installation of the global fall preventig platform
- Dismantling of CRD-h obstructing/overhanging the deployment of remotely operated tool
- Dismantling of CRD-hs and related equipments
- Dismantling of BEAMs



Exemple of robotic arm and remotely control equipments.

Out of scope of studies but scenario establishes some some recommendations for implemantation

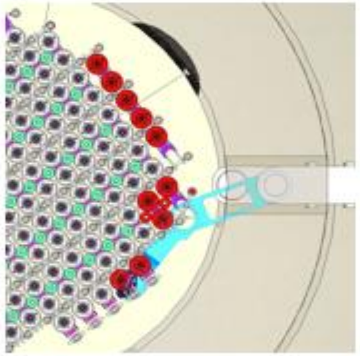


Exemple of a fall prevention plateform as global preventing system.

Several exemples of plateforms has been studied. One of the most relevent is a floating plateforme.

Solutions that will not damage the civil engineering of the pedestal are preferred.

Details in platforms pages N°18-19



Free up space to allow optimal deployment of the remotely operated arm and tools

Minimize the presence of elements being dismantled above the remotely opeated arms during operations

Enable the deployment of remotely operated equipment upwards for the dismantling of CRD-hs

CRD-h identified as obstructing/overhanging the deployement of the remotely operated tools.

Dismantling of these CRD-h will be prioritised

Dismantling row by row
- Front HCU cutout of the entire row
- Rear HCU cutout of the entire row
- CRD cutout of the entire row
- Cutout of GRID of the entire row
- Hanging rods cuttout of the entire row
- Support bars cuttout of the entire row
- ICM cuttout of the entire next row
- Next row

Or

Dismantling of a CRD-h line
- Front HCU cutout of the first row of the line
- Rear HCU cutout of the first row of the line
- CRD cutout first row of the line
- GRID cutout of the first row of the line
- ICM cutting of the entire next row in the line
- Next row in the line
- Next line
- Dismantlingof the free support bars line
- Dismantling of the free hanging rods line

Dismantling CRD-h row by row is the reference scenario.

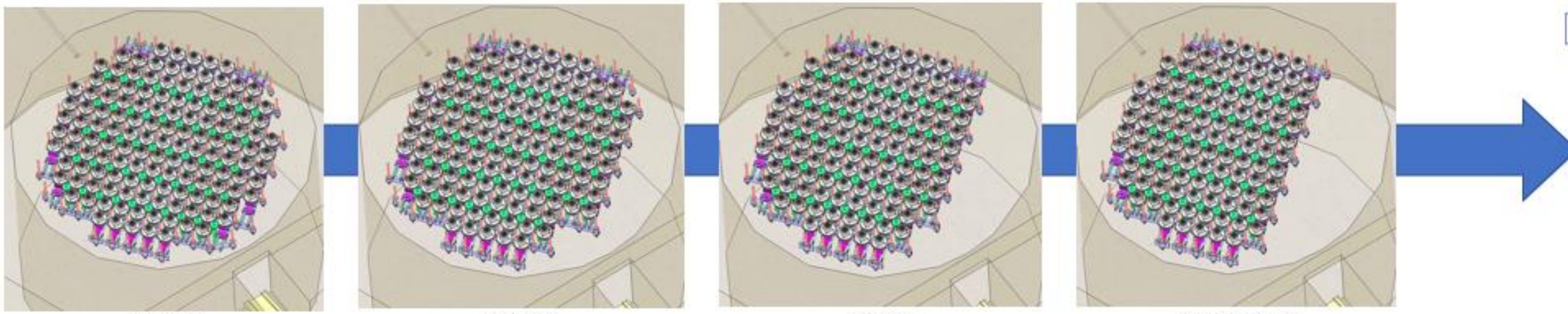
Dismantling CRD-h line by line can be used in degraded case.

IV. IMPLEMENTATION STUDIES

4.3 GENERAL ARRANGEMENT OF THE CRD-H DISMANTLING SCENARIO

Details of row by row dismantling

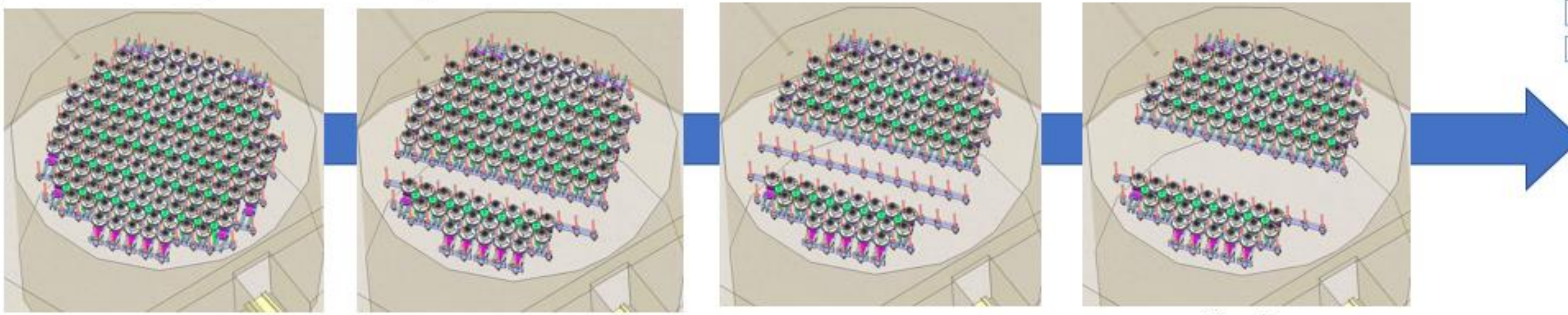
Genenral advance of the scenario is from front to back (on the X-6 axe). Each equipement is dismantled from bottom to top.



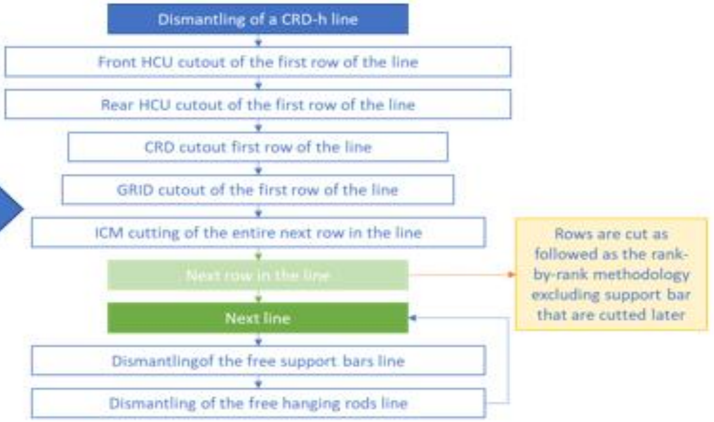
1st row · 2nd row · 3rd row · Next and next row

Dismantling row by row
Front HCU cutout of the entire row
Rear HCU cutout of the entire row
CRD cutout of the entire row
Cutout of GRID of the entire row
Hanging rods cuttout of the entire row
Support bars cuttout of the entire row
ICM cuttout of the entire next row
Next row

Details of line by line dismantling



Initial state · First line · Second line · Line of support bar



Dismantling of a CRD-h line
Front HCU cutout of the first row of the line
Rear HCU cutout of the first row of the line
CRD cutout first row of the line
GRID cutout of the first row of the line
ICM cutting of the entire next row in the line
Next row in the line
Next line
Dismantlingof the free support bars line
Dismantling of the free hanging rods line

Rows are cut as followed as the rank-by-rank methodology excluding support bar that are cutted later

IV. IMPLEMENTATION STUDIES

4.3 GENERAL ARRANGEMENT OF THE CRD-H DISMANTLING SCENARIO

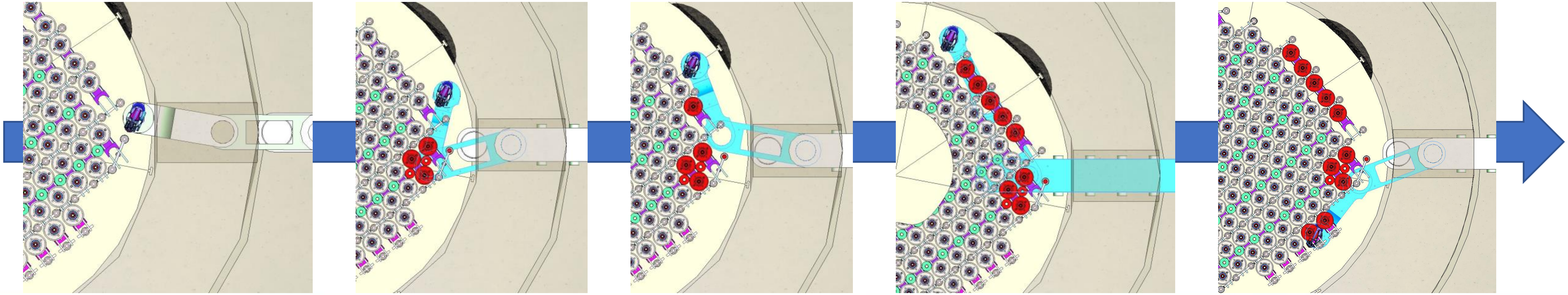
Freeing up space for remotely operated tool deployement

Dismantling of CRD-H obstructing/overhanging the deployment of the remotely operated arm(s)

- Free up space to allow optimal deployment of the remotely operated arm and tools
- Minimize the presence of elements being dismantled above the remotely operated arms during operations
- Enable the deployment of remotely operated equipment upwards for the dismantling of CRD-H

- By simulating deployment of a possible remotely operated arm in the 3D model produced by ONET of the pedestal and CRD-H:
    - Some CRD-H as well as the associated support structures interfere with optimal deployment
    - These CRD-H are shown in the images below

Simulation of deployment of the remotely operated arm and identification of CRD-H obstructing or overhanging its operation



IV. IMPLEMENTATION STUDIES

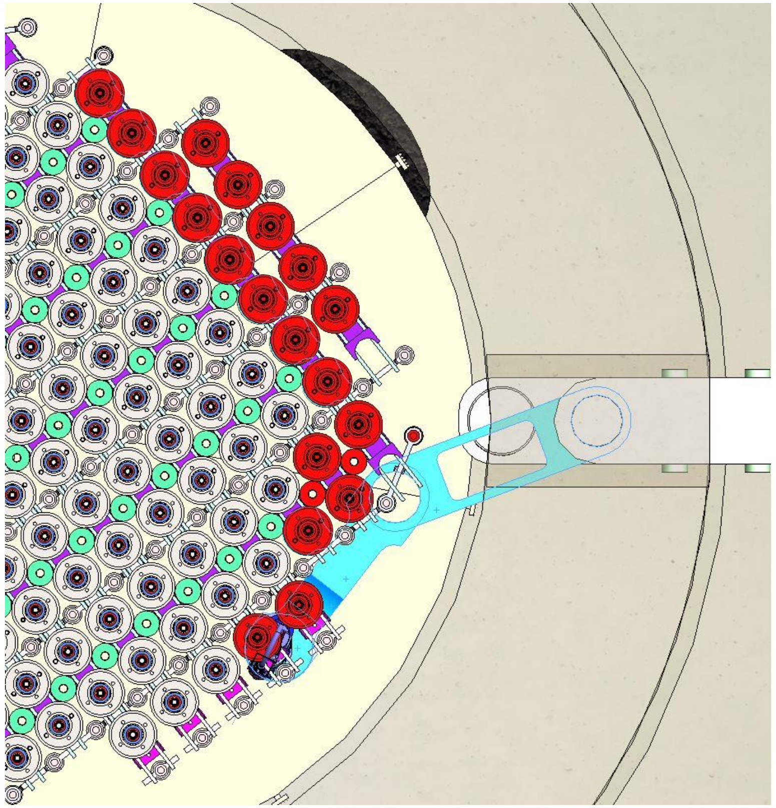
4.3 GENERAL ARRANGEMENT OF THE CRD-H DISMANTLING SCENARIO

Freeing up space for remotely operated tool deployement

- allow the deployment of the two remotely arms configuration and tools

- By simulating deployment of a possible remotely operated arm in the 3D model produced by ONET of the pedestal and CRD-H

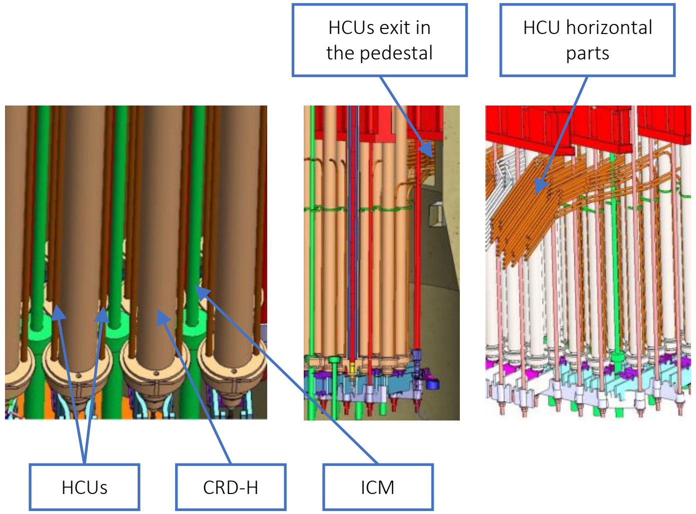
Conclusion : at least, the first two lines of CRD-H (depending of design of the 2 remote arms) need to be removed with the single arm configuration.



CRD-H in red to be cut with one arm configuration

IV. IMPLEMENTATION STUDIES

4.4 GENERAL FEATURES ABOUT HCU AND CRD-H DISMANTLING SCENARIO



Global dismantling method:

HCU are dismantled from bottom to top.

Dismantling is possible either with one or two robotic arms.

A special clip system is used to prevent HCU parts from falling

Global dismantling method:

- Phase 1 : dismantling of the front and back of the vertical part of the row

Initial state: All front and back HCUs are present

↓

Set a clips up all along the HCUs of the row

↓

Set the cutting laser tool up on the arm

↓

Cutting front and back HCUs between clips

↓

Set the wrench tool up on the arm

↓

Remove and drop off each part of the HCUs inside the MUC

↓

All HCU front and back vertical part are removed

Dismantling tool: Curved laser head equiped with dust collection head.

- Phase 2 : dismantling horizontal part of the HCU higher in the piedestal

Initial state: Only the HCU horizontal parts remain

↓

Set the cutting tool: special wrench pinch

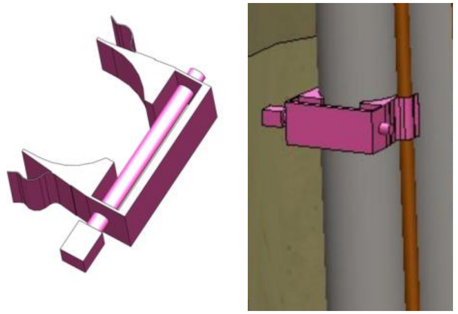
↓

Dismantling of the HCU horizontal parts

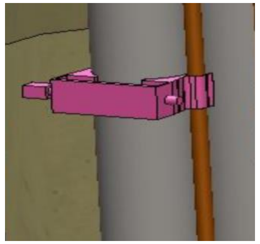
↓

All HCU parts of the row are dismantled

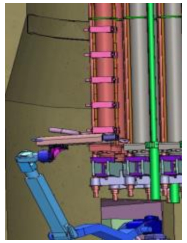
Dismantling tool : Wrench with the shear tool holding a HCU



Clips system



Set clips on the HCUs



Setting clips along HCUs

In order to hold HCUs, clips are set on the CRD-H of the row with the wrench tool on the arm

IV. IMPLEMENTATION STUDIES

4.4 GENERAL FEATURES ABOUT HCU AND CRD-H DISMANTLING SCENARIO

Global dismantling method:

They are dismantled in different phases from bottom to top.

Phase 1: bottom of the flange -> lower flange mass for next step

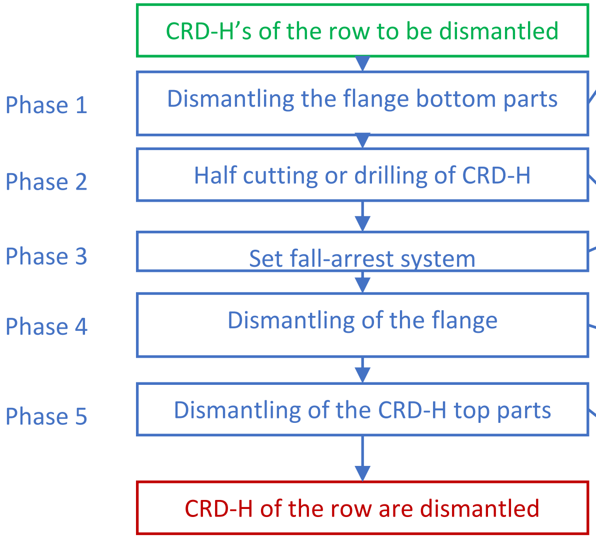
Phase 2 and 3: prevent from falling system are put in place by cutting or drilling the CRD-H in different places to prepare phase 5

Phase 4: Flange is dismantled. A special prevent fall system is put in place on the grid, rest of the flange is cut off from the rest of the CRD-H

Phase 5: the rest of the CRD-H is cut from bottom to top in several pieces.

Several changes of configurations and tools are needed to perform the scenario with one robotic arm.

- Cutting tool : curved head with aspiration
- Wrench tool to put in place prevent fall system and evacuated cut parts.
- Combine equipment to cut CRD-H core (wrench + laser cutting tool)


CRD-H's of the row to be dismantled

Phase 1 — Dismantling the flange bottom parts

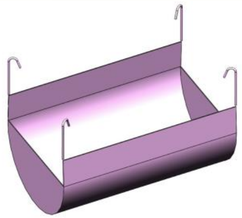
Phase 2 — Half cutting or drilling of CRD-H

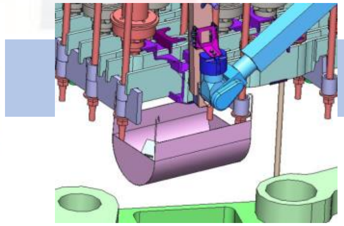
Phase 3 — Set fall-arrest system

Phase 4 — Dismantling the flange

Phase 5 — Dismantling of the CRD-H top parts

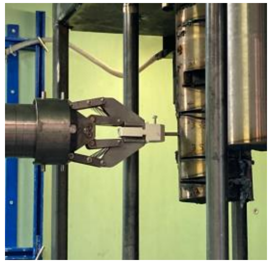
CRD-H of the row are dismantled


Recovery bucket


Recovery bucket held by grid supports

Phase 1


Phase 2


Phase 3


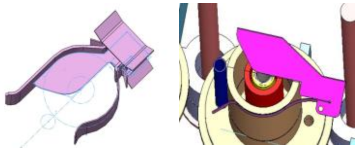
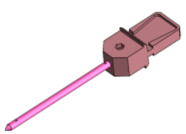
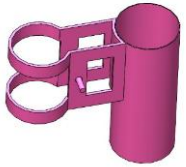
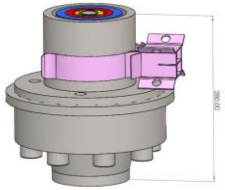


Plate and plate inserted in a CRD-H

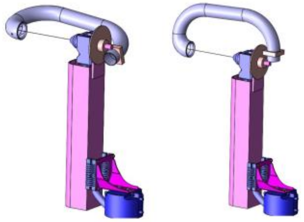

Pin

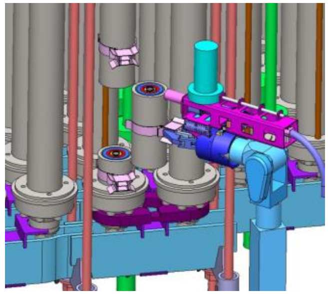

Flange support

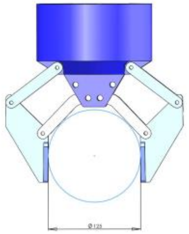

CRD-H bucket

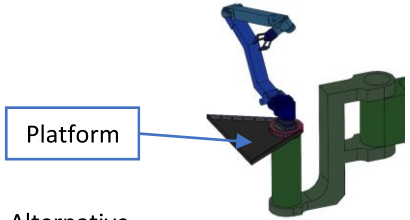
Phase 4


Phase 5



Curved laser head with specific collection head


Straight laser head combined with gripper tool


Example of wrench tool



Alternative prevent fall system

Carrier with the recovery platform

IV. IMPLEMENTATION STUDIES

4.5 GENERAL FEATURES ABOUT GRIDS DISMANTLING

Global dismantling method:

The grid is cut in multiple parts. A specific prevent fall system can be set before cutting.

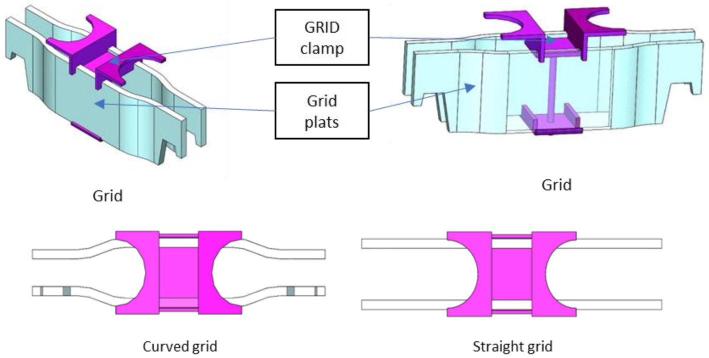
Phase 1: Set of the special prevent fall system (bucket)

Phase 2: Cutting the grid in different parts

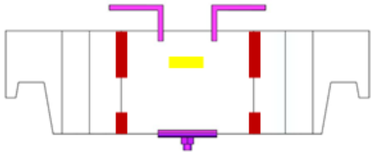
Phase 3: Recovery of the cut parts in the bucket with a wrench tool.

Several changes of configurations is necessary to perform the scenario with one robotic arm.

- Cutting tool : curved head
- Wrench tool to put in place prevent fall system and evacuate cut parts.



Overview of the GRID



Order of cutting:

- Step 1: 🟨 🟨
- Step 2: 🟥 🟥

Line of cut preview

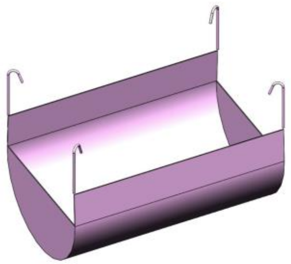
Initial state

Phase 1
- Set the wrench tool on the arm
- Setting the recovery bucket

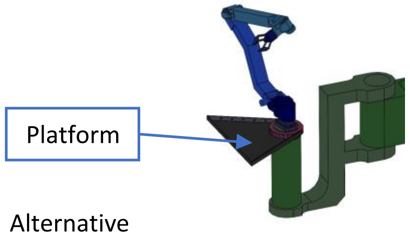
Phase 2
- Set the laser head tool on the arm
- Cutting the grid

Phase 3
- Set the wrench tool on the arm
- Remove each pieces from the recovery bucket and drop them off inside a MUC

The grid is dismantled



Recovery bucket



Alternative prevent fall system

Carrier with the recovery platform

IV. IMPLEMENTATION STUDIES

4.6 GENERAL FEATURES ABOUT BAR DISMANTLING

Global dismantling method:

As for the grid, support bar is cut in multiple parts. A specific prevent fall system is set on the carrier (recovery platform).

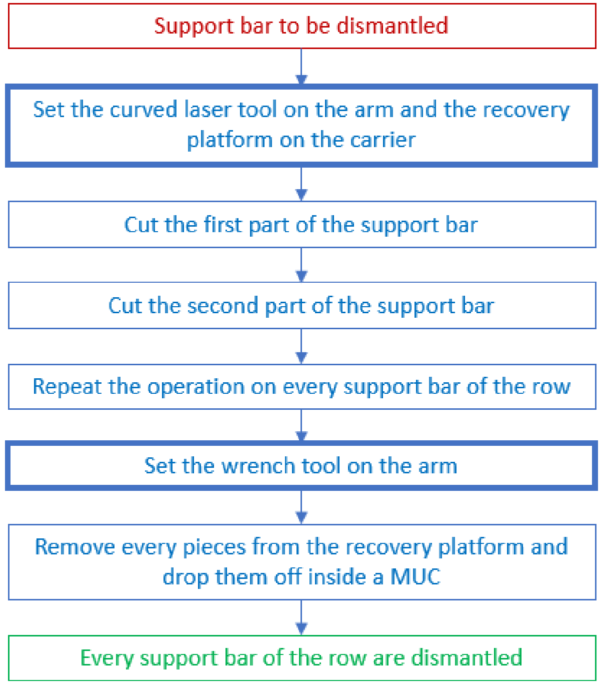
Phase 1: Set cutting tool and recovery platform

Phase 2: Cutting the support bar in different parts

Phase 3: Recovery of the cut parts on the recovery platform with a wrench tool.

Several changes of configurations is necessary to perform the scenario with one robotic arm.

- Cutting tool : curved head
- Wrench tool to put in place prevent fall system and evacuate cut parts.


Support bar to be dismantled

Set the curved laser tool on the arm and the recovery platform on the carrier

Cut the first part of the support bar

Cut the second part of the support bar

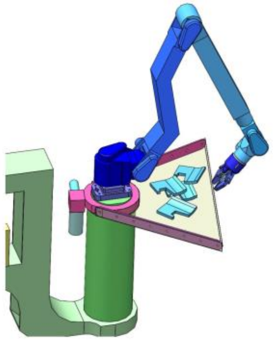
Repeat the operation on every support bar of the row

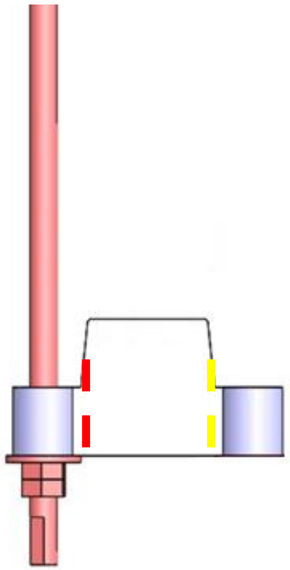
Set the wrench tool on the arm

Remove every pieces from the recovery platform and drop them off inside a MUC

Every support bar of the row are dismantled


Cutting the support bar with the curved laser tool on the arm and the recovery platform on the carrier


Recovery platform


Order of cutting:

- Step 1: 🟨 🟨
- Step 2: 🟥 🟥

IV. IMPLEMENTATION STUDIES

4.7 GENERAL FEATURES ABOUT ICM DISMANTLING

Global dismantling method:

The ICM is cut in parts from bottom to top.

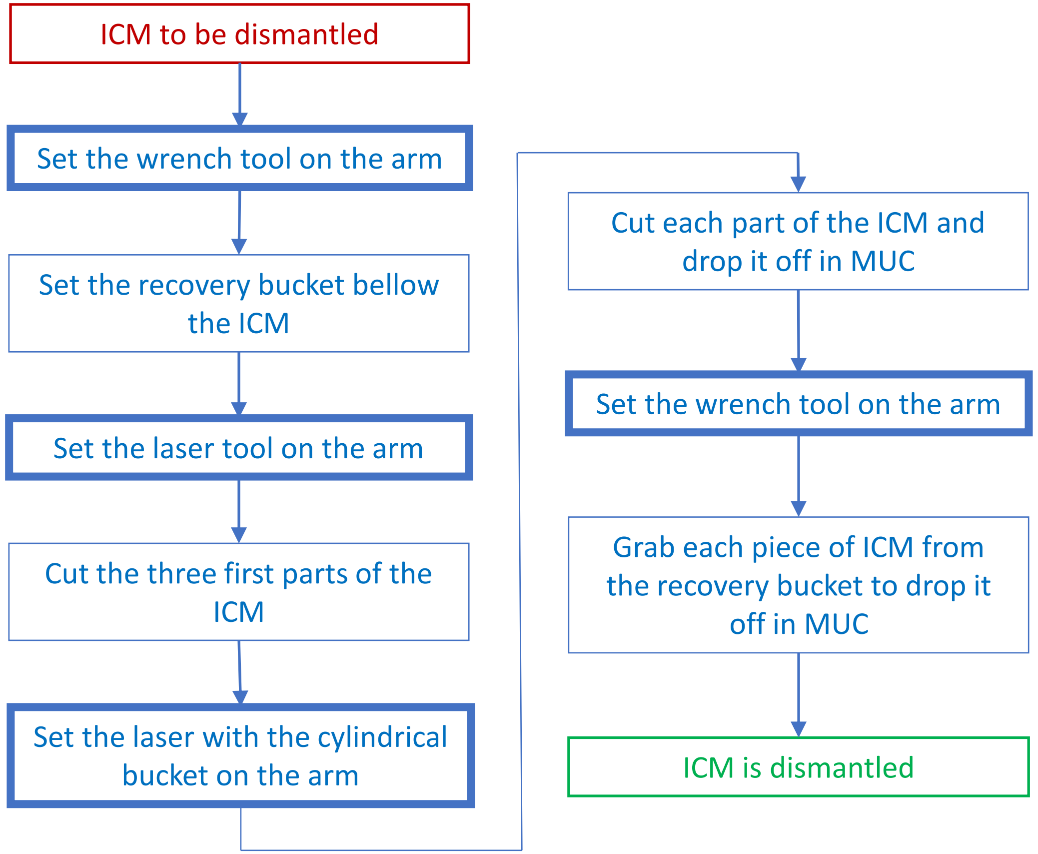
The cut at a distance with the straight laser cutting head.

The bottom part is cut and fall in a recovery bucket.

The other part are cut and fall in a cylindrical bucket that is directly on the robotic arm combined with the cutting head.

Several changes of configurations is necessary to perform the scenario with one robotic arm.

- Cutting tool : linear laser cutting head
- Wrench tool to put in place prevent fall system and evacuate cut parts.
- Cylindrical bucket to prevent from falling,


ICM to be dismantled

Set the wrench tool on the arm

Set the recovery bucket bellow the ICM

Set the laser tool on the arm

Cut the three first parts of the ICM

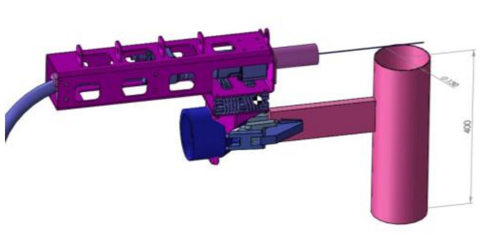
Set the laser with the cylindrical bucket on the arm

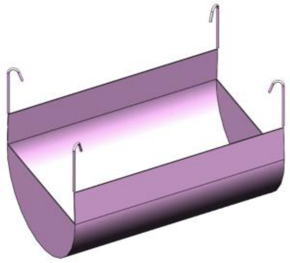
Cut each part of the ICM and drop it off in MUC

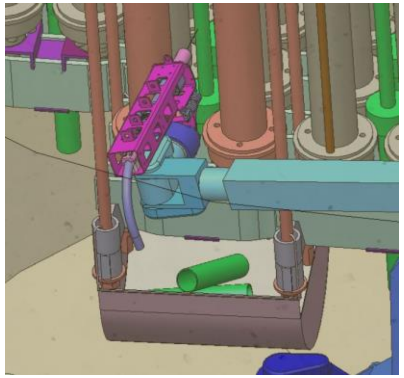
Set the wrench tool on the arm

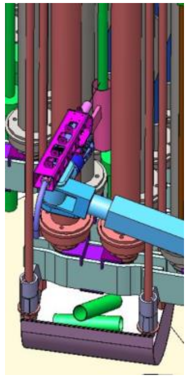
Grab each piece of ICM from the recovery bucket to drop it off in MUC

ICM is dismantled


Cylindrical bucket with the linear laser tool


Recovery bucket


Cutting of ICM with the recovery bucket


Cutting of the ICM with the cylindrical bucket on the arm

IV. IMPLEMENTATION STUDIES

4.8 GENERAL FEATURES ABOUT ROD DISMANTLING

Dismantling scenario

Global dismantling method:

The rod is cut in parts from bottom to top.

They are cut with the curved laser head equipped with aspiration to limit dispersion.

The recovery platform for the falling part is set on the carrier for the bottom part.

The other part are cut and fall in a cylindrical bucket that is directly on the robotic arm combined with the cutting head.

Several changes of configurations is necessary to perform the scenario with one robotic arm.

- Cutting tool : curved laser cutting head
- Wrench tool to evacuate cut parts.
- Cylindrical bucket to prevent from falling

Rods to be removed

Set the curved laser tool and the platform on the carrier

Cut the rods of the row just over the support bar

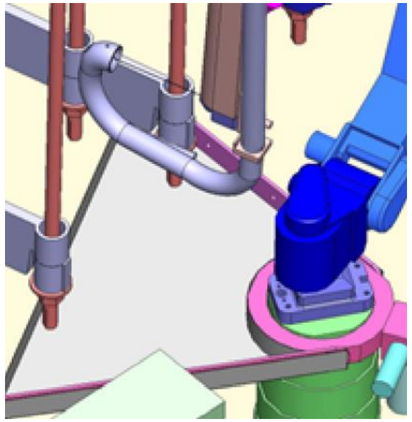
Set the wrench tool on the arm

Remove each pieces from the platform and drop them off in a MUC

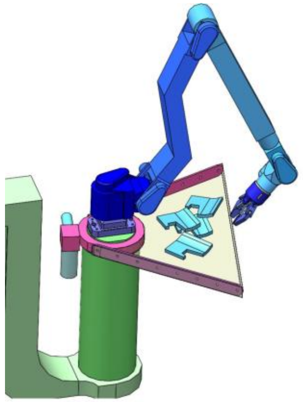
Set the curved laser tool with the cylindrical bucket on the arm

Cut each rod of the row

All rods of the row are removed



Curved laser tool with platform on carrier



Wrench tool to remove pieces from the platform

Curved laser tool + cylindrical bucket on the arm

IV. IMPLEMENTATION STUDIES

4.9 GENERAL FEATURES ABOUT BEAMS DISMANTLING

Global dismantling method :

The beam is cut in place in parts from top to bottom to reduce the global mass. The cut parts are sufficiently little to be moved by the arms. Parts are recovered by two specific recovery systems (angle bracket and recovery bucket)

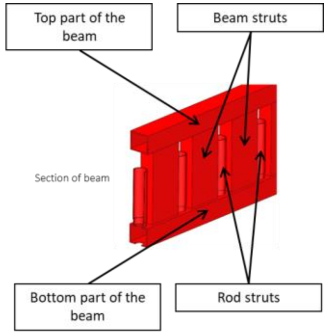
As the beam is reduced in size, the bottom part left in place is then sustained with a specific prevent fall system (angle bracket) set on the next direct parallel beam.

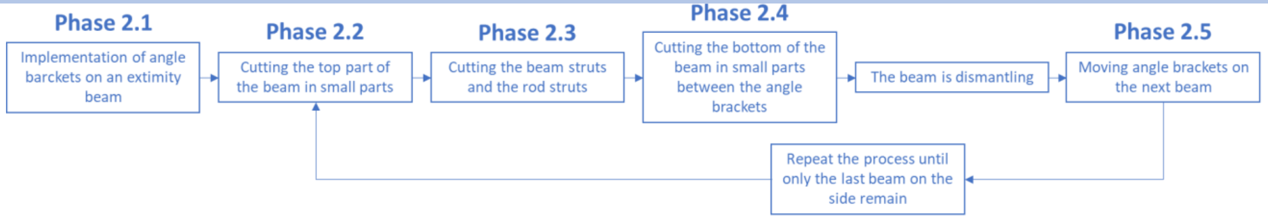
As the prevent fall system maintains the bottom part of the beam, it is possible to cut and evacuate the rest of the beam.

The beams are dismantled from the center beam to edge beams.

Several changes of configurations is necessary to perform the scenario with one robotic arm.

- Cutting tool : curved laser cutting head
- Wrench tool to evacuate cut parts
- Angle bracket and recovery bucket to prevent fall of parts




Phase 2.1
Implementation of angle barckets on an extimity beam

Phase 2.2
Cutting the top part of the beam in small parts

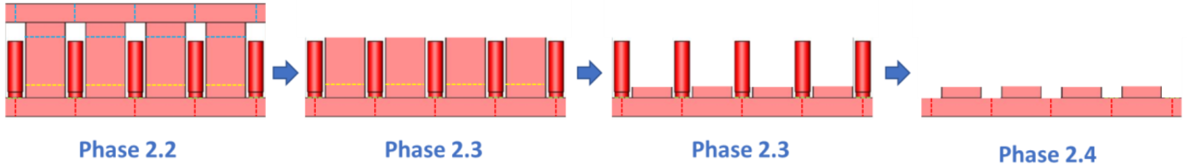
Phase 2.3
Cutting the beam struts and the rod struts

Phase 2.4
Cutting the bottom of the beam in small parts between the angle brackets

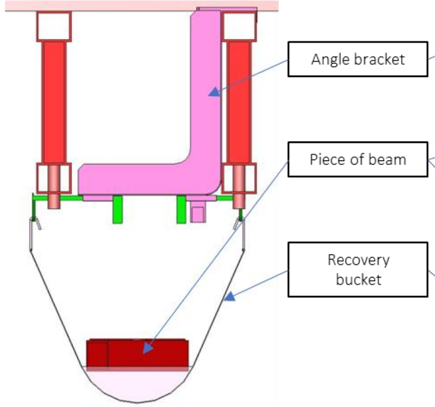
The beam is dismantling

Phase 2.5
Moving angle brackets on the next beam

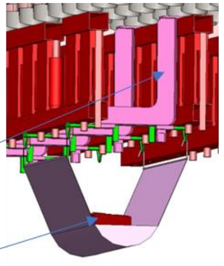
Repeat the process until only the last beam on the side remain

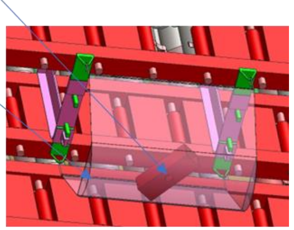


Cutting top parts of the beam

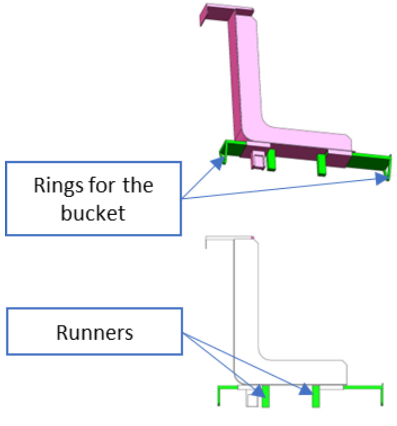


Angle bracket set on a beam

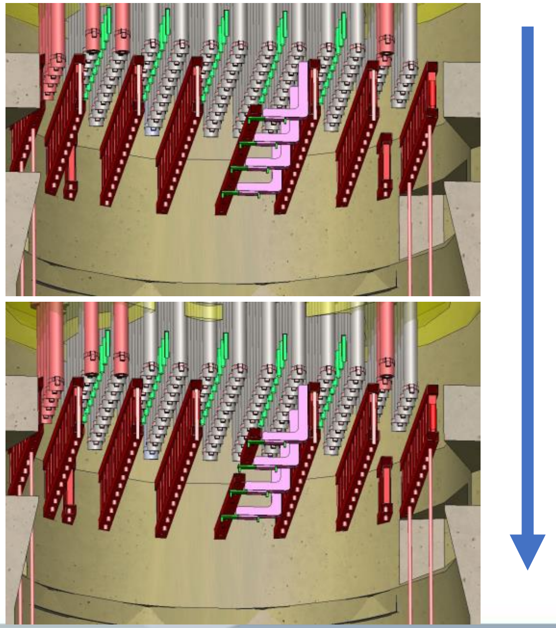




Angle bracket set on a beam



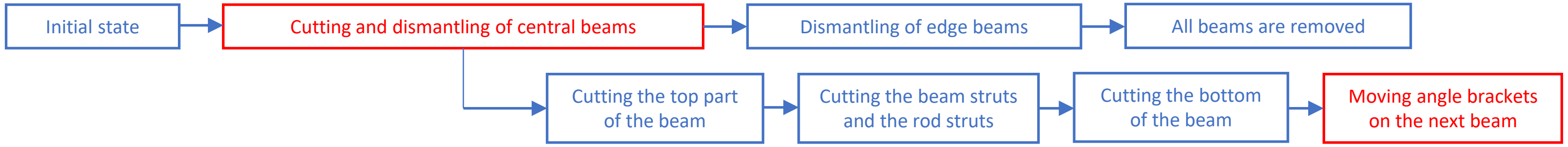
Angle bracket



Cutting bottom part of the beam

IV. IMPLEMENTATION STUDIES

4.9 GENERAL FEATURES ABOUT BEAMS DISMANTLING

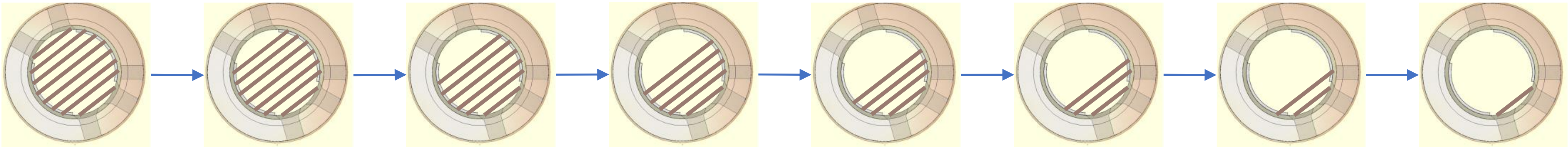


Moving from beam to beam

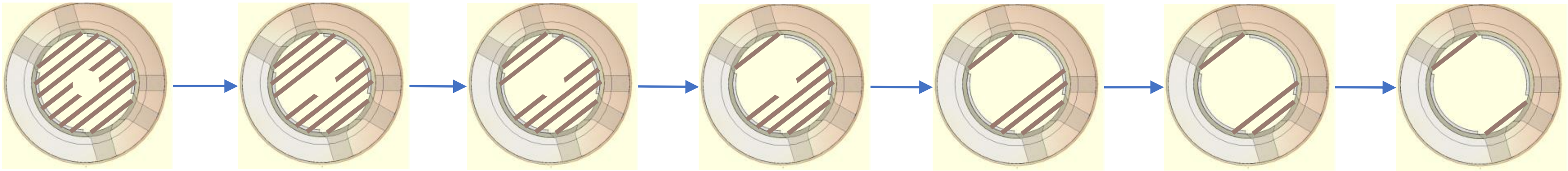
Once the first beam is dismantled, we move each angle bracket to the next beam to hold the beam that was previously held.

There is two situations to chose the first beam:

- In the first situation, if beams are not damaged due to the Fuel Debris, it is possible to start by one of the edge beams and dismantle beams one by one from this beam (see first situation below) and at the end of the process, only one edge beam remain.
- In the second situation, if beams are damaged, it will probably on the middle beams. Therefore, it is better to start the dismantling of beams by the middle (see second situation below) in order to remove the maximum of beams and do not left a beam in the middle. At the end of this situation, two edge beams remain (see next page to these beams).



First situation: the dismantling starts with a edge beam and one beam remains at the end



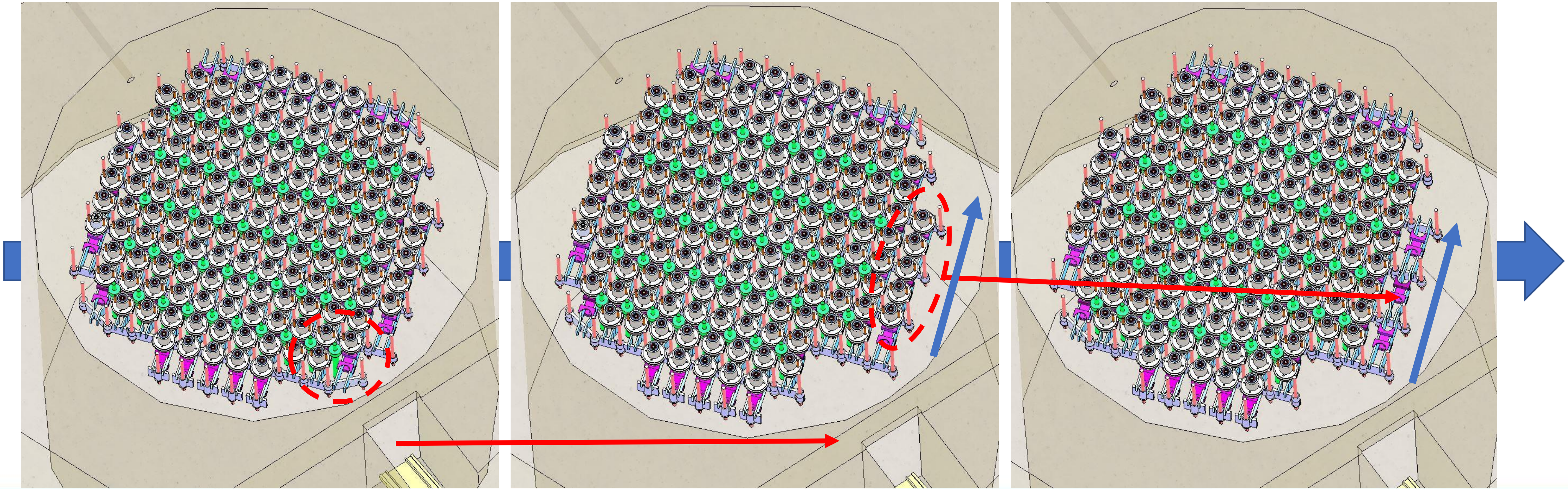
Second situation: central beams are damaged, therefore, the dismantling starts in the middle. Two beams remain at the end

IV. IMPLEMENTATION STUDIES

4.10 DISMANTLING SCENARIO – APPROACH 2.1

Details of dismantling the CRD-H row by row

- Free up space as you cut CRD-H
- Cut out the visible CRD-H before removing the associated support elements
- Limit the presence of equipment being dismantled above the remotely operated tools



1-Initial State

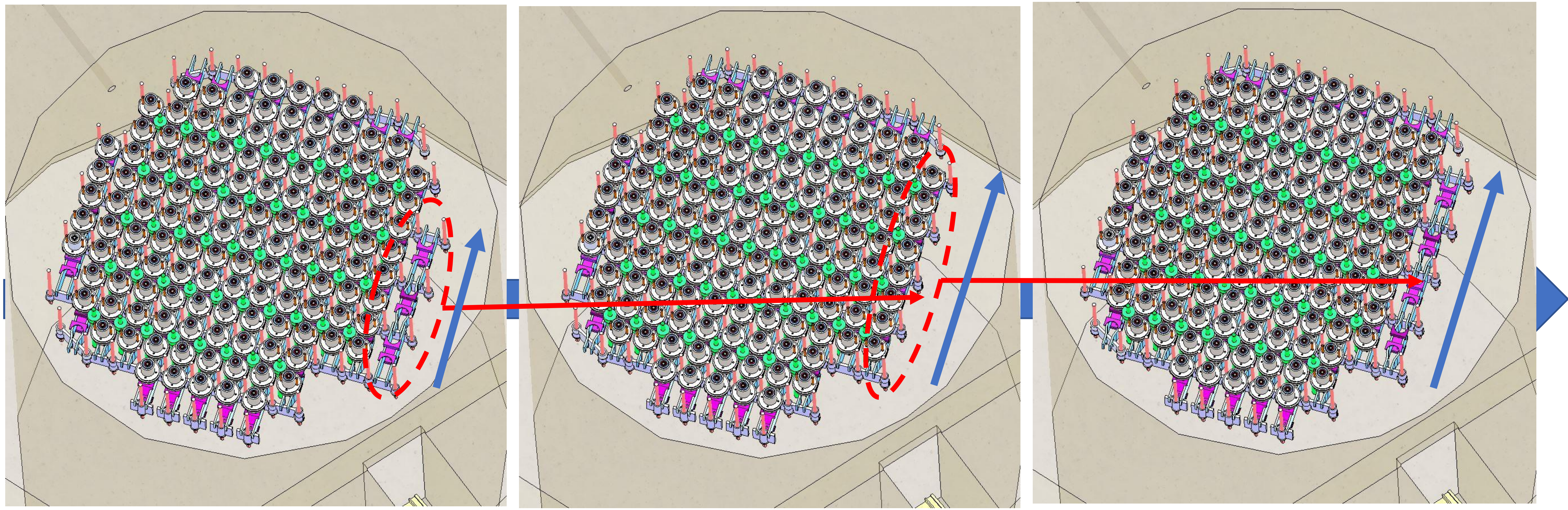
2-Removal of CRD-H and troublesome equipment

3-Withdrawal of the first rank of CRD-H

IV. IMPLEMENTATION STUDIES

4.10 DISMANTLING SCENARIO – APPROACH 2.1

Details of dismantling the CRD-H row by row



Reminder: 3-Withdrawal of the first rank of CRD-H

4-Removal of the first row of GRID+support bars+hanging rods

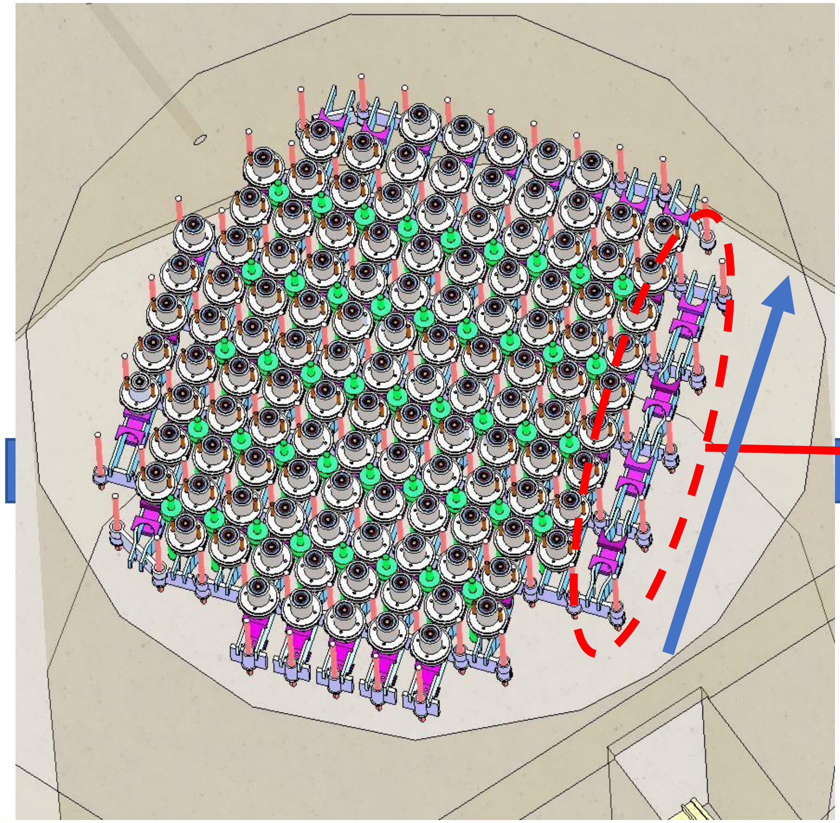
5-Withdrawal of the second rank of CRD-H

IV. IMPLEMENTATION STUDIES

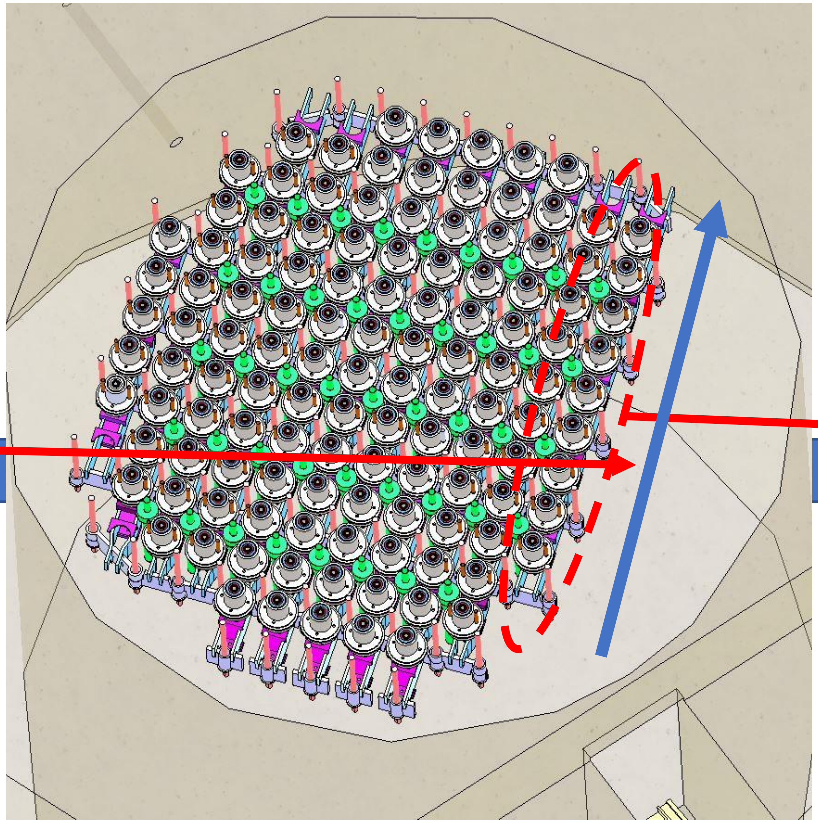
4.10 DISMANTLING SCENARIO – APPROACH 2.1

Details of dismantling the CRD-H row by row

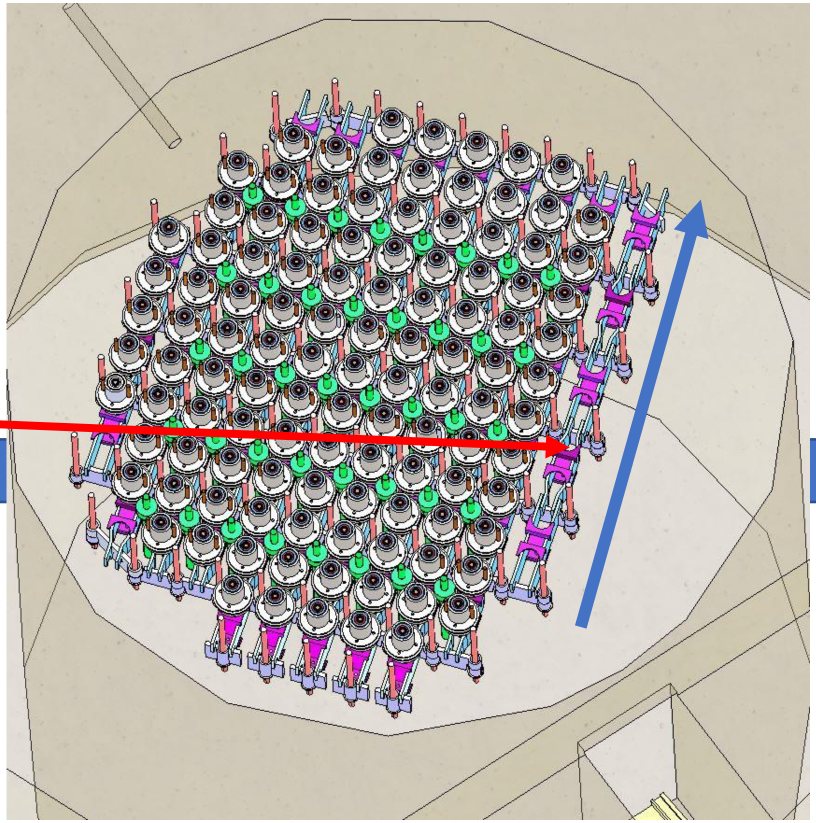
Reminder: 5-Withdrawal of the second rank of CRD-H



6-Removal of the second row of GRID+support bars+hanging rods



7-Withdrawal of third rank from CRD-H



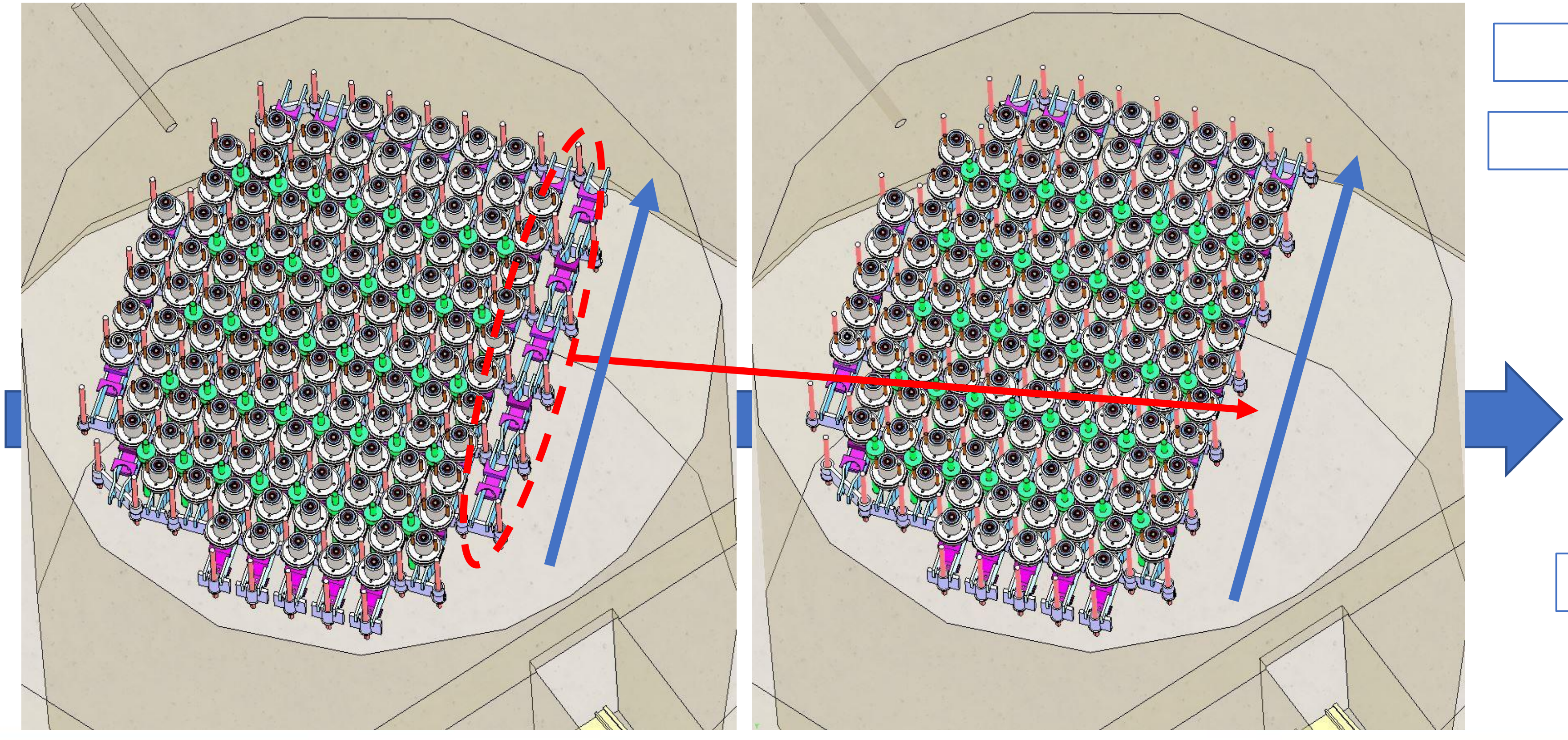
IV. IMPLEMENTATION STUDIES

4.10 DISMANTLING SCENARIO – APPROACH 2.1

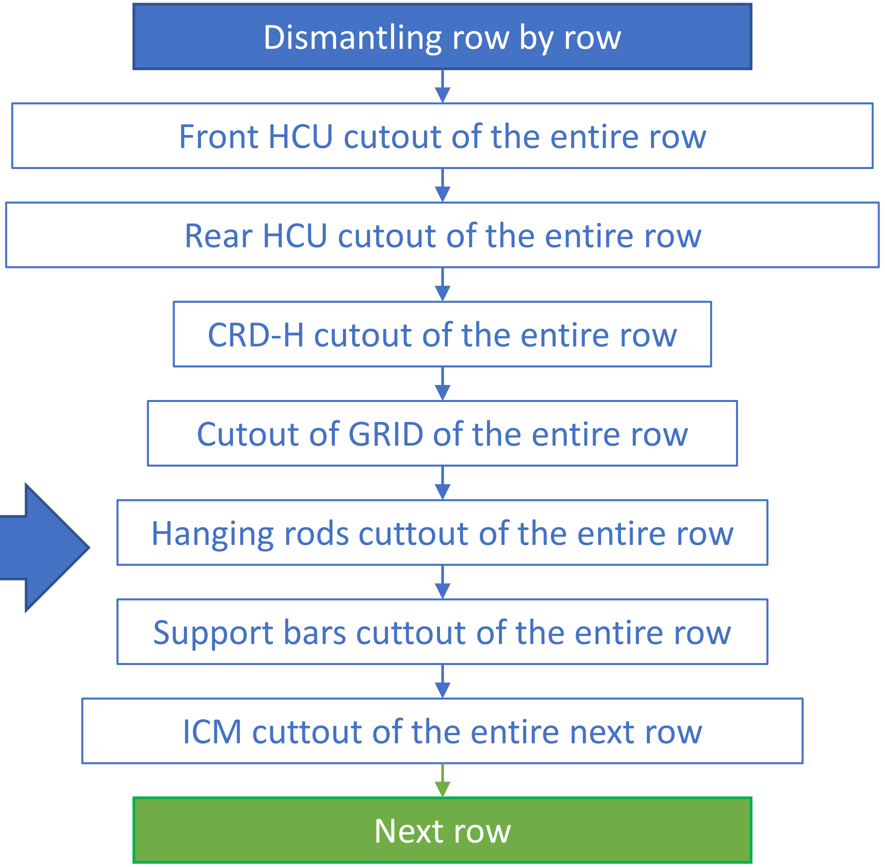
Details of dismantling the CRD-H row by row

Reminder: 7-Withdrawal of third rank from CRD-H

8-Removal of third row from GRID+Support bars+hanging rods



The dismantling operations are repeated until the complete removal of the CRD-H



Dismantling row by row

Front HCU cutout of the entire row

Rear HCU cutout of the entire row

CRD-H cutout of the entire row

Cutout of GRID of the entire row

Hanging rods cuttout of the entire row

Support bars cuttout of the entire row

ICM cuttout of the entire next row

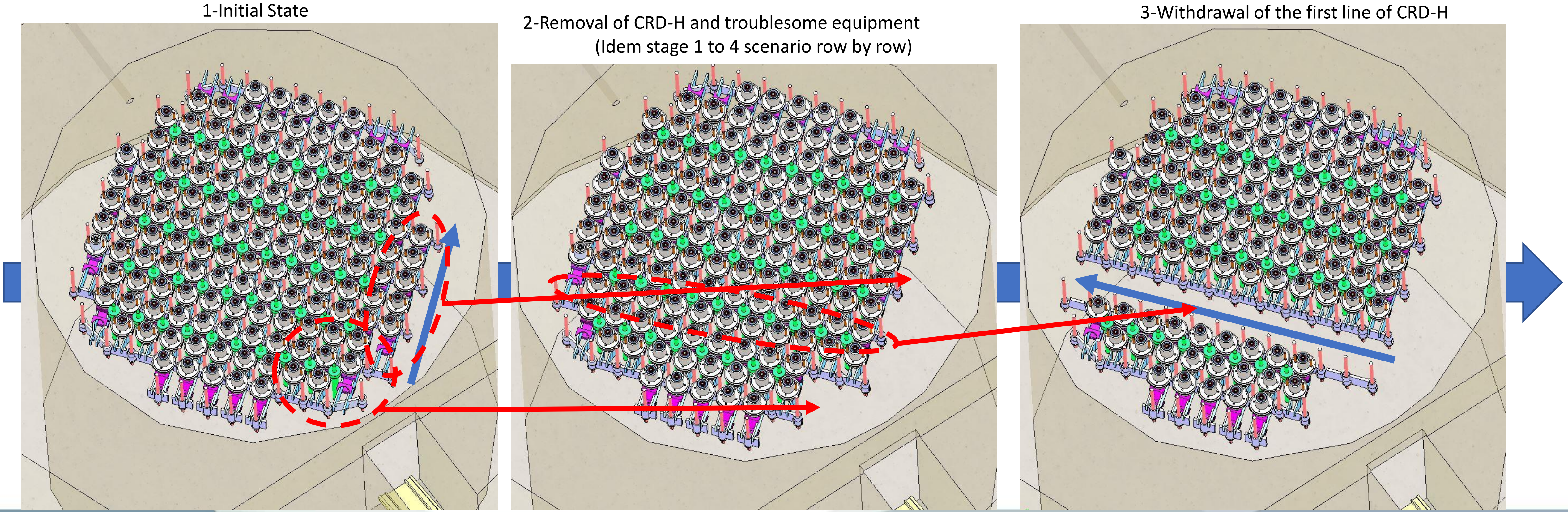
Next row

IV. IMPLEMENTATION STUDIES

4.10 DISMANTLING SCENARIO – APPROACH 2.1

Details of dismantling the CRD-H line by line

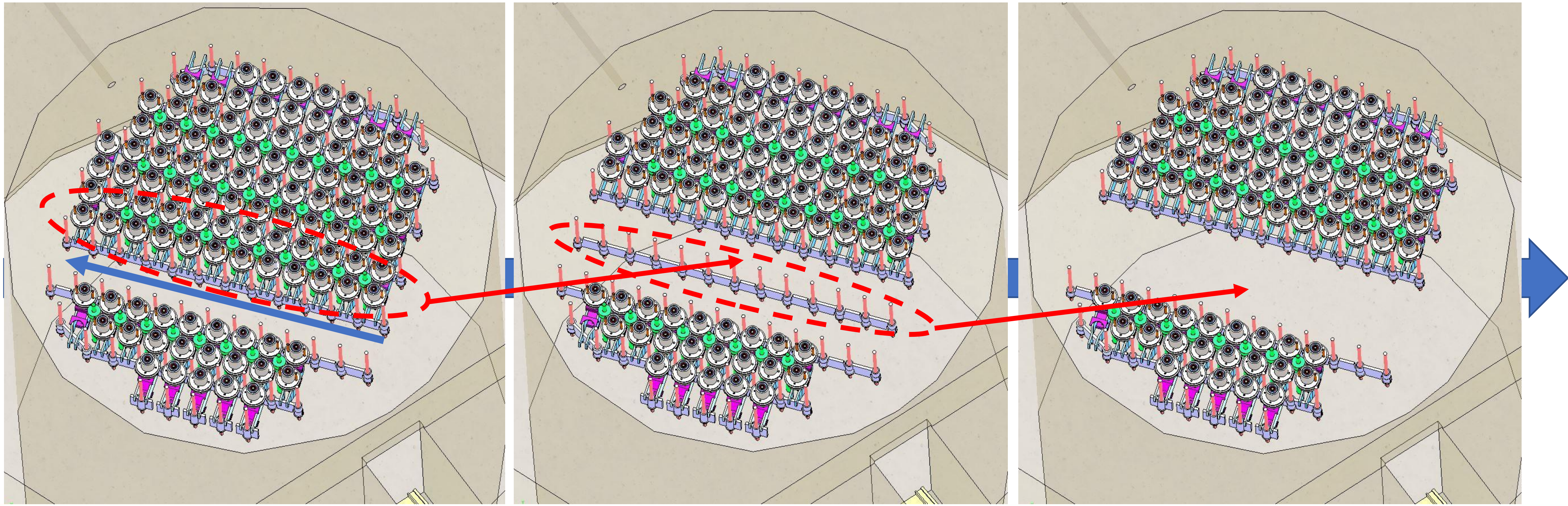
- **Delay the removal of the support bars as late as possible**
- Free up space as you cut CRD-H
- Cuts out the visible CRD-H before removing the associated support elements
- Limit the presence of equipment being dismantled above the remotely operated tools



IV. IMPLEMENTATION STUDIES

4.10 DISMANTLING SCENARIO – APPROACH 2.1

Details of dismantling the CRD-H line by line



Reminder: 3-Withdrawal of the first line of CRD-H

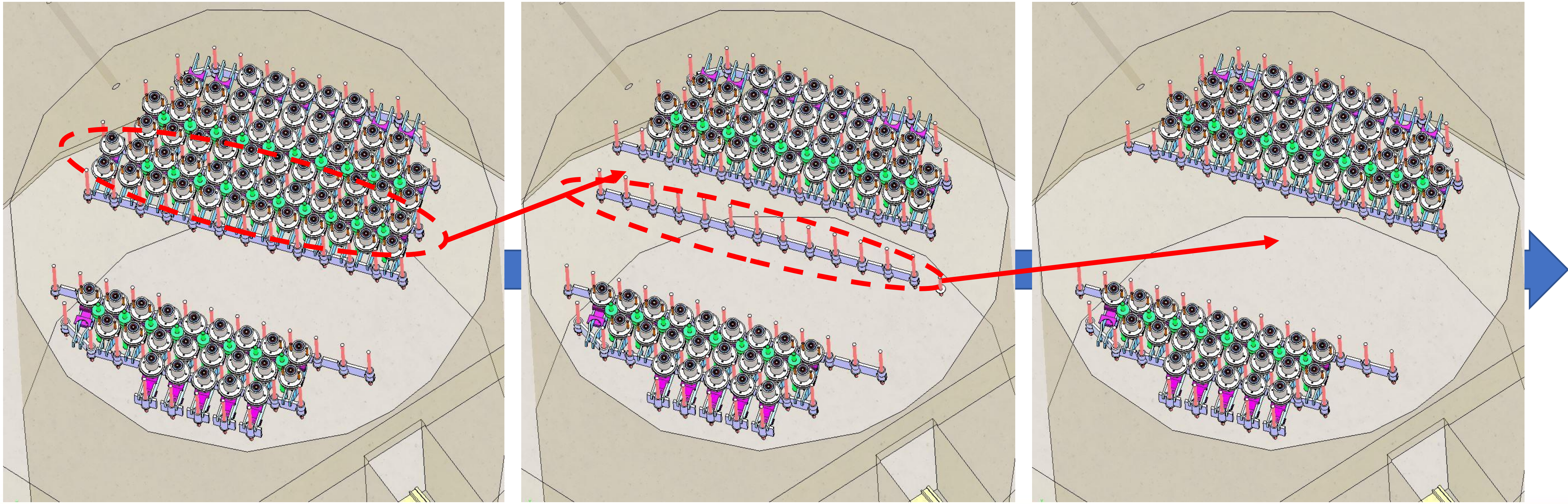
4-Removal of the second line

5-Removal of the free line of support bars

IV. IMPLEMENTATION STUDIES

4.10 DISMANTLING SCENARIO – APPROACH 2.1

Details of dismantling the CRD-H line by line



Reminder: 5-Removal of the free line support bars

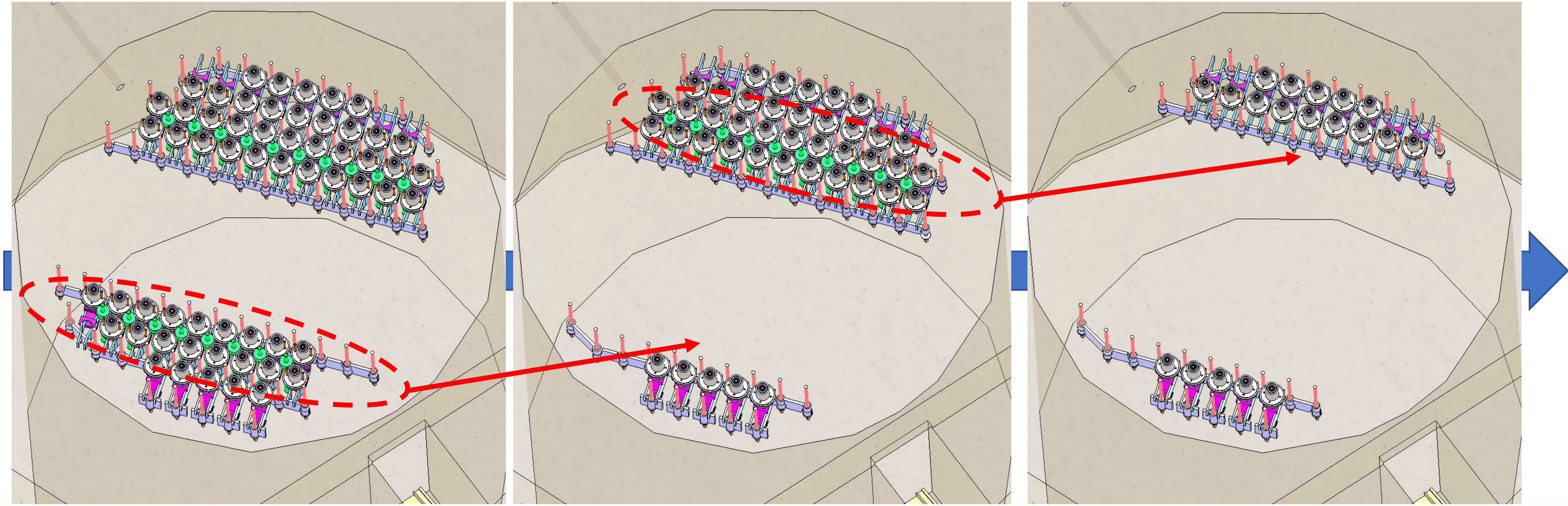
6-removal of next line of CRD-H

7-Removal of next free support bars line

IV. IMPLEMENTATION STUDIES

4.10 DISMANTLING SCENARIO – APPROACH 2.1

Details of dismantling the CRD-H line by line



Reminder: 7-Removal of next free support bars line

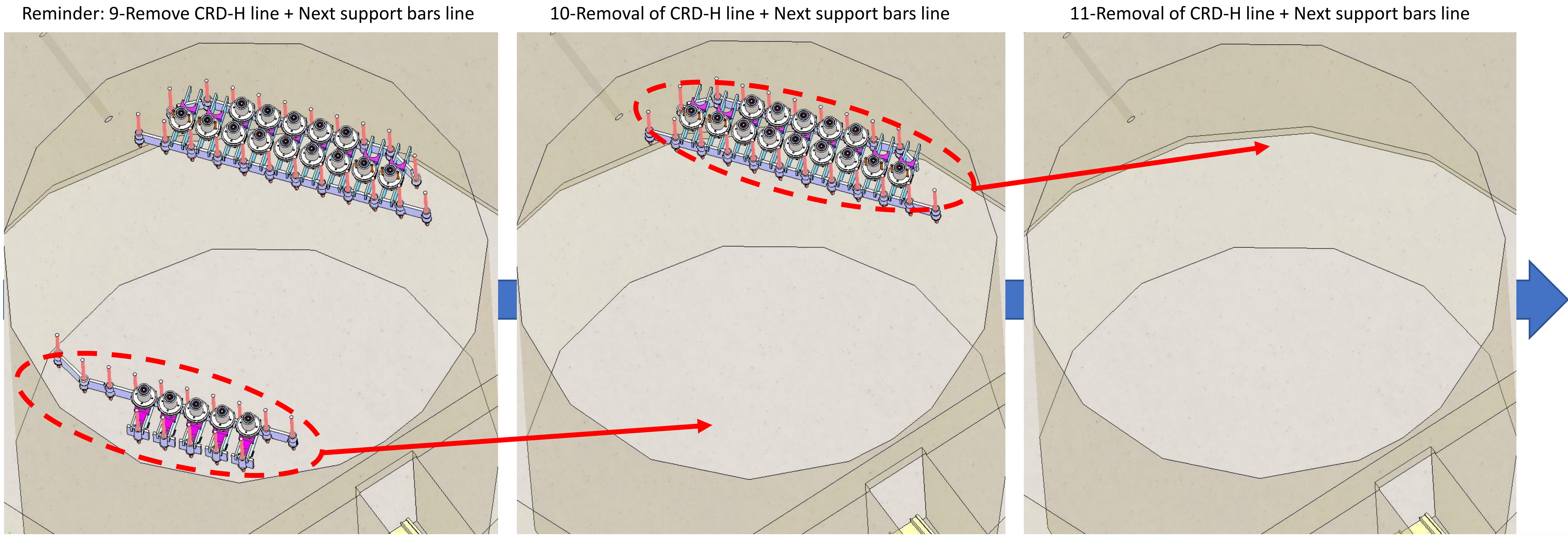
8-Removal of CRD-H line + Next support bar line

9-Removal of CRD-H line + Next support bars line

IV. IMPLEMENTATION STUDIES

4.10 DISMANTLING SCENARIO – APPROACH 2.1

CRD-H dismantling line by line



Reminder: 9-Remove CRD-H line + Next support bars line

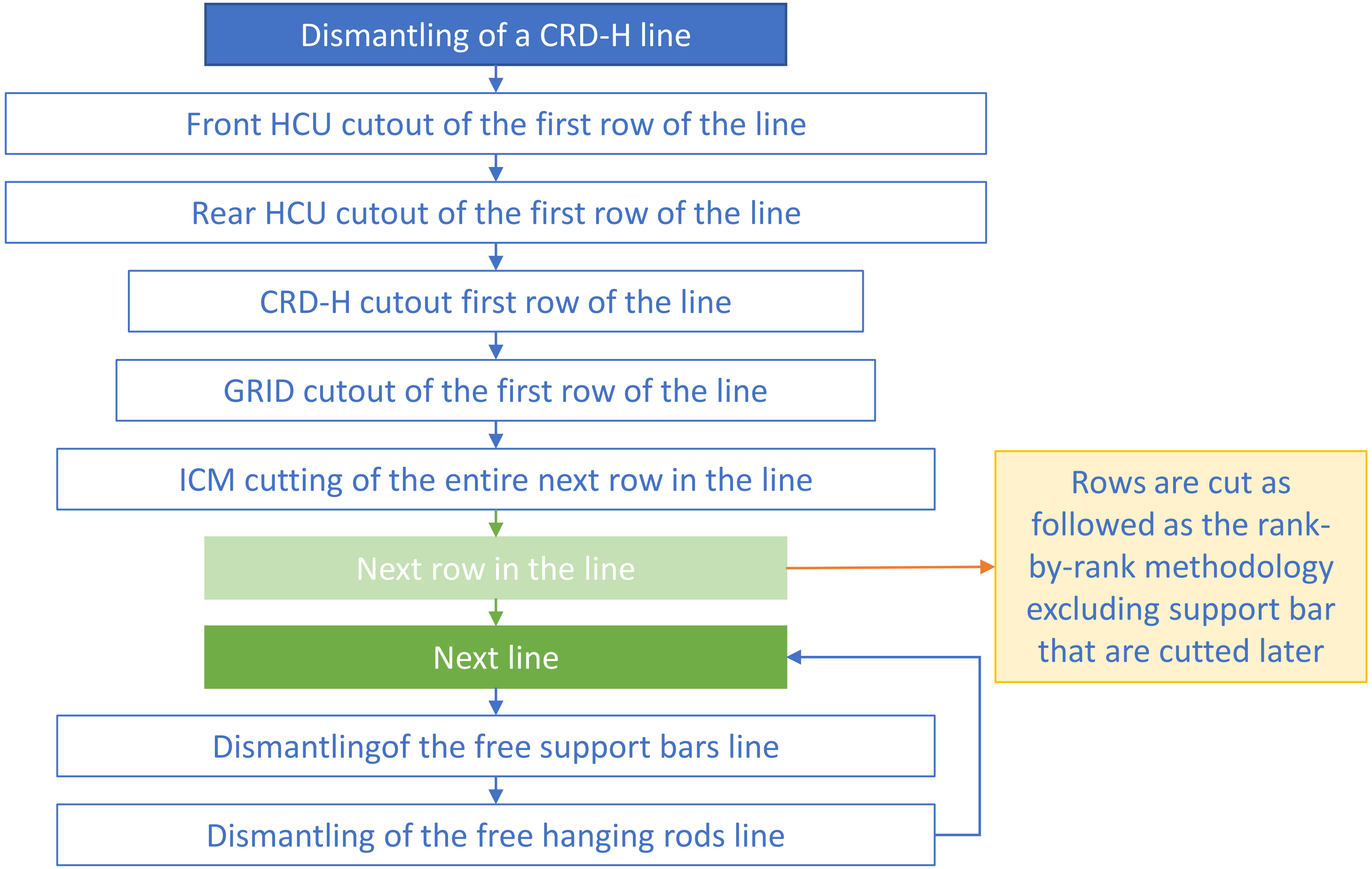
10-Removal of CRD-H line + Next support bars line

11-Removal of CRD-H line + Next support bars line

IV. IMPLEMENTATION STUDIES

4.10 DISMANTLING SCENARIO – APPROACH 2.1

Details Dismantling CRD-H line by line



Dismantling of a CRD-H line

Front HCU cutout of the first row of the line

Rear HCU cutout of the first row of the line

CRD-H cutout first row of the line

GRID cutout of the first row of the line

ICM cutting of the entire next row in the line

Next row in the line

Next line

Dismantlingof the free support bars line

Dismantling of the free hanging rods line

Rows are cut as followed as the rank-by-rank methodology excluding support bar that are cutted later

IV. IMPLEMENTATION STUDIES

4.10 DISMANTLING SCENARIO – APPROACH 2.1

SYNTHESIS OF CONFIGURATIONS USED FOR 1 ARM SCENARIO

Dismantling phases	One arm		
	Arm macro config	Number of configurations per phase	Description
Spreading out	Wrench Curved laser head + dust collection head Curved laser head + wrench + dust collection head	3	**Wrench** to set the bucket and drop off pieces inside MUC **Curved laser head + aspiration bell** to dismantle grids, supports bars **Curved laser head + wrench + dust collection head** to dismatle rods
ICMs	Wrench Curved laser head + wrench Curved laser head	3	**Wrench** to set the bucket bellow the ICM and drop off pieces inside MUC **Linear head** to cut the bottom part of the ICM **Linear head + wrench** to remove top part of the ICMs
HCUs	Wrench Curved laser head + dust collection head Shear tool	3	**Wrench** to set clips on CRDs and HCUs and to drop off pieces inside MUC **Curved laser head + dust collection head** to cut HCUs **Shear** in order to cut the HCU horizontal parts
CRDs	Wrench Curved laser head Curved laser head + wrench + dust collection head	3	**Wrench** to set the bucket bellow the CRD, drop off pieces inside MUC, remove the flange and set the fall-arrest systems in CRDs **Curved laser head** to cut the bottom part of the flange **Curved laser head + wrench + dust collection head** to cut and carry each part of the CRD
Grids	Wrench Curved laser head + dust collection head	2	**Wrench** to set the bucket bellow the grid and drop off pieces inside MUC **Curved laser head + dust collection head** to cut each part of grids
Support bar	Wrench Curved laser head + dust collection head	2	**Wrench** to set the bucket bellow the grid support and drop off pieces inside MUC **Curved laser head + dust collection head** to cut each parts of support bar
Rods	Curved laser head + wrench + dust collection head	1	**Curved laser head + wrench + dust collection head** to cut and carry rods
Beams	Wrench Curved laser head Curved laser head + dust collection head	3	**Wrench** to set angle brackets, the bucket and drop off pieces inside MUC **Curved laser head** to cut the top part of beams **Curved laser head + dust collection head** to cut the rest of beams

IV. IMPLEMENTATION STUDIES

4.10 DISMANTLING SCENARIO – APPROACH 2.1

SYNTHESIS OF CONFIGURATIONS USED FOR 2 ARMS SCENARIO

Dismantling phases	Two arms		
	Arm macro config	Number of configurations per phase	Description
Spreading out	Arm 1: Curved laser head + dust collection head Arm2: Wrench	1	**Wrench** to set the bucket if it is necessary, grab every pieces and drop them in a MUC **Curved laser head + dust collection head** to cut grids, support bars and rods
ICMs	Arm 1: Curved laser head Arm2: Wrench	1	**Wrench** to set the bucket if it is necessary, grab every pieces and drop them in a MUC **Curved laser head** to cut each parts of the ICMs
HCUs	Arm 1: Curved laser head + dust collection head Shear tool Arm2: Wrench	2	**Wrench** to set clips on CRDs and HCUs and to drop off pieces inside MUC **Curved laser head + dust collection head** to cut HCUs **Shear** in order to cut the HCU horizontal parts
CRDs	Arm 1: Curved laser head Curved laser head + dust collection head Arm2: Wrench	2	**Wrench** to set the bucket bellow the CRD, drop off pieces inside MUC, remove the flange and set the fall-arrest systems in CRDs **Curved laser head** to cut the bottom part of the flange **Curved laser head + dust collection head** to cut each parts of the CRDs
Grids	Arm 1: Curved laser head + dust collection head Arm2: Wrench	1	**Wrench** to set the bucket if it is necessary, grab every pieces and drop them in a MUC **Curved laser head + dust collection head** to cut grids
Support bar	Arm 1: Curved laser head + dust collection head Arm2: Wrench	1	**Wrench** to set the bucket if it is necessary, grab every pieces and drop them in a MUC **Curved laser head + dust collection head** to cut each parts of grid supports
Rods	Arm 1: Curved laser head + dust collection head Arm2: Wrench	1	**Wrench** to set the bucket if it is necessary, grab every pieces and drop them in a MUC **Curved laser head + dust collection head** to cut each parts of the rods
Beams	Arm 1: Curved laser head Curved laser head + dust collection head Arm2: Wrench	2	**Wrench** to set angle brackets, the bucket if it is necessary and drop off pieces inside MUC **Curved laser head** to cut the top part of beams **Curved laser head + dust collection head** to cut the rest of beams

4.11 DAMAGED EQUIPMENTS MANAGEMENT

Damaged HCU scenario

Possible Damaged Situation	Scenario impact	Alternative scenario	Feasibility Test	Limit	Additionnal information
Contaminated water inside	YES	YES Additionnal phase to empty: drilling HCU	YES, draining shoot done in CEA	/	No too high pressure during drilling => contaminated water remains in the pedestal
One HCU on the CRD-H is missing	NO	Not needed	/	/	/
Twisted	YES	Specific Clips or shears	/	/	/
Welded to the CRD-H	YES	Additionnal phase: laser cutting to free space for the clip	YES, same as long distance cut of HCU	/	/

Damaged elements will take longer to process than an intact element. This variation is estimated to be 20-50% more time depending on the size and initial complexity of the element.

4.11 DAMAGED EQUIPMENTS MANAGEMENT

Damaged CRD-H scenario

Possible Damaged Situation	Scenario impact	Alternative scenario	Feasibility Test	Limit	Additionnal information
Full of Fuel Debris	NO	Not needed	YES, thickest CRD-H configuration	/	/
Partial lack of external layer	YES	Additionnal phase: using cylindrical bucket	/	/	/
Top part of CRD-H broken blocked in the structure	YES	Depending of blocking	/	YES, if access to blocked part is too limited	Require additionnal investigation
Flange overloaded with corium	YES	Additionnal phase: laser cut in smaller parts the flange	/	YES, needs the 2 arms configuration	/
Twisted CRD-H	NO		YES, same as angular cut	/	Maybe smaller parts
Missing grid below the flange	YES	Additionnal phase: set the recovery bucket or the recovery platform	/	/	/

Damaged elements will take longer to process than an intact element. This variation is estimated to be 20-50% more time depending on the size and initial complexity of the element.

IV. IMPLEMENTATION STUDIES

4.11 DAMAGED EQUIPMENTS MANAGEMENT

Damaged ICM scenario or damaged rod scenario

Possible Damaged Situation	Scenario impact	Alternative scenario	Feasibility Test	limit	Additionnal information
Broken Bottom part	NO	/	/	/	/
Unable to reach	YES	/	YES, long distance cut	More than 500 mm	/
Top part broken and blocked in the structure	YES	Depending of blocking	/	/	Require additionnal investigation
Twisted ICM/rod	NO	/	/	/	/

Damaged elements will take longer to process than an intact element. This variation is estimated to be 20-50% more time depending on the size and initial complexity of the element.

4.11 DAMAGED EQUIPMENTS MANAGEMENT

Damaged grid scenario or damaged support bar scenario

Possible Damaged Situation	Scenario impact	Alternative scenario	Feasibility Test	Limit	Additionnal information
Impossibility to set the recovery bucket	YES	Set the recovery platform	/	/	/
Welded	YES	Additionnal cut	/	/	/
Unable to reach	YES	/	YES, long distance cut	More than 500 mm	/
One rod is missing	NO	/	/	/	/

Damaged beam scenario

Possible Damaged Situation	Scenario impact	Alternative scenario	Feasibility Test	Limit	Additionnal information
Central part of the beam broken	NO	Compatible with one of the proposed scenario	/	YES if more than 3 beams damaged side by side	/
Central beam twisted	NO	Compatible with one of the proposed scenario	/	/	/

IV. IMPLEMENTATION STUDIES

4.12 OPERATIONAL TIME – ESTIMATION OF DISMANTLING TIME & WASTE MANAGEMENT

Assumptions and estimates of elements to be dismantled

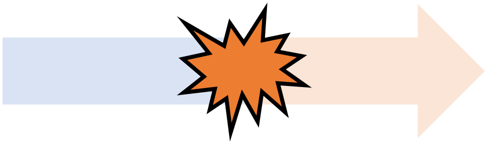
For the studies, a number of intact and damaged elements in the pedestal were estimated. Between 20 and 40% of the elements are damaged, mainly those in the center of the pedestal. The following figures are estimated for the pedestal of a single reactor unit (reactor unit 2 or 3).

Estimated number of **elements** in the pedestal

137	CRD-H
137	HCU pairs
50	ICM
75	Grid elements
88	Support bars
95	Hanger rods
8	Beams

For an **intact** pedestal

The events caused damage to the pedestal and therefore to the elements to be treated



Between 20 and 40% of the elements were damaged

Estimated number of **damaged elements** in the pedestal

30	CRD-H	/ 137
30	HCU pairs	/ 137
15	ICM	/ 50
25	Grid elements	/ 75
25	Support bars	/ 88
30	Hanger rods	/ 95
2	Beams	/ 8

For a **damaged** pedestal

Deformed, merged with other elements, skewed, etc.

Longer to dismantle

Damaged elements will take longer to process than an intact element. This variation is estimated to be 20-50% more time depending on the size and initial complexity of the element.

IV. IMPLEMENTATION STUDIES

4.12 OPERATIONAL TIME – ESTIMATION OF DISMANTLING TIME & WASTE MANAGEMENT

Dismantling time with 1 arm configuration

The scenario with a 1-arm configuration is the longest of the scenarios presented. The main constraints with this configuration are the multiple tool and configuration changes (alternation between cutting tool and gripping tool) and the need to constantly install local fall arrest solutions to retain the dismantling element.

x1

Dismantling with a **1 arm** configuration scenario

For **one** reactor unit	For **all** reactor units
662 Days = 1,81 Years	1724 Days = 4,72 Years

FOR ONE REACTOR UNIT (2 OR 3)

ELEMENTS TO BE DISMANTLED		CONFIGURATION FOR DISMANTLING		DISMANTLING TIME	
137	CRD-H	137	with a 1 arm configuration	5003	Hours
137	HCU pairs	137	with a 1 arm configuration	4756	Hours
50	ICM	50	with a 1 arm configuration	1370	Hours
75	Grid elements	75	with a 1 arm configuration	273	Hours
88	Support bars	88	with a 1 arm configuration	155	Hours
95	Hanger rods	95	with a 1 arm configuration	1993	Hours
8	Beams	8	with a 1 arm configuration	351	Hours

579 days
+ Equipment maintenance and availability
+ Waste disposal
= **662 days**

1724 days
FOR ALL 3 REACTOR UNITS

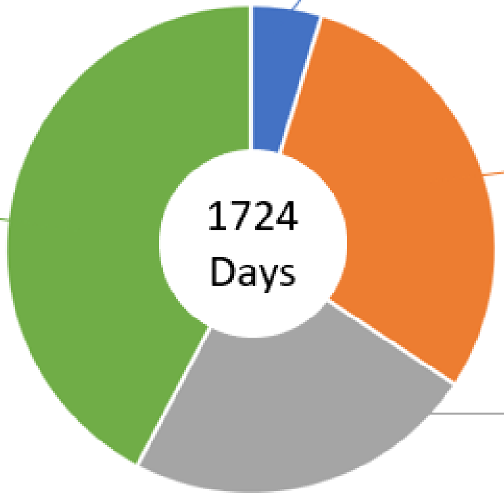
IV. IMPLEMENTATION STUDIES

4.12 OPERATIONAL TIME – ESTIMATION OF DISMANTLING TIME & WASTE MANAGEMENT

Dismantling time with 1 arm configuration

The breakdown of days to dismantle the 3 reactor units with this configuration is shown below. The number of days associated with the performance of the cutting tool (laser tool) is fixed and is estimated at 80 days (which represents about 5% of the total estimated time). The longest times are for tool and configuration changes and gripping tool management.

	For **one** reactor unit	For **all** reactor units
x1 Dismantling with a **1 arm** configuration scenario	662 Days = 1,81 Years	**1724 Days** = 4,72 Years



About **80 days of pure cutting** (performance of the laser cutting tool)

For a total distance of about 1.5 km* of cutting

About 510 days of cut preparation

About 400 days of tooling and configuration changes

About 730 days of maintenance and waste management

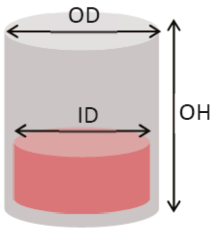
* : hypothesis next page

IV. IMPLEMENTATION STUDIES

4.12 OPERATIONAL TIME – ESTIMATION OF DISMANTLING TIME & WASTE MANAGEMENT

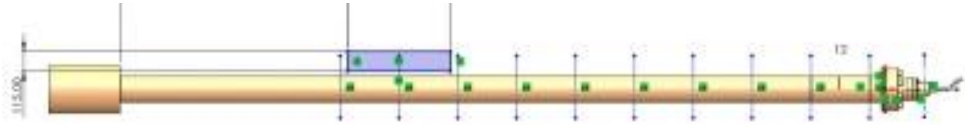
Hypothesis of the dimensions of the cut sections leading to cutting length

The size of the cut sections of an element is calculated so as to respect the dimensional constraints of the waste containers (UC and MUC) as well as to respect the lifting capacities of the system. For small components, their cut-outs are sized so that as many as possible can be placed in the associated container (while respecting the maximum mass imposed). Otherwise, for larger components (such as a CRD-H), they are sized to fit as snugly as possible into the container.



UNIT CAN - Geometry	
ID [mm]	198
IH [mm]	360
OD [mm]	210
OH [mm]	366
Wall/Bottom thickness [mm]	6
Material	SUS304L Stainless Steel
Housing volume [L]	11,1
Dry weight[1] [kg]	10

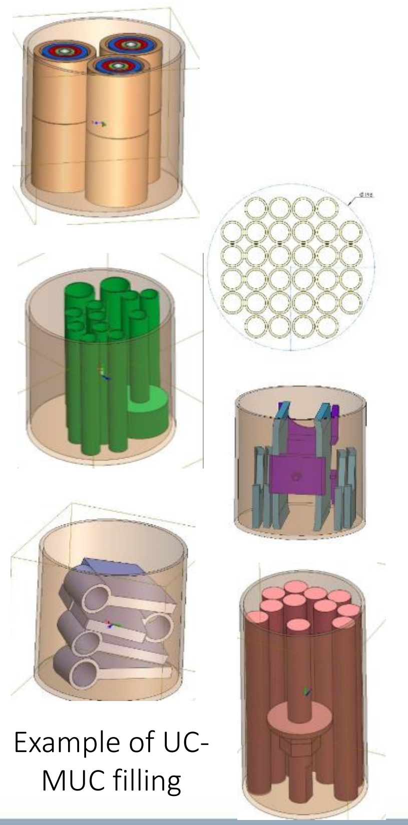
MITIGATING UNIT CAN – Geometry	
ID [mm]	370
IH [mm]	360
OD [mm]	390
OH [mm]	370
Wall/Bottom thickness [mm]	10
Material	SUS304L Stainless Steel
Housing volume [L]	38,7



Example of cutting a CRD-H

- For the CRD-H (not including the flange), these are cut into 9 pieces so that each section can be fitted with an MUC container (each section is 340mm long).
- For the HCUs, these are cut into 15 pieces so that each section can be fitted with a UC container (each section is 330mm long on average).
- For the ICMs, these are cut into 12 pieces so that each section can be fitted into an MUC container (each section is 340mm long).
- The pieces of the grid structure are cut into 8 pieces so that an entire element can be integrated into an MUC container.
- The support bars are cut into 2 pieces so that 2 complete elements can be integrated into an MUC container.
- The tie rods are cut into 11 pieces, so that a whole element can be fitted into a UC container (each section is 345mm long).
- For the beams, they are cut so that each small piece can be integrated into a UC container.

The number of cutting parts multiplied by the section of each part leads to a cutting length close to 1,5 km.



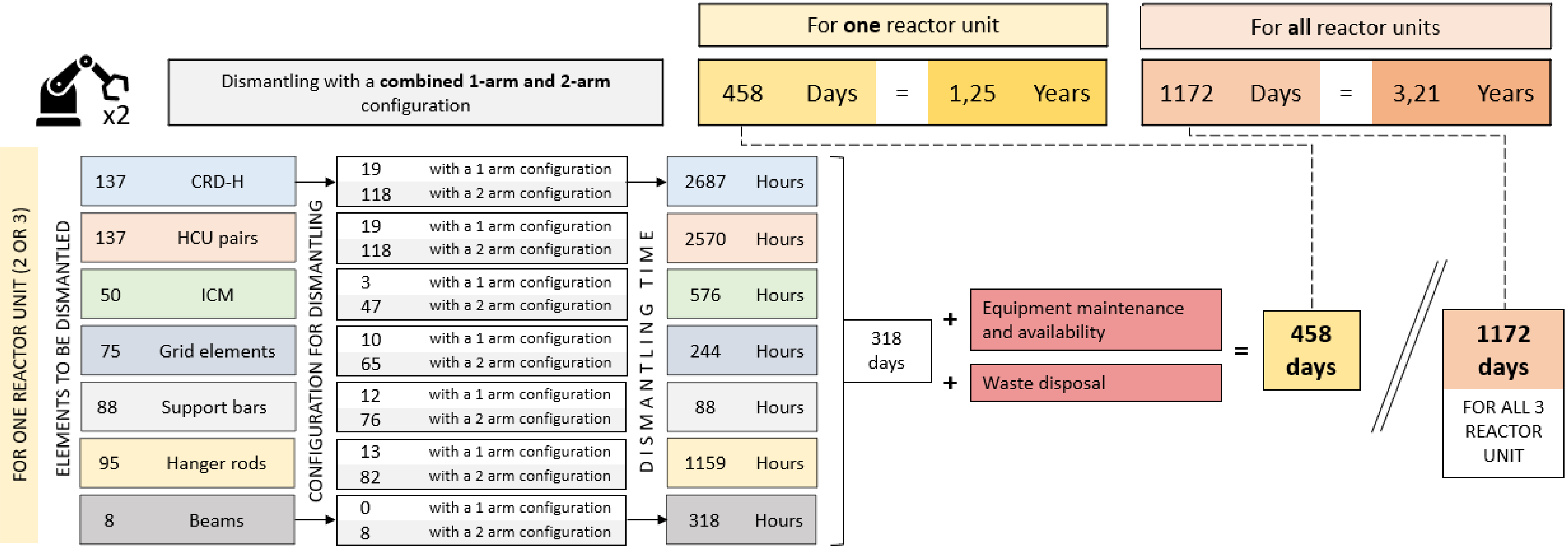
Example of UC-MUC filling

IV. IMPLEMENTATION STUDIES

4.12 OPERATIONAL TIME – ESTIMATION OF DISMANTLING TIME & WASTE MANAGEMENT

Dismantling time with a combined configuration of 1 arm and 2 arms

Compared to the 1-arm configuration, the 2-arm configuration is much faster since the processing time of the elements is shortened (possibility to perform cutting and gripping operations in parallel). This scenario is not purely with 2 arms since the space requirement in the pedestal requires processing of the elements with 1 arm first (in order to allow deployment of 2 arms).



x2

Dismantling with a **combined 1-arm and 2-arm** configuration

For **one** reactor unit: 458 Days = 1,25 Years

For **all** reactor units: 1172 Days = 3,21 Years

FOR ONE REACTOR UNIT (2 OR 3)

ELEMENTS TO BE DISMANTLED		CONFIGURATION FOR DISMANTLING	DISMANTLING TIME
137	CRD-H	19 with a 1 arm configuration 118 with a 2 arm configuration	2687 Hours
137	HCU pairs	19 with a 1 arm configuration 118 with a 2 arm configuration	2570 Hours
50	ICM	3 with a 1 arm configuration 47 with a 2 arm configuration	576 Hours
75	Grid elements	10 with a 1 arm configuration 65 with a 2 arm configuration	244 Hours
88	Support bars	12 with a 1 arm configuration 76 with a 2 arm configuration	88 Hours
95	Hanger rods	13 with a 1 arm configuration 82 with a 2 arm configuration	1159 Hours
8	Beams	0 with a 1 arm configuration 8 with a 2 arm configuration	318 Hours

318 days + Equipment maintenance and availability + Waste disposal = **458 days**

1172 days
FOR ALL 3 REACTOR UNIT

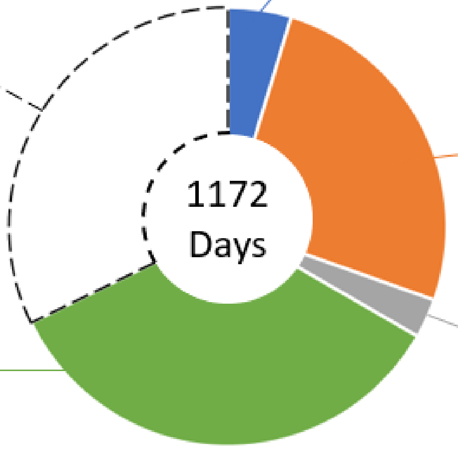
IV. IMPLEMENTATION STUDIES

4.12 OPERATIONAL TIME – ESTIMATION OF DISMANTLING TIME & WASTE MANAGEMENT

Dismantling time with a combined configuration of 1 arm and 2 arms

The breakdown of days to dismantle the 3 reactor units with this configuration is shown below. The number of days associated with the performance of the cutting tool (laser tool) is fixed and is estimated at 80 days (which represents about 7% of the total estimated time). Compared to the pure 1-arm configuration, this one requires more maintenance as 2 arms are deployed. Approximately 30% days saved compared to a purely 1-arm configuration.

	For **one** reactor unit	For **all** reactor units
x2 Dismantling with a **combined 1-arm and 2-arm** configuration	458 Days = 1,25 Years	**1172 Days** = 3,21 Years



About **80 days of pure cutting** (performance of the laser cutting tool)

For a total distance of about 1.5 km of cutting

Around 550 days saved compared to dismantling with a 1 arm configuration only

About 440 days of cut preparation

About 50 days of tooling and configuration changes

About 600 days of maintenance and waste management

IV. IMPLEMENTATION STUDIES

4.12 OPERATIONAL TIME – ESTIMATION OF DISMANTLING TIME & WASTE MANAGEMENT

Dismantling time in different configurations

At first, estimates of dismantling times were made according to 2 selected scenarios: with a 1 arm configuration & with a combined 1 arm and 2 arm configuration. These time estimates take into account all dismantling operations (processing of all elements to be dismantled, movement of the system, operator reflection, maintenance, etc.).

		For **one** reactor unit	For **all** reactor units
x1	Dismantling with a **1 arm** configuration scenario	662 Days = **1,81 Years**	1724 Days = **4,72 Years**
x2	Dismantling with a **combined 1-arm and 2-arm** configuration	458 Days = **1,25 Years**	1172 Days = **3,21 Years**
		Estimate for reactor unit 2 or 3	*Estimate for reactor unit 1, 2 and 3*

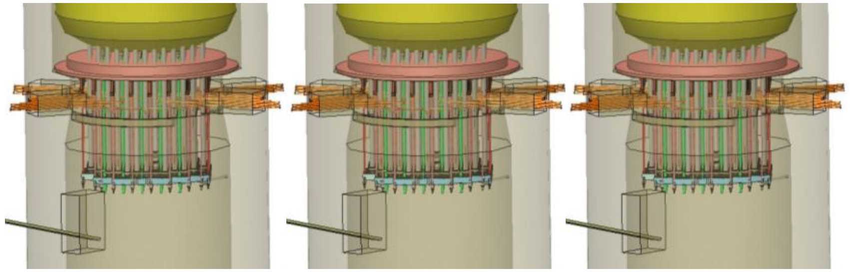
Onet Technologies CN considers that Reactor Unit 1 is smaller than Reactor Units 2 and 3. There are fewer components to dismantle inside Reactor Unit 1: it is faster to dismantle.

IV. IMPLEMENTATION STUDIES

4.12 OPERATIONAL TIME – ESTIMATION OF DISMANTLING TIME & WASTE MANAGEMENT

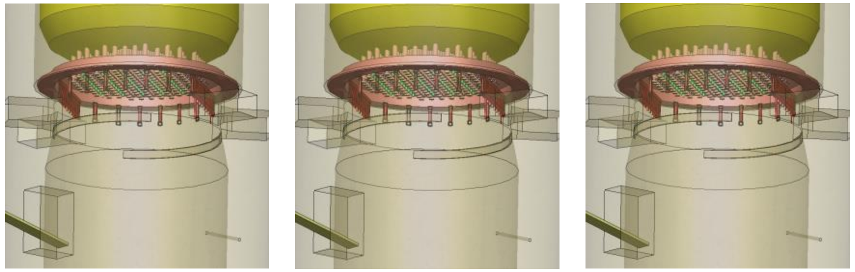
Balance of waste treated, number of cuts and containers deployed

In order to support the time calculations needed to estimate the dismantling time, calculations were made to determine the total number of cuts to be made, the total cutting distance, the total mass of elements to be dismantled and the number of waste disposal containers to be deployed (for the 3 units). Briefly, the results of the calculations for each of these categories are given below .

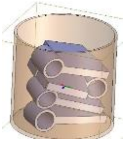


Initial state (the 3 reactor units)

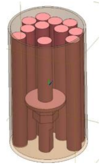
DISMANTLING



Final state (the 3 reactor units)



Unit Can



Mitigating Unit Can

- Approximately **220,000 kg of waste** to be extracted

This is a primary waste balance: induced waste (produced by the cutting tool or fall prevention solutions for example) is not considered. Only dismantled elements are considered.

- Approximately **3,750 waste containers** to be deployed (Around 1800 Unit Can and 1950 Mitigating Unit Can)

With maximum filling of each container with pieces of the same category (dismantling order) cut to dimensions defined by the established scenario.

- Approximately **21,700 cuts**

For an average of around 64 mm per cut.

- Approximately **60 kg of waste on average** per container

And approximately 70 kg including the weight of the container (Unit Can or Mitigating Unit Can).

V. RISKS & OPPORTUNITIES AND GLOBAL SYNTHESIS OF THE PROJECT

5.1 RISKS & OPPORTUNITIES

Remaining risks

Theme	Topics	Risk and challenge	Potential impact	Action plan proposal
Risk: Performance worksite	Laser design	Unsuccessful cutting of CRD-H due to limited power of the bent laser head (8kW)	Impossibility to unroll the scenario due to a lack of power	Design and develop a higher power **bent** laser head up to 14kW
Risk: Fall prevention	Robotics arms	Fall of a broken part on the robotic arms	Robotics arms blocked in the pedestal	Scenario already limit exposure to this risk Investigate in detail the part at the entrance of the pedestal Design and develop a robotic arm structure to lower the risk of jamming
Risk : Initial State	Dismantling scenario	A broken part in balance in the structure Too many possibilities of situations	Difficulty to unroll the scenario	Improve knowledge of the pedestal through visual investigation Define a platform that can resist to the fall of a CRD-H from 3 meters (martyr tiles protective mat for example)

V. RISKS & OPPORTUNITIES AND GLOBAL SYNTHESIS OF THE PROJECT

5.1 RISKS & OPPORTUNITIES

Remaining risks

Theme	Topics	Risk and challenge	Potential impact	Action plan proposal
Opportunity : Performance worksite	Robotics arms	Set as soon as possible the two arms robotics solution And automate part of interventions	Important gain on time schedule	Study and develop both robotics arms solutions : the one with one arm and the one with two arms Develop an automatic trajectory system
Risk &Opportunity : Fall prevention	Fuel debris	Fall of a damaged part on the fuel debris. Set quickly in place a bench of “sand” or neutrophage balls on the fuel debris and then martyr tiles protective mat	Possible criticality accident	Study to define the safety requirements, the compatible materials, the calculation sizing and the scenario to implement the solution Opportunity: allow the fall of object during the worksite on those martyr tiles, greatly simplify one arm scenario and replace the platform

V. RISKS & OPPORTUNITIES AND GLOBAL SYNTHESIS OF THE PROJECT

5.1 RISKS & OPPORTUNITIES

Fall prevention : highest risk and probably highest opportunity

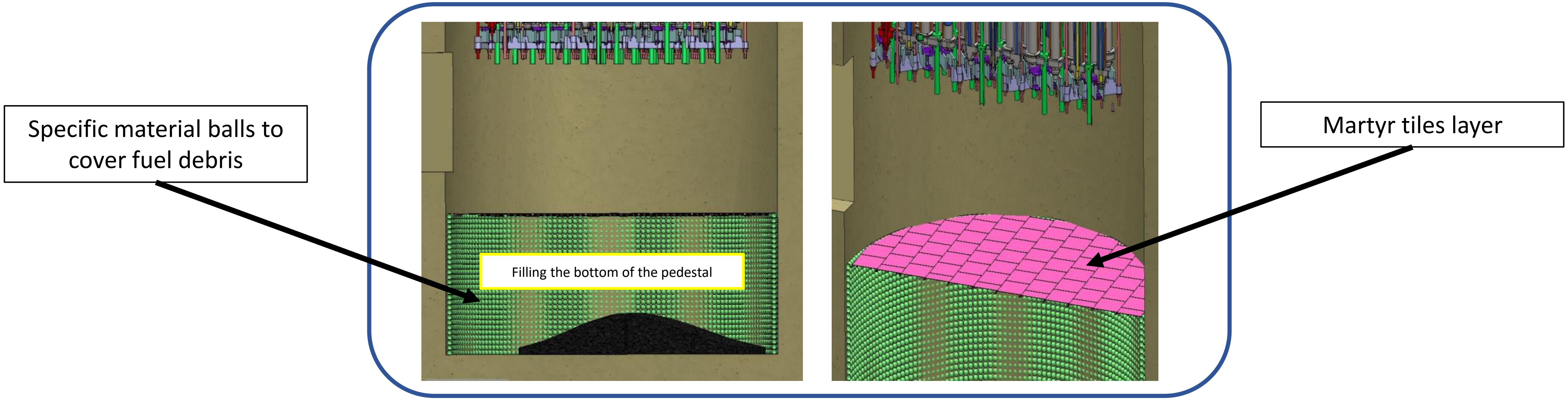
Recent investigation results in F1 show a high level of damages of the concrete walls.
Nota: These damages are not compatible with most of the platform concept.

The weakness of this state induces, in case of an earthquake, a raise of the risk a part to fall on the Fuel Debris without any control.

A proposal to lower this risk can be to set in place a shock absorbing layer.

This shock absorbing layer has to meet two challenges:
- Be easily spread on the Fuel Debris
- Maintain integrity during the fall of an object

Onet proposes a two layers concept platform :
- A first layer to cover the fuel debris safely
- A second layer made of martyr tiles to resist fallen object shock



Shock absorbing platform concept

V. RISKS & OPPORTUNITIES AND GLOBAL SYNTHESIS OF THE PROJECT

5.1 RISKS & OPPORTUNITIES

Fall prevention : highest risk and probably highest opportunity

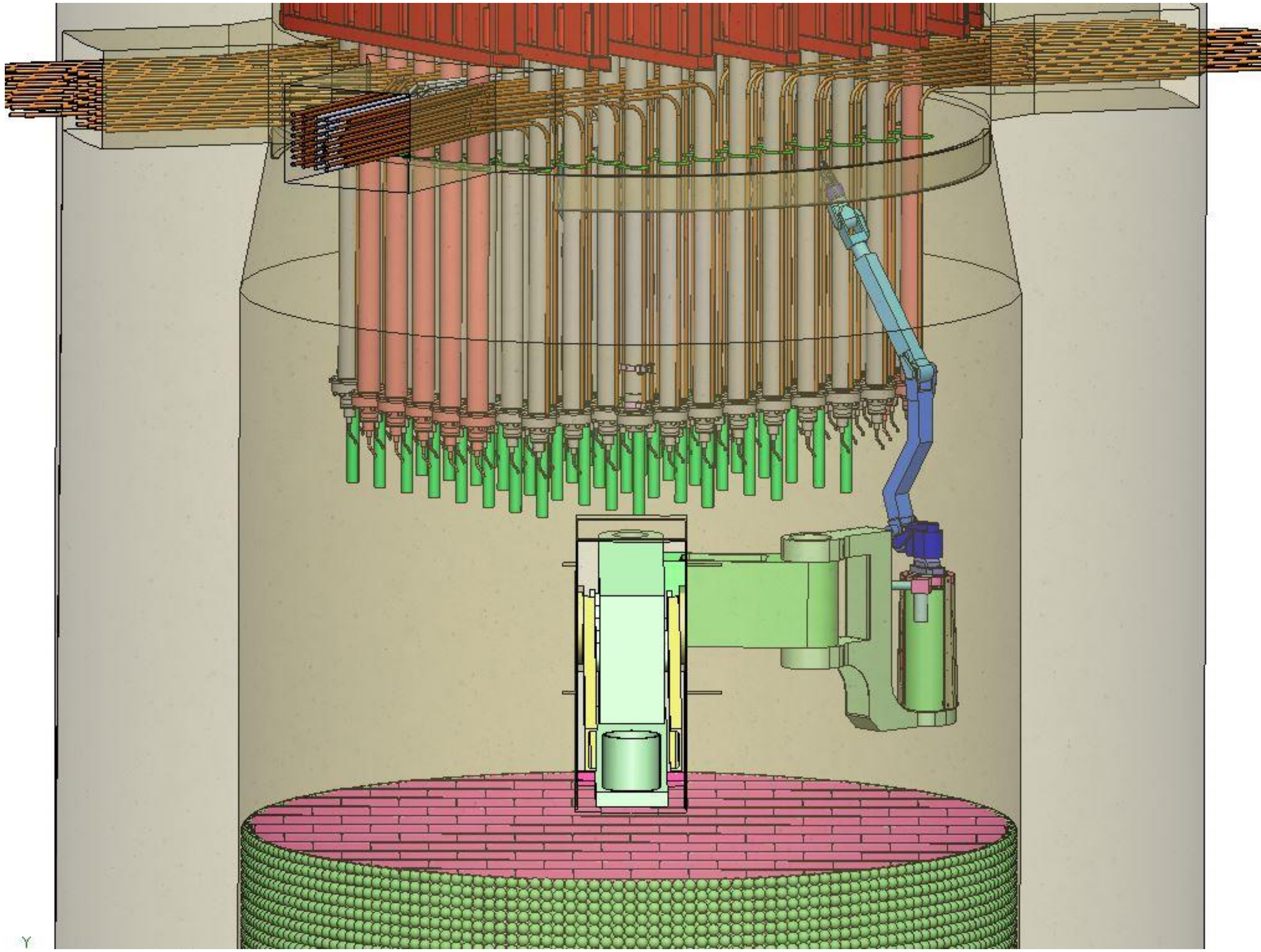
Explanation about the highest opportunity :

Once such a platform is set, the need and/or the requirement to prevent the fall of any cut parts does not exist anymore.

Nota: the cutting preparation includes to set in place the prevention fall system, which is an important part of the planning.

Without the prevent fall requirement :
- Dismantling scenario becomes easier
- Mechanical systems (robotic arm, …) are simplified
- The waste management can be optimised, by chosing the cut parts

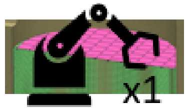
This is why it is probably the highest opportunity, that has been evaluated through a time schedule estimation.



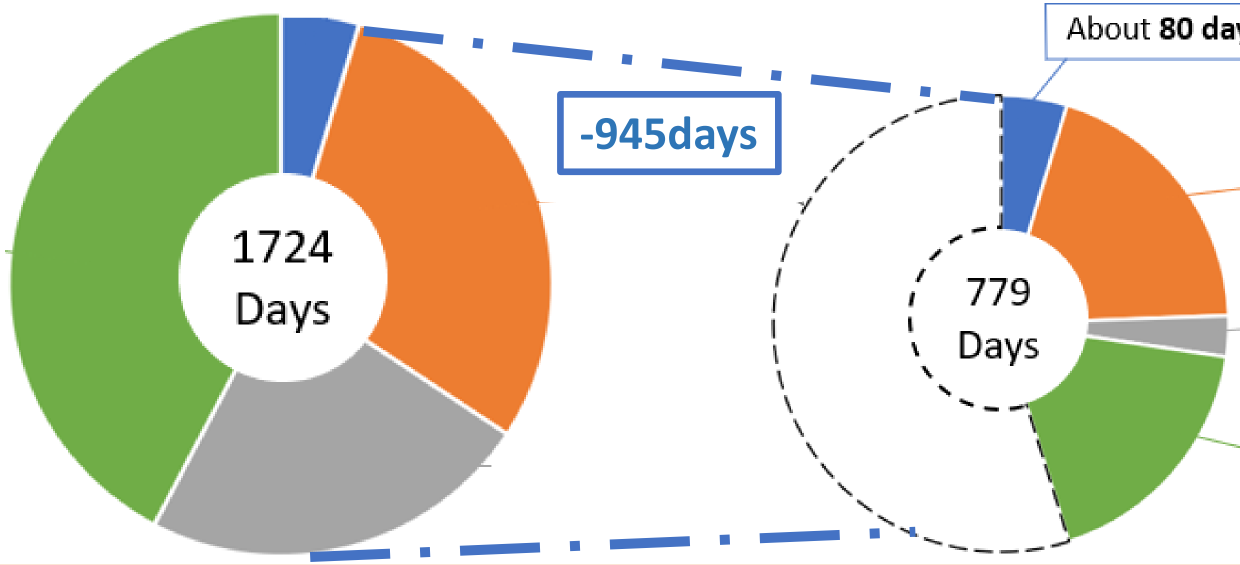
V. RISKS & OPPORTUNITIES AND GLOBAL SYNTHESIS OF THE PROJECT

5.1 RISKS & OPPORTUNITIES

Fall prevention : highest risk and probably highest opportunity



	For **one** reactor unit	For **all** reactor unit
Dismantling with a scenario of a **1 arm** configuration and the global fall arrest solution **"Shock-absorbing layer"**	282 Days = 0,77 Year	**717 Days** = 1,96 Years



About **80 days of pure cutting** (performance of the laser cutting tool)
For a total distance of about 1.5 km of cutting

About 340 days of cut preparation

About 50 days of tooling and configuration changes

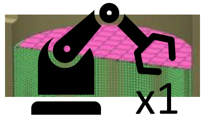
About 310 days of maintenance and waste management

V. RISKS & OPPORTUNITIES AND GLOBAL SYNTHESIS OF THE PROJECT

5.1 RISKS & OPPORTUNITIES

Fall prevention : highest risk and probably highest opportunity

Estimates of dismantling times were made according to 3 selected scenarios: with a 1 arm configuration; with a combined 1 arm and 2 arm configuration and a combined 1 arm and global shock absorption solution. These time estimates take into account all dismantling operations (processing of all elements to be dismantled, movement of the system, operator reflection, maintenance, etc.) but this does not consider the installation of the potential global fall arrest solution.

		For **one** reactor unit	For **all** reactor unit
x1	Dismantling with a **1 arm** configuration scenario	662 Days = **1,81 Years**	1724 Days = **4,72 Years**
x2	Dismantling with a **combined 1-arm and 2-arm** configuration	458 Days = **1,25 Years**	1172 Days = **3,21 Years**
 x1	Dismantling with a scenario of a **1 arm** configuration and the global fall arrest solution **"Shock-absorbing layer"**	282 Days = **0,77 Years**	717 Days = **1,96 Years**

-60%

Estimate for reactor unit 2 or 3

Estimate for reactor unit 1, 2 and 3

V. RISKS & OPPORTUNITIES AND GLOBAL SYNTHESIS OF THE PROJECT

5.2 Global synthesis of the project

The tests and study of this project have permit to :

- *compare and give an orientation in the choice of cutting tool for CRD-H*
- *propose a bunch o technical solutions to prevent the fall of object*
- *confirm the reachability and feasibility of tele-operability*
- *establish a scenario to dismantle the CRD-H zone with a one robotic arm solution equiped with a cutting laser head*
- *propose variants to take into account the 1F actual situation, a damaged installation*
- *give a first estimation of the duration of worksite*

To be fully feasible, this scenario requires the development of a 14kW bent laser head.

The shock absorbing layer, if feasible, represent a great opportunity to lower the earthquake risk
and, at the same time, simplify and accelerate worksite dismantling.
Another great potential acceleration of onsite work is to develop an automate trajectory generator.

Thank you for your attention.