Assessment of ultrasonic cutting technology for nuclear de-comissioning projects

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Abstract. Traditional cutting methods for decommissioning operations are not effective for viscoelastic materials such as the bitumen used in subcritical tanks, coatings and joints. Ultrasonic cutting, as currently used in the plastics and food industries, guaranties a clean cut with no substantial fouling of the tool for these materials. This technology has not yet been adapted to the needs of the nuclear industry. The feasibility of ultrasonic cutting for bitumen has therefore been investigated by defining the operating range with respect to the constraints of a nuclear environment. A prototype has been developed to evaluate the process with teleoperation in a non-radioactive but otherwise representative environment.

KEYWORDS: Dismantling, Bitumen, Ultrasonic, Assessment

1. Introduction

The cutting tools traditionally used on decommissioning sites or in nuclear waste management, such as band saws, reciprocating saws and grinders tend to become stuck when used to cut viscoelastic materials such as nuclear waste bitumen. Ultrasonic cutting has been identified as promising for this type of operation but has never been applied in a nuclear setting.

Ultrasound is widely used in industry, agriculture and medicine as an effective and precise means of cutting particular types of material such as viscoelastic fluids. Driven by an electroacoustic transducer, the micrometer-scale ultrasonic vibrations of the sonotrode allow products to be cut in precise patterns [4, 5].

Pure bitumen behaves as a viscoelastic fluid at low frequencies, with the loss modulus (G'') greater than the storage modulus (G'). At high frequencies however, the loss modulus decreases and in the operating domain of ultrasonic cutters (20–70 kHz), the material behaves as a solid, allowing it to be cut without fouling the tool. Automated and robotic ultrasonic cutting is widespread in industry. In nuclear decommissioning however, where operations are typically unique and cannot be repeated automatically, specific remote-control systems are required.

To verify the adaptability of ultrasonic cutting to the constraints of teleoperated interventions in hostile nuclear-type environments, the CEA has tested the process in normal operation and explored technical solutions to make it resilient to exceptional events.

2. Material and methods

The evaluation program was designed to firstly consider normal operation conditions, namely a clean cut without fouling of the ultrasonic tool and with cutting temperatures lower than 150°C. Malfunctions leading to temperature increases in the bitumen material and associated elements were then studied to evaluate technical solutions to maintain temperatures below 180°C.

2.1. Evaluation tests of the ultrasonic cutting system in normal operation

The operational range in which high quality ultrasonic cuts (clean, without tool fouling) are obtained and temperatures remain below 150°C was determined in several stages with:

1. Cutting Optimization (CO) tests on pure bitumen over the complete operational range of the cutting devices, to identify the limits of the process.
2. Temperature Optimization (TO) tests on pure bitumen over a more limited operational range to determine the maximum cutting temperature as a function of the cutting parameters.
3. Cutting and Temperature Optimization (CTO) tests on pure bitumen and bitumen coating with salt concentrations of 23–46 wt% over the same range as the TO tests.

feed rate
These tests were used to determine the optimal parametric domain for the ultrasonic cutting of bitumen in all environments (temperature, amplitude, feed rate). Samples were not cut in batches but following a protocol that ensured the same starting conditions for each cut (resetting the reference frequency, cleaning the probe of all bitumen residues, and ensuring the sonotrode was at the recommended temperature).
The CTO experiments performed on pure bitumen and bitumen coating with 23–46 wt% salt were used to confirm the results of the CO and TO tests on pure bitumen and evaluate the effects of the presence of salts in the bitumen matrix on cut/extraction quality and on the maximum cutting temperature.
The experimental setup used involved ultrasonic cutting tools mounted on an instrumented electronic press inside an air-conditioned and ventilated chamber. Bitumen samples with different salt concentrations were then cut in batches (Figure 1).

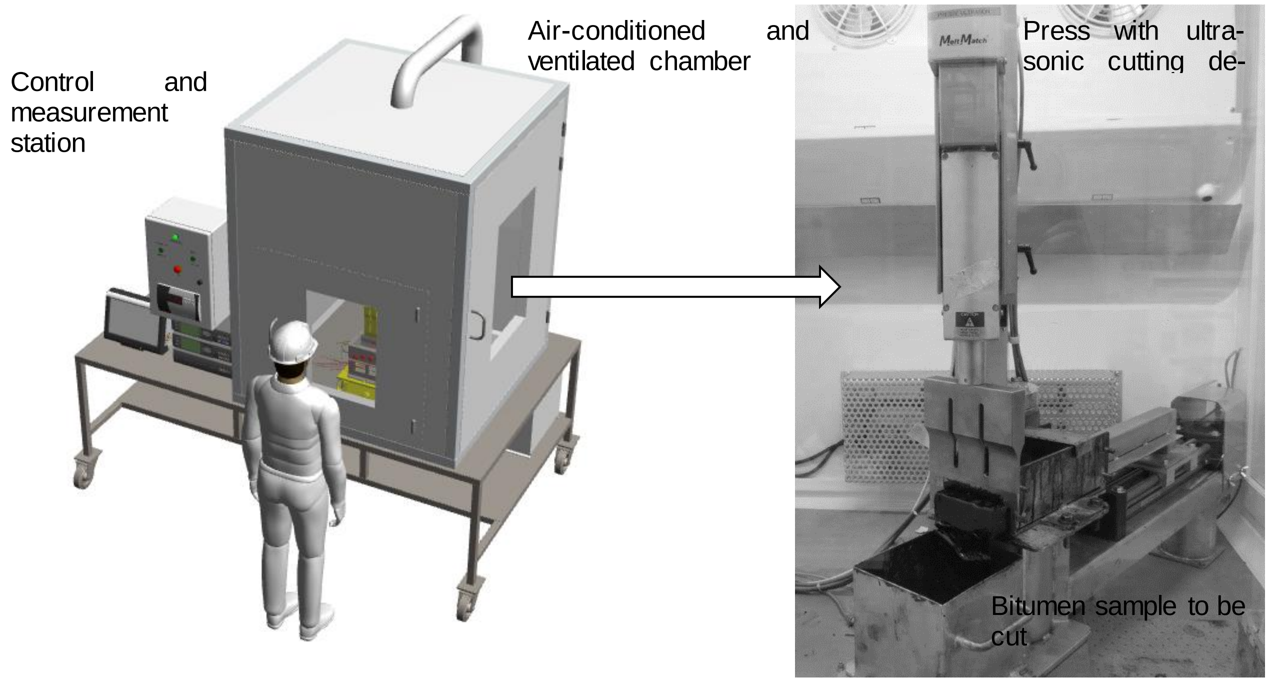

Figure 1 – Experimental setup used for the cutting optimization tests.

2.2. Robustness tests of the ultrasonic cutting system in exceptional events

The “exceptional” events considered were those caused by device malfunction and/or incorrect parameterization leading to the temperature of the bitumen or environment rising above 180°C.
To exhaustively survey these situations, all system malfunctions not directly caused by the ultrasonic cutter were considered. The latter were not investigated because the decrease in cutting performance and/or power loss or frequency instabilities they cause immediately trigger shutdown of the ultrasounds. Regarding parameterization errors of the ultrasonic cutting system, these can be avoiding by limiting oscillation amplitudes, feeding rates and the complexity of control operations.
The system used to operate the ultrasonic cutter—a manual or motorized rail or a teleoperated robotic arm—can block the sonotrode in the bitumen with the ultrasounds turned or bring it into contact with other materials, leading in both cases to substantial heating. These two types of events were studied through specific tests to identify possible corrective measures, designed to control the process and meet thermal requirements.

2.2.1. Exceptional event tests involving the sonotrode becoming stuck in the bitumen

Ultrasonic cutting is a chiefly mechanical process and the associated friction and dissipation of acoustic power from the compression waves lead to local heating in the cutting area. For safety reasons, the temperature must not rise above the autoignition temperature of bitumen either in normal operation or exceptional circumstances. Tests at the limits of the operational range were conducted with pure bitumen and bitumen coating with 46 wt% salt (STEL WB) by applying ultrasounds with 20 and 30 kHz cutters continuously for up to 2 h.

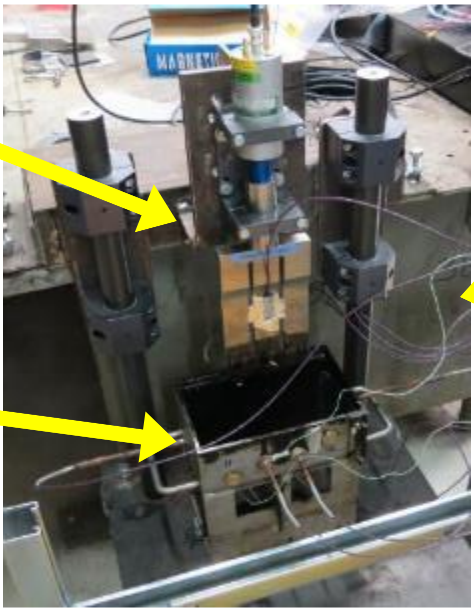

Figure 2 – General view of the device with the stage, cutter and container equipped with thermocouples, used to test ultrasonic cutting on bitumen coatings.

2.2.2. Exceptional event tests involving contact between the sonotrode and non-bitumen material

Tests were first carried out with the Maestro teleoperated robotic arm (short version; Cybernetix; Figure 3, left), which is well established in decommissioning processes such as mechanical (sabre sawing, grinding) and thermal (laser) cutting. The robotic arm was mounted on a Brokk 90 platform with a tracked undercarriage [2,3]. This device was not specifically designed for performing ultrasonic cutting but helped:

- Evaluate different types of cutters such as ultrasonic chisels and knifes.
- Compare devices from different manufacturers.
- Verify the accessibility of cutting areas.
- Determine cut quality as a function of cutting parameters (feed rate, cutting time, oscillation amplitude, orientation of the cutter, and state of wear of the sonotrode).
- Define the cutting method.
- Make an inventory of likely difficulties, with a particular focus on contact between the sonotrode and materials other than bitumen.

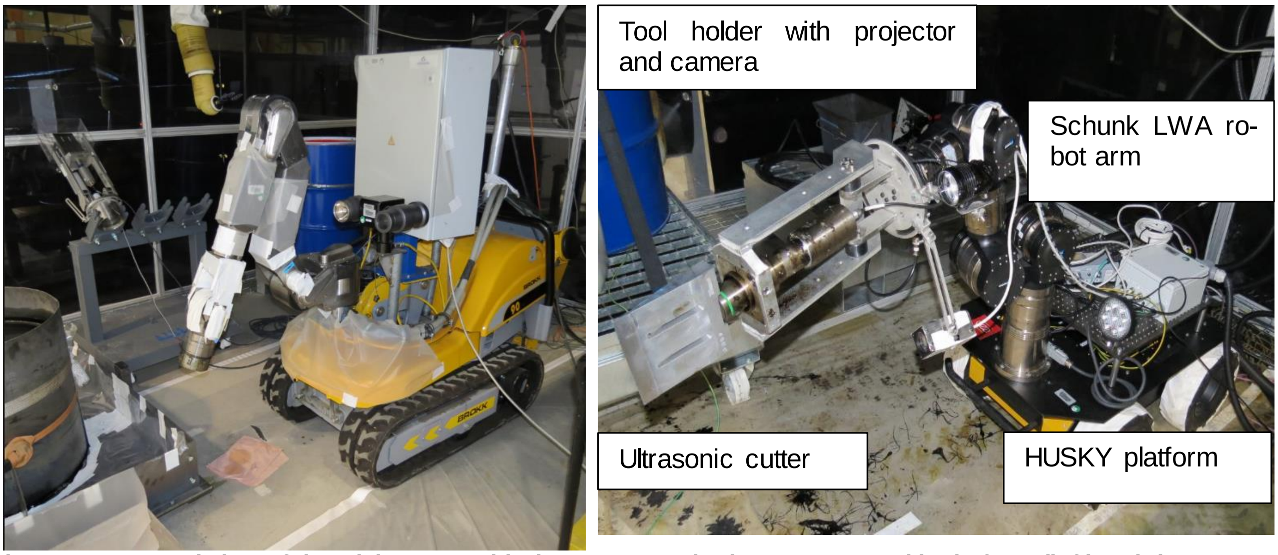

Figure 3 – General view of the trial setups with the Maestro robotic arm on a Brokk platform (left) and the specifically designed prototype with a Schunk robotic arm on a Clearpath platform (right).

A teleoperated experimental prototype adapted to the requirements of ultrasonic bitumen cutting was used in a second stage. This included controlling the feed rate and retraction of the cutter and automatic monitoring of the robotic arm's force and torque sensor readings to trigger the programmed movement responses. This prototype consists of a Schunk LWA 6DOF industrial robot arm with a 6 axis and a force/torque sensor mounted on a Clearpath Husky platform (Figure 3, right). Tests were performed with the device to determine the cause of sparks when the sonotrode contacts materials other than bitumen and evaluate various mitigation solutions.

3. Results and discussion

3.1. Normal operation

The results of CO, TO and CTO tests were used to define the operational range under normal conditions of the device, namely:

→ An ambient temperature of 5–30°C,
→ Oscillation amplitudes of between 20 and 59 µm,
→ Feed rates of 0.5 to 10 mm/s

3.2. Adjusting the operational range to the technical solutions implemented for exceptional events

No thermal ignition reaction was observed during operating tests at limit conditions in the event of the sonotrode becoming stuck in the bitumen. On the other hand, maximum temperatures were found, close to the sonotrode, between 203 ° C to 319 ° C for pure bitumen and between 136 ° C to 298 ° C for bitumen coating with salt concentrations of 23–46 wt%. In order to meet the threshold temperature of 180 ° C, the application time of US during the cutting phase must be reduced and the operating range at the level of the oscillation amplitudes must be adjusted.
Considering a thickness of bitumen to be cut is 50 mm and a minimum feed speed of 0.5 mm / s, the limitation of the application time is 2 minutes. Only oscillation amplitudes of less than 50%, ie 34 µm for 20 kHz and 36 µm for 30 kHz, respect these constraints, both thermal and temporal, whatever the material (pure or coated bitumen).
The operational range determined in a first stage was adapted to account for the restriction at 20 kHz to a maximum oscillation amplitude of 34 µm. Furthermore, given unquantifiable uncertainties in the CTO results for low amplitudes and high feed rates, the recommendation was made to use oscillation amplitudes as high as possible, thus 34 µm. The corresponding restricted operational range with an oscillation amplitude of 34 µm and feed rates of 4.5 to 10 mm/s is shown in Figure 4.

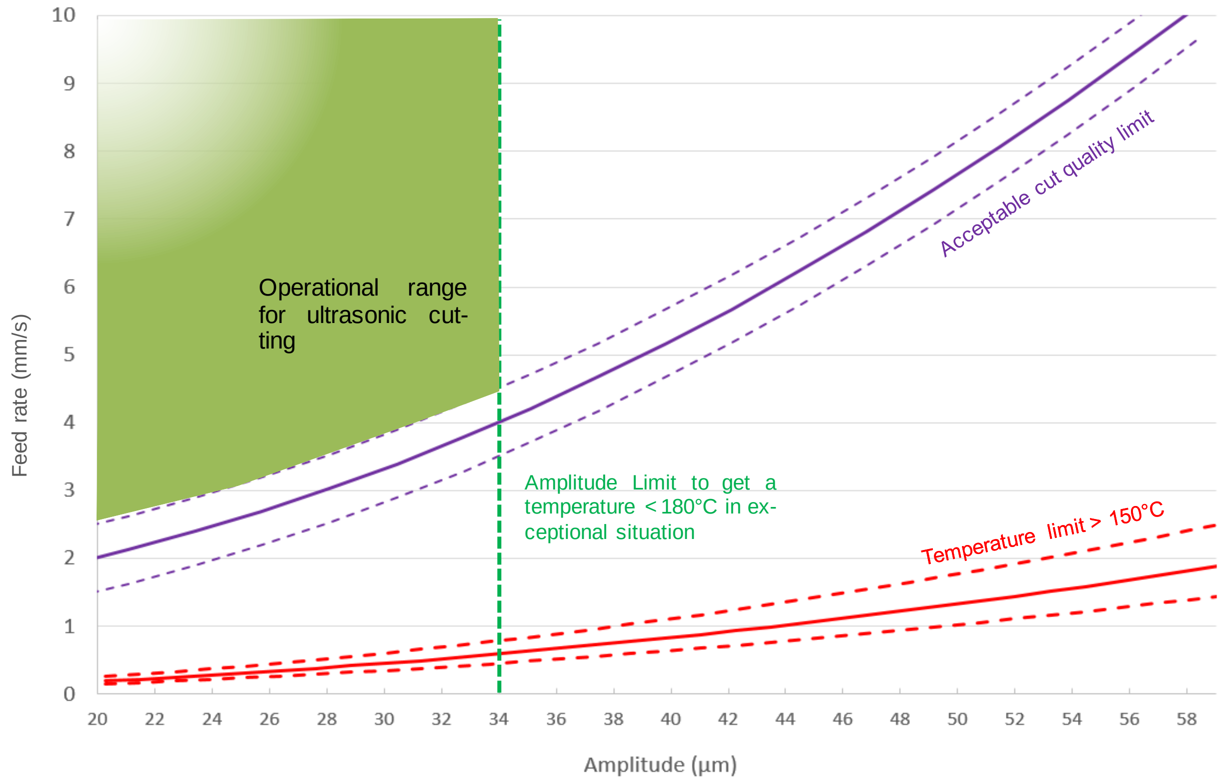

Figure 4 – Operational range at 20 kHz (in green) based on normal operation and exceptional event management measures for all ambient temperatures and bitumen salt contents (0–46 wt%)

To identify the start of the cut, it is possible to use the power of the ultrasonic cutting tool which increases sharply during penetration. From this detection, the ultrasound can be applied for 2 minutes. Increasing the penetration force may be another solution to detecting the onset of penetration, but this requires a displacement mechanism with an accurate force sensor.

In all cases, it is necessary to provide a control command which takes into account the penetration information and the time delay which stops the operation of the ultrasound via the generator. Note that stopping the ultrasound during a cutting phase in bitumen whose viscosity is low, risks causing the sticking of the active zone of the sonotrode. It is therefore recommended to enter a withdrawal phase after the automatic shutdown of the US.

3.3. Origin of sparks when the sonotrode contacts non-bitumen material

The first tests with the Maestro arm showed that sparks were produced when the titanium sonotrode was brought into contact with metallic materials (Figure 6, left). This type of highly exothermic event cannot be overlooked because contacts with metallic objects are difficult to avoid under teleoperation. Analysis of the sparking events revealed that the source of this phenomenon was the titanium in the sonotrode.
Complementary tests with an aluminum sonotrode, chosen as a non-sparking alternative, showed no sparking whatever the contacted material was. The temperature increases on contact remain large but the rates of temperature change are much lower than with a titanium sonotrode (Figure 6, right). Aluminum sonotrodes are therefore preferable for these applications.

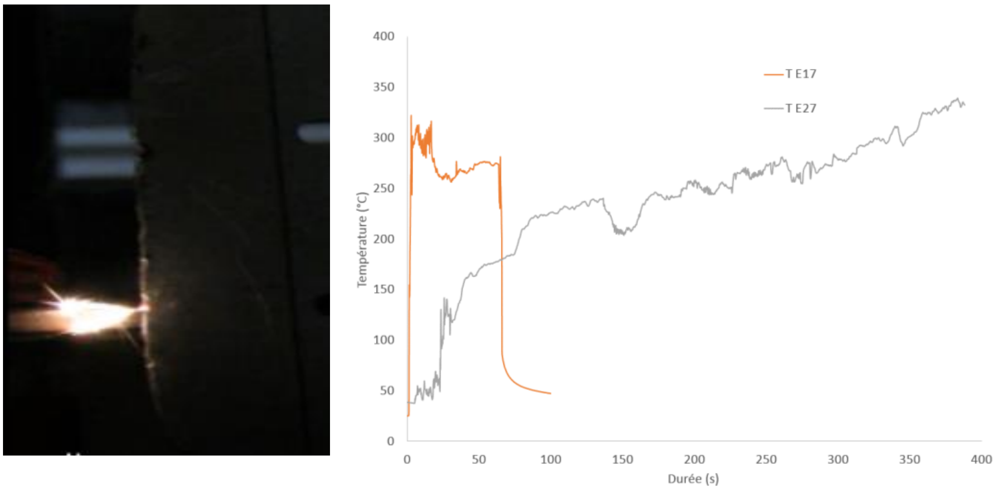

Figure 5 – Sparks emitted by a titanium sonotrode (left) and temperature-time profiles of a titanium (E17) and an aluminum (E27) sonotrode in contact with a metallic object (right).

Even with an aluminum sonotrode, additional measures are required to keep the contact temperature below 180°C. Several options were evaluated:

- → An additional "cut-off" module that ensures the ultrasounds are automatically turned off when the sonotrode makes contact with a conducting material. No temperature elevation or sparks were observed in tests with this module.
- → Reflex movements in the robotic arm. Threshold currents in the activator and force sensors were defined for the device and used in a series of tests.

In combination therefore, the aluminum sonotrode, "cut-off" module and reflex function ensure sparkless operation and limit temperature increases on contact for all oscillation amplitudes.

3.4. Analysis of applicable technical solutions for exceptional events

As a reminder, the solutions evaluated were:

- To stop the ultrasounds on contact between the titanium sonotrode and a conducting material such as steel, with the "cut-off" module
- To change the sonotrode material based on tools used in ATEX environments made of non-sparking materials such as aluminum
- To limit contacts via a reflex function using thresholds for the device's activator and force sensors

3.4.1. Solution 1: turn off ultrasounds on contact

In spite of its effectiveness, the "cut-off" solution has tree major disadvantages. The first is that it is only effective for conducting materials. The presence of a layer of paint can prevent the flow of current and thus the automatic shutoff of the ultrasounds.
The second disadvantage is the need for a connection with the cut-off module, either by including an extra functionality in the robotic arm or by integrating an extra device. The connection and its positioning have to be maintained throughout the cutting process regardless of the mobile platform's position. Furthermore, this device has not been qualified.
The third disadvantage is the fact that this solution does not avoid contacts with the concrete found on sites. Nevertheless, a collision avoidance algorithm can be integrated into the robotic arm's movement control system. Provided the ground is level and that the bearing surface of the platform is maintained, the device's position is always known without any need for localization equipment.
These three disadvantages mean that this very effective technical solution is limited to particular configurations in which contacts with conducting parts are readily established. It is well suited for fixed processes in reconditioning chambers for instance. In this setting indeed, there are many possible ways to establish a reliable (internal or surface) connection before cutting.

3.4.2. Changing the sonotrode material

The initial choice of a titanium sonotrode was based on the manufacturer's recommendation of a material resistant to large variations in oscillation amplitude (greater than 100 µm). In light of the results described in section 3.3, the oscillation amplitudes have to remain low (less than 34 µm for the 20 kHz sonotrode), which allows for a wider choice of sonotrode materials. Various commercial steel or aluminum sonotrodes are available. Aluminum was chosen for its mechanical and non-sparking properties.
As shown in Figure 6, temperatures in the contact area do not exceed 180°C in the first minute of contact but can reach as high as 340°C thereafter. As mentioned above however, the heating rate is 120 times lower with aluminum than with a titanium sonotrode.
No sparking was observed however long the ultrasounds were applied with the aluminum sonotrode to S235 or 904L steel. This suggests that the sparking was due to the titanium sonotrode, which is extremely pyrophoric as a powder.
One disadvantage of aluminum however is that it is less durable. During operation indeed, while the sonotrode does not loose material, it does become deformed in the active area, leading to frequency variations that appear twice as fast with an aluminum sonotrode as with a titanium one. Therefore, in spite of their better thermal behavior on contact, aluminum sonotrodes have to be replaced more frequently.
The ultrasonic cutting performances of the two types of sonotrode were then compared. Comparative CTO tests were performed under the same experimental conditions on pure bitumen. The temperature characteristics of the aluminum cuts were better and the overall quality of the cuts identical to those performed with the titanium sonotrode.
In light of these results validating the use of an aluminum sonotrode instead of titanium, the characterization process must now be repeated with an aluminum sonotrode to confirm or possibly extend the operational range to release jams more rapidly, and confirm the limits on operational times defined in section 3.2.
This technical solution ensures the heating rate in the contact area is much slower and therefore manageable, avoiding ignition.

3.4.3. Automatic retraction on contact

The prototype's control system includes a reflex function to retract the robotic arm above a certain force threshold measured in the force sensors or in the activator currents.
Tests showed that this solution was not reliable because the thresholds have to be sufficiently high to not interfere with the cutting process but sufficiently low to be reached when the sonotrode makes contact with the tank. Furthermore, the forces required for cutting vary with the temperature of the bitumen, which makes setting appropriate thresholds complicated.
This solution was thus determined to be too unreliable and complex to be implemented.

3.5. Process validation level

This section describes the validation of the process in terms of the requirements of decommissioning projects. This highlights the features that have been validated for ultrasonic cutting as part of the above-described qualification process and what remains to be tested for the viability of the process. Figure 8 shows the current validation state of the process in terms of general requirements, with items that have already been validated by tests, leading to acceptable or non-applicable process configurations, and other items that have not yet been investigated. Also highlighted are items evaluated in a representative environment with teleoperation and those tested at scale in a specially designed cell. All validated items, regardless of the context, were considered acceptable.

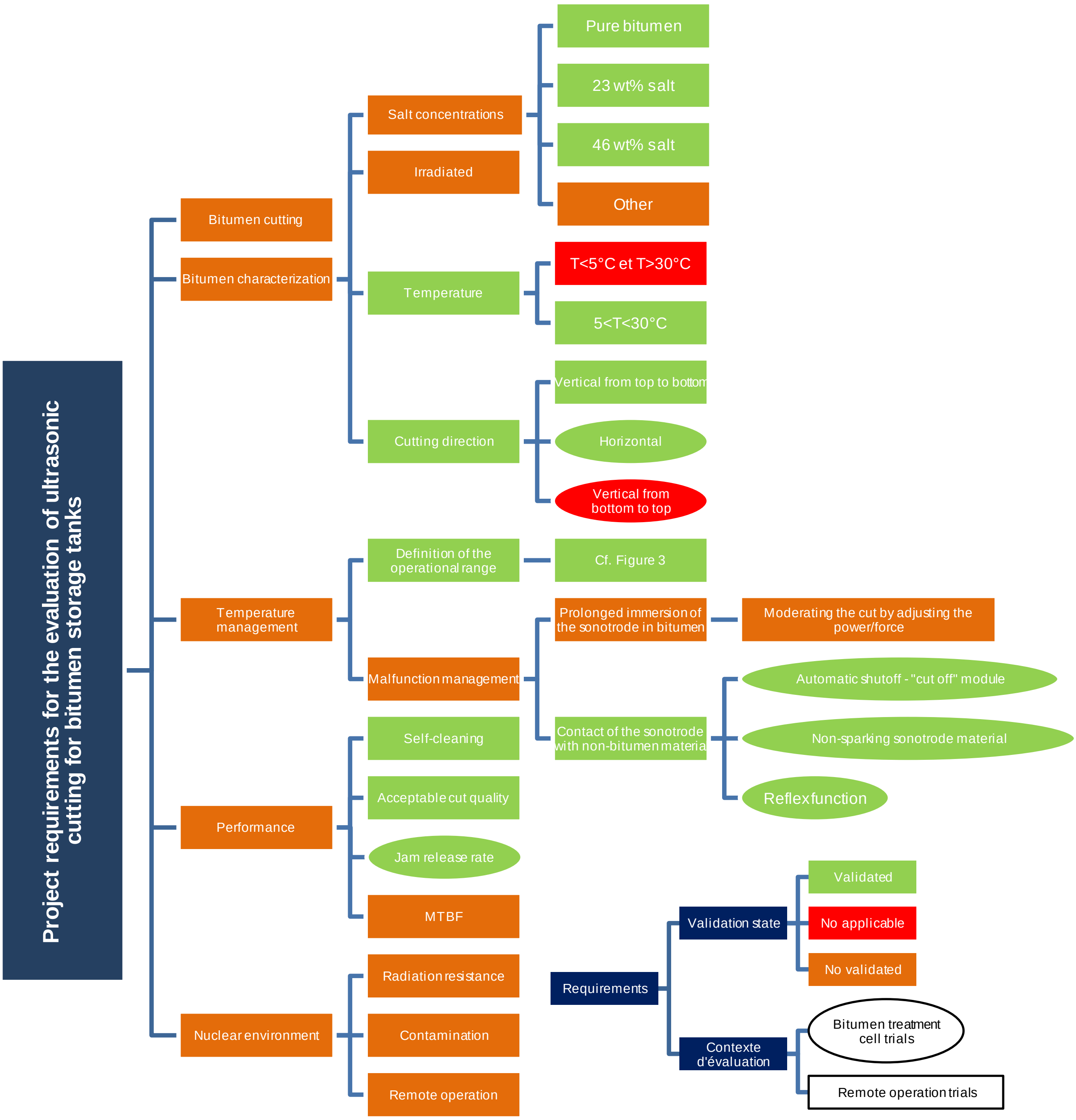

Figure 6 – Validation state of the process

By the same logic, non-validated "child" items induce the same state in the corresponding "parent" item and none of the project requirements has yet been fully validated by live tests.

The conclusions that can be drawn are that ultrasonic cutting has been validated for non-irradiated bitumen with salt concentrations of 0, 23 and 46 wt%, at temperatures of between 5 and 30°C, and likewise for horizontal and downward vertical cuts, within the defined operational range. There are technical solutions to maintain temperatures below 180°C and the performance of the process meet the general requirements of decommissioning projects.
The evaluation program should nevertheless be continued to:

- Better understand the reliability of the process by measuring the operational time (MTBF).
- Manage the force–torque relationship more precisely during insertion at the start of the cut.

- Understand the true capabilities of the device to in terms of its robustness under irradiation, its amenability to decontamination, and remote operation, notably the robustness of coaxial cable connections longer than 20 m, and the possibility of integrating a system for online sonotrode wear monitoring.

4. Conclusions

Firstly, characterization tests validated the operational range in which the 20 kHz ultrasonic cutting device delivers clean cuts without tool fouling in bituminous materials and with temperatures kept below the limit for normal operation of 150°C. Secondly, while in exceptional situations, such as the sonotrode becoming stuck in the bitumen and contact between the sonotrode and non-bitumen material, temperature increases above this limit are possible, various technical solutions exist and were tested at the limits of the operational range and in teleoperation. Two solutions were found to be indispensable for the process to function properly. The first involves restricting the range of normal operation by limiting ultrasonic cutting times to 2 min and oscillation amplitudes to 34 µm at 20 kHz. The second is to use an aluminum sonotrode to avoid sparking and limit the heating rate. This solution nevertheless requires more frequent replacement of the sonotrode and therefore more downtime. Other solutions were also found to be useful but only in particular situations. A module to automatically cut off the ultrasounds on contact limits the risk of temperature increases but only works for conducting materials. An automatic reflex function in the force and/or activator sensors of the robotic arm was found to be of uncertain reliability and complicated to implement while also avoiding unnecessary interruptions.

All tests performed with titanium sonotrodes were found to respect the operational range defined in this note, confirming the reliability of the process. The tests conducted so far with aluminum sonotrodes are too few and limited in scope to validate a specific operational range. At this stage of the evaluation process, staying within the operational range defined for titanium should guarantee that temperature and non-sparking requirements are satisfied. Some uncertainty remains however as to the quality of the cuts obtained with an aluminum sonotrode.
In light of these considerations, the recommendations for the use of ultrasonic cutting in this context are:

- To use an aluminum sonotrode at 20 kHz
- Preferentially use an oscillation amplitude of 34 µm and feed rates of between 4.5 and 10 mm/s.

This analysis focusses only on thermal and qualitative aspects of the cut and validates the technical feasibility of the process for fixed and automated use in a bitumen treatment cell. Note however that irradiated bitumen materials were not studied and complementary tests on these types of material should therefore be performed to fully master the use cases for the nuclear industry. This could be done at the same time as optimizing the operational range of the aluminum sonotrodes. A new distribution of measurement points may allow the range to be extended and thereby increase jam release rates.

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