Deliverable D2.3

Report on the REX-CO_2 well screening tool

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Executive summary

Existing oil and gas fields are one of the potential options for geologic CO_2 storage as part of the energy transition and reduction of CO_2 emissions. Oil and gas fields offer several advantages, including availability of characterization data, knowledge of field based on prior operations and availability of existing infrastructure. Conversion of existing oil and gas wells to CO_2 storage wells can potentially result in cost savings, especially for offshore fields where drilling and well completion costs can be significant.

The major goal of the REX-CO_2 project is to develop procedures and a publicly-available, dedicated well-screening-tool for re-using existing wells for CO_2 storage operations. This report, deliverable “D2.3: Report on REX-CO_2 well screening tool”, provides information on the well screening tool, including details of the screening process using multiple decision trees and the computer programming approach. The decision trees were developed starting from the conceptual framework that was described in deliverable “D2.2: Summary report of well assessment tool framework”.

As described in detail in the D2.2 report, our well screening workflow is designed to assess a well’s suitability based on its ability to maintain integrity under expected operational conditions (such as high pressures and corrosive environment) as well as to meet its desired operational purpose. The workflow includes the following primary components:

- Initialization including basic field information, well data and storage operation parameters.
- Assessment of appropriateness of well design, barrier materials and well integrity to ensure safe operations and CO_2 containment.
- Assessment of suitability of well for desired purpose (e.g. injector, monitoring well, producer).
- Assessment of potential CO_2 leakage through primary cement barrier above storage reservoir.

Decision trees with detailed, step-by-step assessment were developed. In addition, models for estimating CO_2 leakage potential through combined predictions of probability of cement debonding and CO_2 leakage rates through resulting micro-annuli have been developed. A programming framework based on the NRAP-Open-IAM software framework has been implemented to develop multiple tool components, including tool initialization and data input interface, some of the decision trees and their graphical user interfaces. We expect to have a preliminary version of the tool available by October 30, 2020. The tool will be continuously updated based on the industry and other partners feedback as well as its application to national well and field re-use cases.

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1. Introduction

Existing oil and gas fields are one of the potential options for geologic CO_2 storage. Oil and gas fields offer several advantages, including availability of characterization data, knowledge of field based on prior operations and availability of existing infrastructure. Conversion of existing oil and gas wells to CO_2 storage wells can potentially result in cost savings, especially for offshore fields where drilling and well completion costs can be significant. An existing well can potentially be repurposed as an injector, a producer (for pressure management) or a monitor.

Recently, multiple projects have explored the potential of converting existing oil and gas fields into CO_2 storage sites. A couple of these projects, including Shell's Peterhead-Goldeneye project (Shell, 2016) and Eon's Kingsnorth project (E.ON, 2011), both offshore UK, resulted in the publication of detailed Front-End Engineering Design (FEED) studies for commercial-scale CO_2 storage site developments. Both of these projects were developed with the purpose of converting existing gas fields that are approaching the end of their respective production life to CO_2 storage sites. In spite of extensive work undertaken in developing these projects, neither of these projects became operational for various reasons. Currently, the PORTHOS consortium in the Netherlands is exploring the feasibility of converting the P18 gas field (offshore Netherlands), operated by TAQA, to a CO_2 storage site and Pale Blue Dot Energy in the UK is exploring the feasibility of using existing North Sea oil and gas infrastructure to develop a scalable CCS (Carbon Capture and Storage) system (Acorn, 2019). The UK's Oil and Gas Authority awarded its first CO_2 appraisal and storage license to the Acorn CCS Project in 2018 (OGA, 2018).

The above-mentioned projects demonstrate growing interest in utilization of existing infrastructure, including converting existing oil and gas wells to CO_2 storage wells. The steps undertaken by these projects demonstrate that repurposing existing oil and gas wells is a deliberate process that needs to evaluate and assess an extensive set of issues ranging from suitability of well design and construction to its integrity for CO_2 storage purposes. Additionally, they also highlighted the need for a tool and a workflow that can be used to perform careful assessment of the feasibility of repurposing existing oil and gas wells. The REX-CO_2 project is focused on responding to this need through the development of a publicly available tool. As part of the tool development process we first developed a conceptual approach (Deliverable 2.2) and as part of this deliverable we have developed a detailed approach for the assessment process. This approach is encapsulated in multiple decision trees and a coding approach to translate the decision trees in a tool.

1.1. Objective

The primary objective of REX-CO_2 Deliverable 2.3 is to develop the details of the well screening tool based on the conceptual approach that was described in Deliverable 2.2 "Summary report of well assessment framework" (Pawar et al., 2020). This involves development of detailed decision trees for different steps related to well assessment as well as a coding approach that convert the decision trees into computational algorithms and integrates them in a user-friendly tool.

1.2. Motivation

Currently, no tool is publicly available to assess the feasibility of reusing existing oil and gas wells as CO_2 storage wells. Similarly, no standard workflow has been published for performing such assessments. Both became obvious in a state-of-the-art review of selected previous projects related to using existing fields for CO_2 storage which is provided in a separate REX-CO_2 deliverable "D2.1 - Current state-of-the-art assessments and technical approach for assessment of well re-use potential and CO_2/brine leakage risk” (Opedal et al., 2020). On the other hand, details of the steps undertaken to evaluate the existing wells as potential CO_2 storage wells for the Peterhead-Goldeneye (Shell, 2016) and Kingsnorth (E.ON, 2011) projects is publicly available. Also, TNO has been involved in the assessment of the P18 gas field wells for potential repurposing as CO_2 storage wells. The report will become public in the near future. In addition to these, the IEAGHG (International Energy Agency’s Greenhouse Gas R&D Programme) has published a technical report on reusing existing oil and gas infrastructure for CO_2 transport and storage (IEAGHG, 2018a). This report identifies the various issues that need to be considered prior to reusing existing oil and gas infrastructure. The experience with the aforementioned projects has led to a good understanding of the state-of-the-art process that should be undertaken to evaluate existing wells.

2. CO_2 storage well design

In order to assess the suitability of an existing oil and gas well as a potential CO_2 storage well it is necessary to understand the design and functional requirements for a storage well. Currently there is only one international standard and a single regulation exclusively developed for CO_2 storage well designs. The ISO 27914, developed for CO_2 capture, transport and geologic storage, includes a design standard for CO_2 storage wells (ISO, 2017a). The US Environmental Protection Agency's (US-EPA) Underground Injection Control (UIC) program's Class-VI well construction guidance identifies the requirements for techniques and materials for constructing CO_2 storage wells (EPA, 2012). Both of these have taken into consideration existing standards for oil and gas well construction including ISO 16530 (ISO, 2017b) and NORSOK D010 (Standards Norway, 2013). The primary objective of the standards and regulations mentioned above is to ensure that the wells are constructed such that they maintain integrity during their lifetime under the operational conditions. Most of the standards, guidelines as well as regulations recommend the presence of multiple well barriers to ensure that injected CO_2 and in-situ fluids are contained within the well to prevent un-intended and uncontrolled flow of fluids within or out of a well or surrounding environment.

A well barrier is a combination of one or several well barrier elements (WBEs). The objectives of a well barrier are to:

- Withstand the maximum anticipated combined loads to which it can be subjected.
- Function as intended under the expected pressure, temperature, chemical (CO_2-rich, HC-rich, high-salinity), mechanical stress conditions throughout its entire life cycle.
- Prevent uncontrolled and un-intended flow of injected CO_2 and in-situ fluids (HC and/or brine) within the wellbore or to the external environment.

Table 1 below provides examples of well barrier elements and their function. Note that different barrier elements can be connected together to form a barrier.

Table 1. Description of well barrier elements.

Barrier Element	Function
Caprock	Provides a continuous, permanent and impermeable hydraulic seal above the reservoir
Casing/liner	Contains fluids within the wellbore such that they do not leak out into other concentric annuli or into exposed formations
Cement (Casing/liner)	Provides a continuous, permanent and hydraulic seal along wellbore between formations and a casing/liner or between casing strings Provides mechanical support to the casing/liner and prevents corrosive formation fluids coming into contact with the casing/liner
Completion tubing	Provides a conduit for fluid to/from the reservoir to/from surface
Production packer	Provides a mechanical seal between the completion tubing and the casing/liner, establishing the A-annulus above and preventing communication from the formation into the A-annulus
Liner top packer	Provides a hydraulic seal in the annulus between the casing and the liner, to prevent flow of fluids and resist pressure from above or below
Wellhead	Provides mechanical support for the suspending casing and tubing strings

	Provides mechanical interface for connection of a riser, BOP or X-mas tree Prevents flow from the wellbore to annuli or environment
Annuli fluid column	Exerts a hydrostatic pressure in the wellbore that prevents inflow of formation fluid
Surface-controlled downhole/sub-surface safety valve	Safety valve installed in tubing designed to close automatically to prevent fluid flow in case of loss of control
Annulus surface-controlled sub-surface safety valve	Safety valve device installed in the annulus to prevent flow of fluids from the annulus to the annulus wing valve
Tubing hanger	Supports weight of the tubing and prevents flow from the tubing to the annulus and vice-versa
Surface tree	A system of valves and flow conduits attached to the wellhead to control the flow out of the well

As a minimum requirement, two barriers are recommended at all times; a primary barrier and a secondary barrier (Figure 1). In certain cases, more than two barriers could be required or present. The primary barrier is the first barrier and is in direct contact with reservoir fluids at reservoir pressures. The secondary barrier is not directly exposed to fluids or pressures and provides redundancy in case of failure of primary barrier elements. It is the secondary line of defense against unintended, uncontrolled fluid flow from the wellbore to the environment.

Primary well barrier: The primary well barrier is composed of a combination of the following barrier elements:

- Caprock.
- Production (long-string) casing/liner cement.
- Production (long-string) casing/liner.
- Production packer.
- Liner hanger/packer.
- Tubing.
- Downhole/sub-surface safety valve (SSSV).

Secondary well barrier: The secondary well barrier is composed of a combination of the following barrier elements:

- Impermeable formation.
- Casing cement.
- Casing with hanger and seal assembly
- Annuli fluids.
- Wellhead with valves.
- Tubing hanger with seals.
- X-mas tree and tree valves, connections.

We have developed the well assessment decision trees by assuming that a double barrier is required.

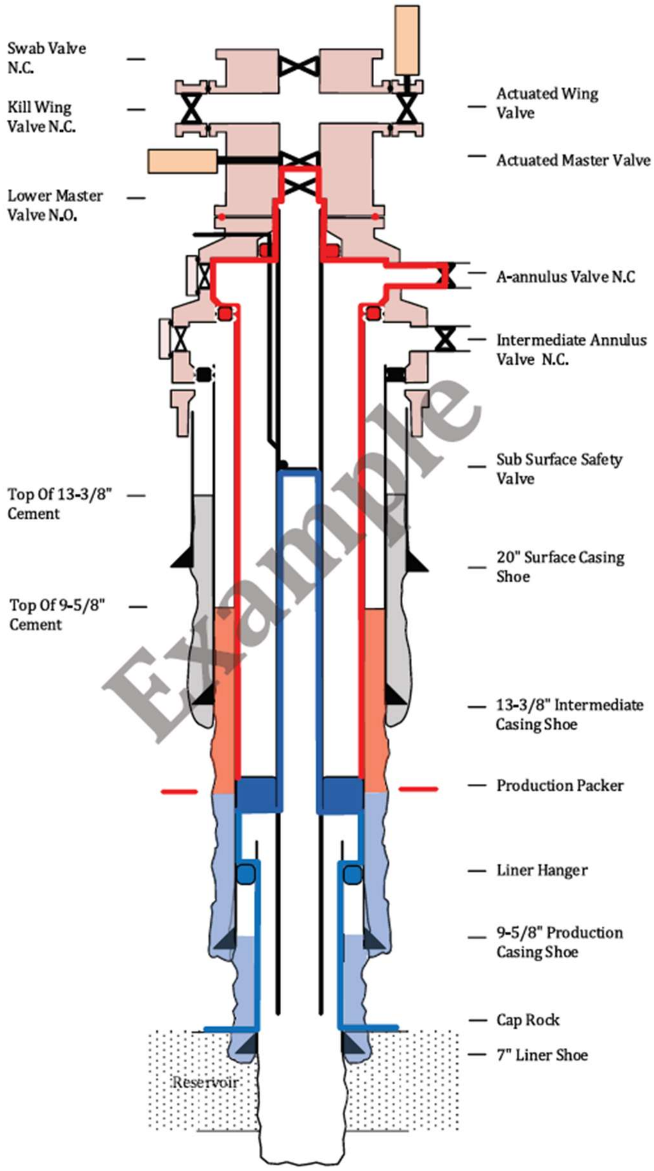


Figure 1. An example wellbore barrier schematic from ISO-16530 (ISO, 2017). The primary barrier is indicated by blue lines & secondary barrier is indicated by red lines.

3. Details of the assessment tool

Our assessment framework is described in Deliverable 2.2 "Summary report of well assessment framework" (Pawar et al., 2020) and shown in Appendix A. The different steps in our assessment framework include: 1) Tool initialization 2) Well design assessment 3) Well suitability assessment and 4) Cement integrity predictions. In following sections, we provide details of steps 1, 2 & 4. Details of step 3 are currently being developed and will be described in following reports. As part of Step 2, we have developed detailed decision trees for well integrity assessment, out of zone injection risk assessment, well structural integrity assessment and well material compatibility assessment. These decision trees are developed based on the CO_2 storage well requirements identified by well integrity standards as well as regulations. The decision trees are intended to be used by people with access to information about the wells and the means to assess the information. The decision trees guide the user through the checks and balances but some (basic) understanding is required. It should be noted that even though the decision trees developed to date are comprehensive, we expect both the decision trees and the tool to evolve further during the course of the project based on the feedback from industry partners as well as applications to national case studies. Already submitted reports will be updated if deemed necessary. In addition to the well design assessment, we have developed models for Step 4 to provide quantitative estimates of the probability of debonding of the caprock/cement interface under expected operational conditions and resulting CO_2/brine leakage rate.

3.1. Tool initialization

Prior to going through the assessment process the tool user is asked to provide field-specific, reservoir-specific and well-specific inputs as well as information about available data as shown in detail in Figure 2. The information includes:

- General information such as name and location of the oil/gas field or storage sites for which the assessment is being performed, whether it is onshore or offshore and the applicable legal jurisdiction.
- Availability of data for reservoir, wells (including past and proposed well operation data), any recent pertinent tests such as cement bond logs, noise logs, casing corrosion logs, anomalous annular pressure data, etc.
- Field details such as depositional environment, type of storage reservoir (saline aquifer or depleted oil/gas reservoir), primary storage reservoir details (including, depth, average permeability, average porosity, current/original pressure, formation strength, geothermal gradient, fluid composition, etc.), primary caprock details (including, type, thickness, fracture pressure, etc.), indication of secondary permeable formations and caprocks as well as their physical characteristics, proposed operational details (including injection rate, injection pressure, predicted bottom hole pressure, etc.).
- Well details including number of wells and specifics of each well (including name, current status, past operational history, proposed purpose, sidetrack/deviated well etc.). While the tool is primarily designed for currently operational wells, we recognize that there may be interest in reusing abandoned wells. In such cases the user is recommended to undertake a detailed engineering study of the workover required to make the abandoned well useful while the tool can be useful to assess other aspects of well suitability similar to an operational well. The tool can be potentially used to evaluate abandoned wells based on quality of annular cement and predict potential CO2 leakage using the built-in leakage models.

User questions	Goal/step
Input Field Data: - Target field name - Location (country) - Onshore/offshore - Which legal jurisdiction (country-specific)	1. Initialize assessment with general info

Does the user have required data?
- List of data recommended for assessment:
    - Reservoir data (target formation, caprock, pressure, temperature, in-situ fluid composition)
    - Well construction (well age, drilling and completion data, well design, side-track, well material specifications, cement composition)
    - Well historic operation data (operational pressures, temperatures)
    - Well maintenance/work-over data
    - Proposed well operation data (injection rate, duration, maximum injection pressure, temperature, fluid composition)
- Potential additional data that could be used:
    - EOWR, MIT data, LOT, FIT, Annular pressure data, cementing reports, logs (CBL, Noise, Temperature, Corrosion)
 	
Include a Note saying that it is recommended but not required to have all this data, the tools can also deal with missing data.
	2.
	Data availability checklist

Reservoir data gather, ask questions like:
- Specify CCS/EOR project
- Type of reservoir (carbonate/sandstone)
- Saline aquifer/depleted oil & gas field/CO2-EOR field
- Caprock type (salt/shale) and thickness
- Are there multiple caprocks? Depth and thickness
- Reservoir capacity
- General reservoir data (multiple for stacked storage):
    - Depth
    - average permeability
    - average porosity
    - temperature/thermal gradient
    - Pressure (current, original)
    - Reservoir fluid composition
    - Formation strength, reservoir compaction
    - Caprock fracture pressure
- Maximum expected injection pressure
- Maximum expected injection rate
- Injectate composition
- Are there other permeable zones of commercial interest through which the wells penetrate, are the wells completed in other zones?
- Is there evidence of communication between the target reservoir and other zones?
	3.
	Reservoir/project input

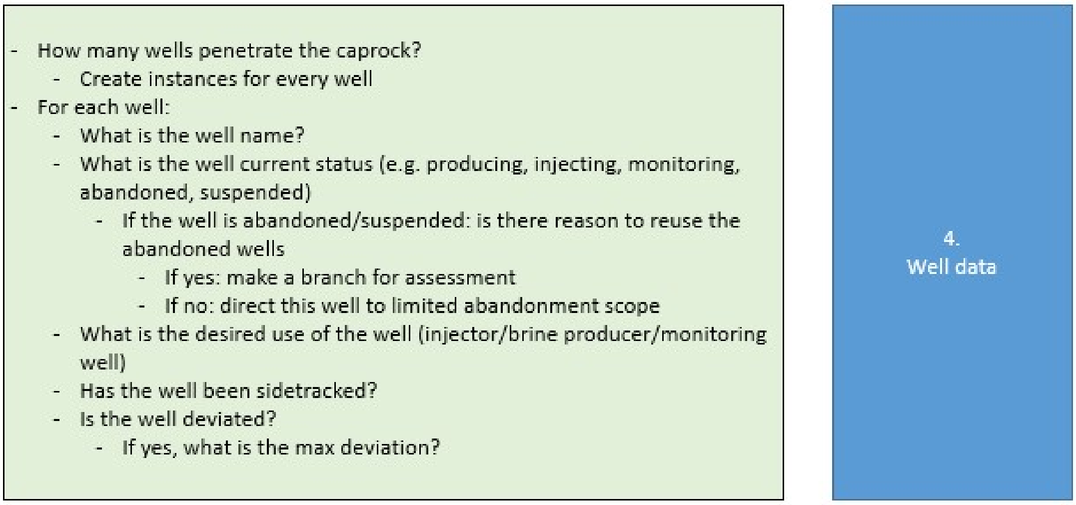


Figure 2. Tool initialization steps.

Following the tool initialization, the different steps of the well design assessment are performed, commencing with well integrity assessment.

3.2. Well design assessment

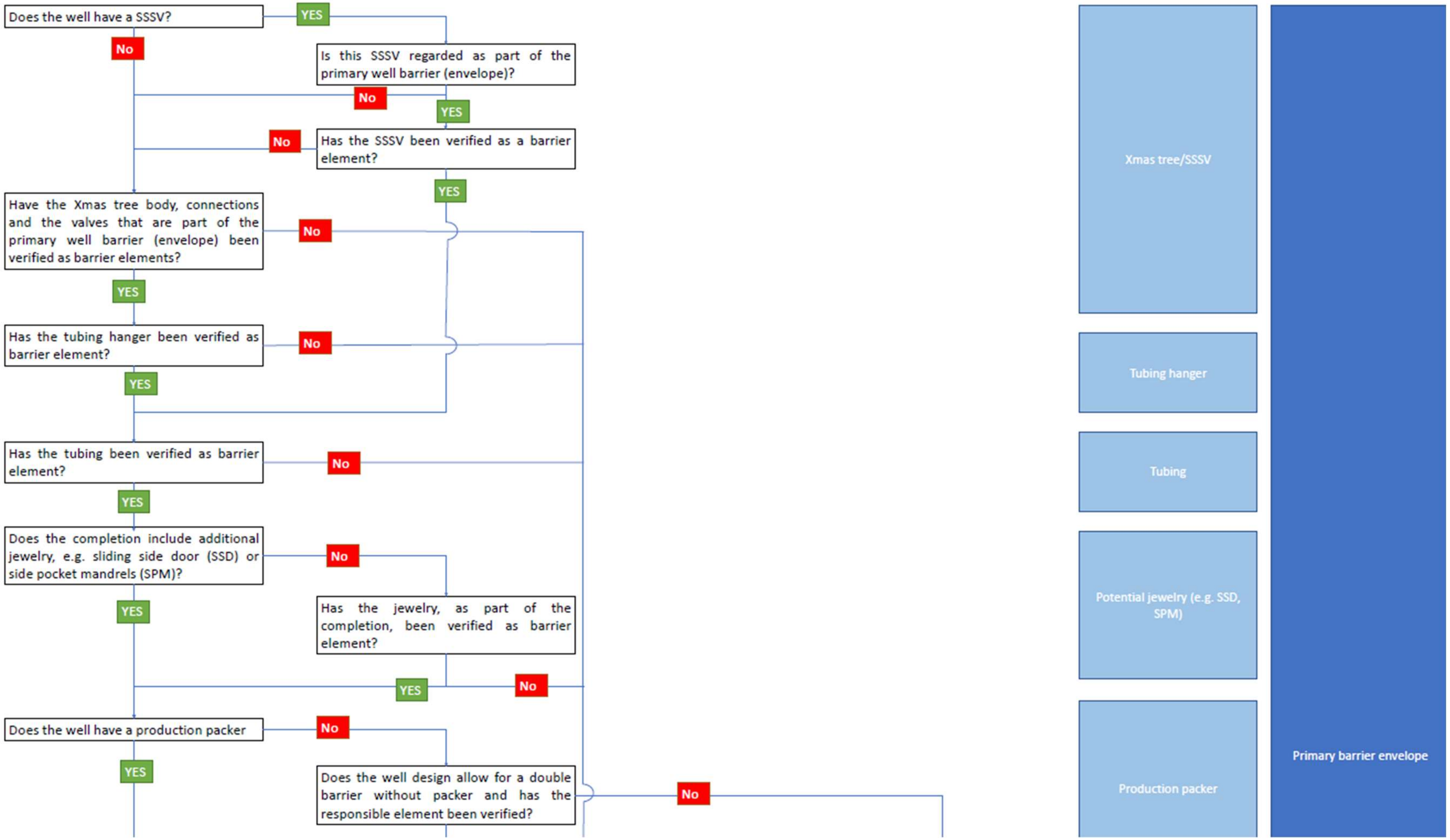
3.2.1. Well integrity assessment

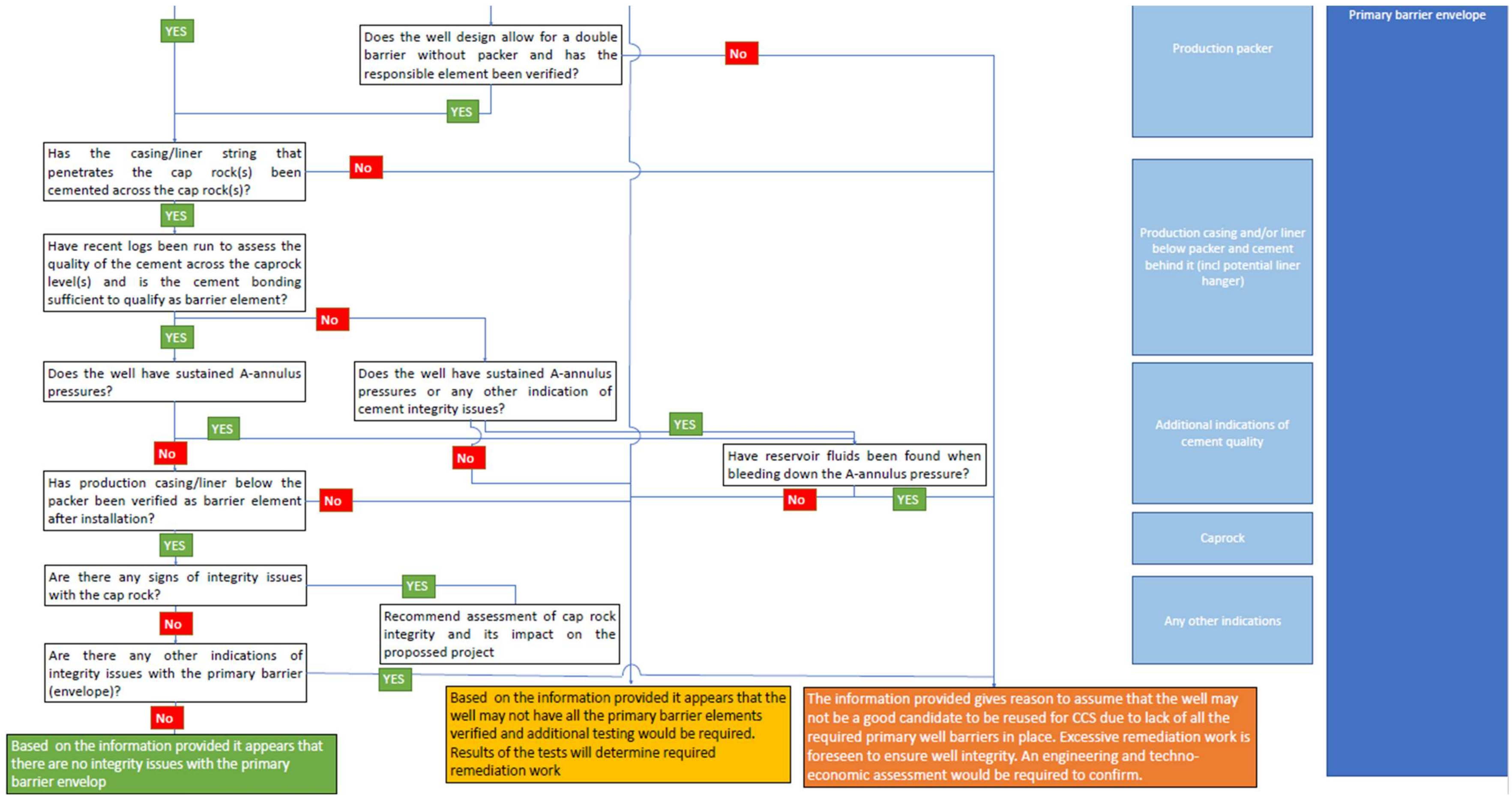
The well integrity assessment process is designed to assess the integrity and effectiveness of the well barrier elements in the different well phases. As mentioned in Section 2, the current standards and regulations for well integrity recommend the presence of two barriers, a primary and secondary barrier. We have developed the decision tree for assessment assuming the presence of the two barriers as shown in Figure 3. The two barriers differ mainly through the combination of WBEs which make up the individual barriers. Even though there are two separate barriers, the assessment steps are similar and are essentially repeated through application to different WBEs that make up the individual barriers.

The first step in the decision tree is verification of primary WBEs including SSSV, tubing, tubing hanger, casing or liner, primary caprock, cement across primary caprock, packer and other jewelry that may exist and be directly contacted by the pressure and/or injected CO_2.

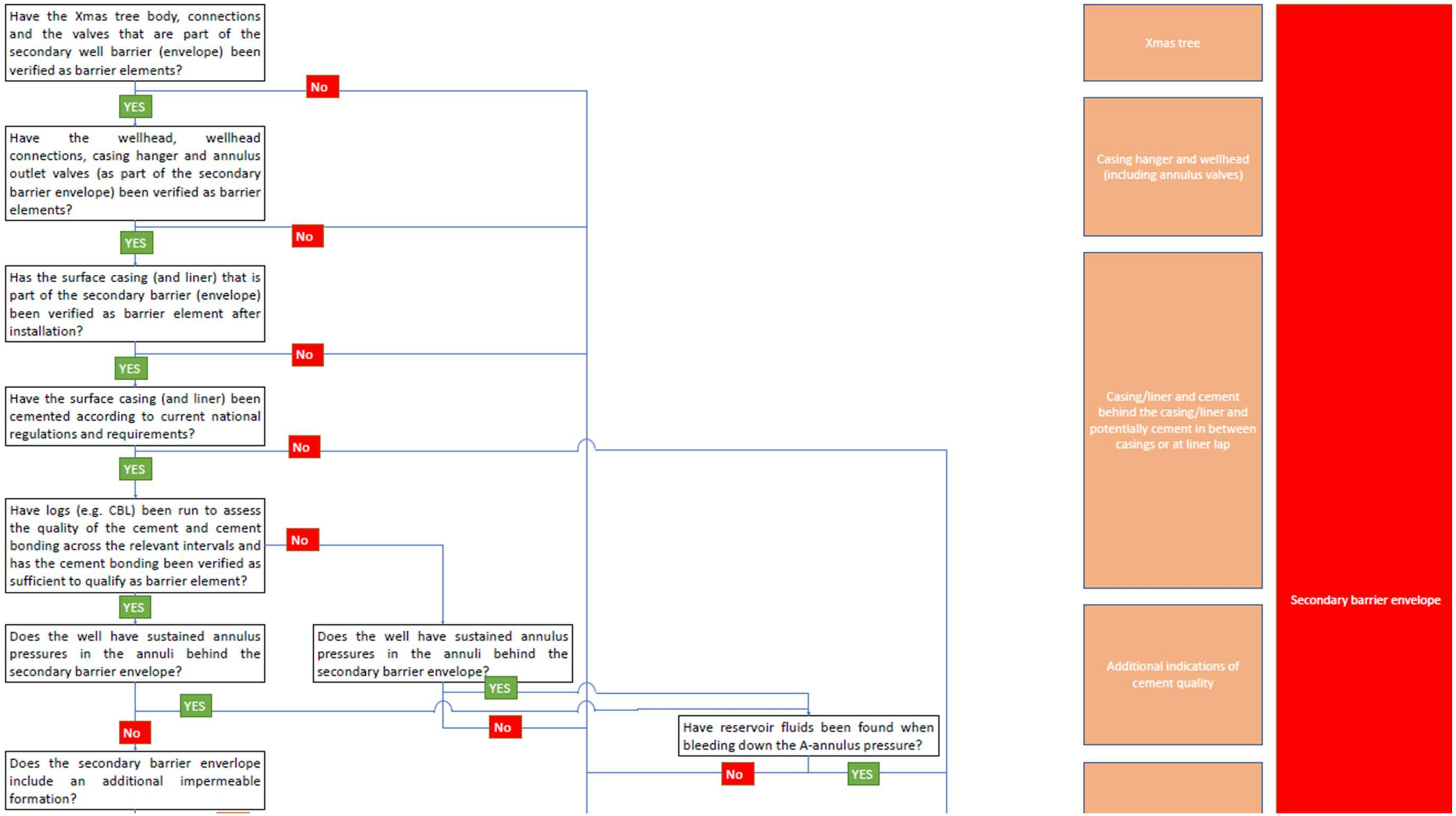
Any indication of sustained pressure and/or fluid leakage in the A annulus is verified. Following verification of primary well barrier, the integrity of secondary barrier is verified through assessment of its WBEs including the wellhead, Christmas tree, casing and/or liner, liner hanger, cement, secondary barriers, secondary impermeable formations, etc. Additionally, any indication of sustained pressure and/or fluid leakage in the annuli behind the secondary barrier envelope is verified.

Well integrity part 1 – primary barrier (envelope)




YES
Does the well design allow for a double barrier without packer and has the responsible element been verified?
No
YES
Has the casing/liner string that penetrates the cap rock(s) been cemented across the cap rock(s)?
No
YES
Have recent logs been run to assess the quality of the cement across the caprock level(s) and is the cement bonding sufficient to qualify as barrier element?
No
YES
Does the well have sustained A-annulus pressures?
Does the well have sustained A-annulus pressures or any other indication of cement integrity issues?
YES
YES
No
No
Have reservoir fluids been found when bleeding down the A-annulus pressure?
Has production casing/liner below the packer been verified as barrier element after installation?
No
No
YES
YES
Are there any signs of integrity issues with the cap rock?
YES
Recommend assessment of cap rock integrity and its impact on the propossed project
No
Are there any other indications of integrity issues with the primary barrier (envelope)?
YES
No
Based on the information provided it appears that there are no integrity issues with the primary barrier envelop
Based on the information provided it appears that the well may not have all the primary barrier elements verified and additional testing would be required. Results of the tests will determine required remediation work
The information provided gives reason to assume that the well may not be a good candidate to be reused for CCS due to lack of all the required primary well barriers in place. Excessive remediation work is foreseen to ensure well integrity. An engineering and techno-economic assessment would be required to confirm.
Production packer
Production casing and/or liner below packer and cement behind it (incl potential liner hanger)
Additional indications of cement quality
Caprock
Any other indications
Primary barrier envelope

Well integrity part 2 – secondary barrier (envelope)



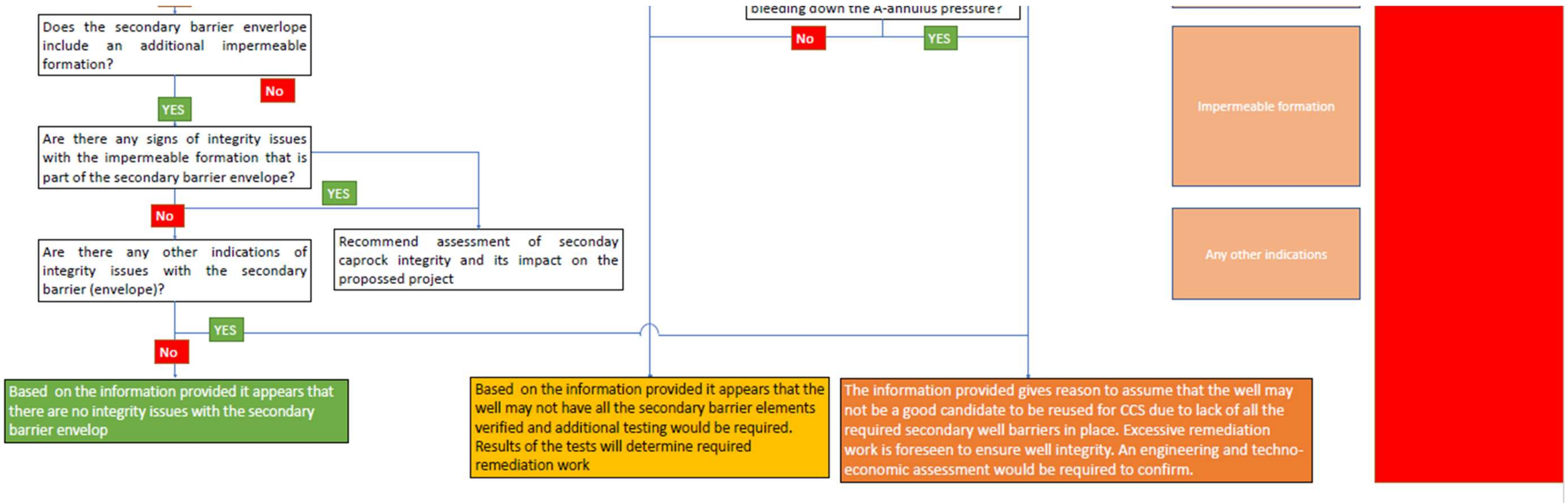


Figure 3. Draft detailed decision tree for assessing well integrity.

As the user proceeds through the different verification steps, the results are collected and used to develop a final assessment for well integrity. The result of the final assessment could be one of the following:

- The well in its current state meets the requirements for well integrity and can be used for CCS application without any modification.
- The well in its current state may not meet the requirements for well integrity but can be used for CCS application with verification of integrity and some modification if needed.
- The well in its current state does not meet the requirements for well integrity, and its use for CCS application will require significant modification and verification of integrity.

3.2.2. Risk of out of zone injection assessment

The second decision tree is for assessment of the risk of out of zone injection. The out of zone injection risks primarily arise due to potential unwanted migration of CO_2 and in-situ reservoir fluids (brine and/or hydrocarbons) out of the CO_2 storage reservoir through pathways behind the primary casing as demonstrated in Figure 4.

The pathways could be pre-existing or could be created due casing shoe failure, poor cement job quality, loss of cement sealing, failure of caprock or inadequate sealing of overlaps. The decision tree is shown in Figure 5 and is designed with queries to:

- Verify that an adequate quantity of cement was used to ensure proper length of cement to cover the primary caprock and all permeable zones. Verify that the cementing job was undertaken properly with centralizers to ensure proper coverage all around the casing.
- Verify that the cement has integrity as demonstrated through cement bond logs, noise logs.
- Verify that the casing shoe was installed properly at an appropriate depth.
- Assess whether the formation strength or fracturing pressure at the casing shoe depth was determined through leak off test (LOT) or formation integrity test (FIT) and assure that its value is higher than the anticipated maximum pressure at casing shoe depth.
- Verify that the casing shoe has integrity as demonstrated through pressure testing.
- Verify that the casing and/or liners do not exhibit any evidence of corrosion.
- Verify that any overlaps are properly sealed.
- Verify that the production packer was installed at proper depth where the formation has sufficient strength to avoid out of zone injection risk.

The results of the assessment will be similar to those output by the well integrity assessment.

3.2.3. Material compatibility assessment

The third step in the assessment is related to assessing the ability of the well materials to withstand the chemical conditions that result due to exposure to CO_2 in addition to the temperature changes that may occur during injection. The decision tree for this assessment is shown in Figure 6.

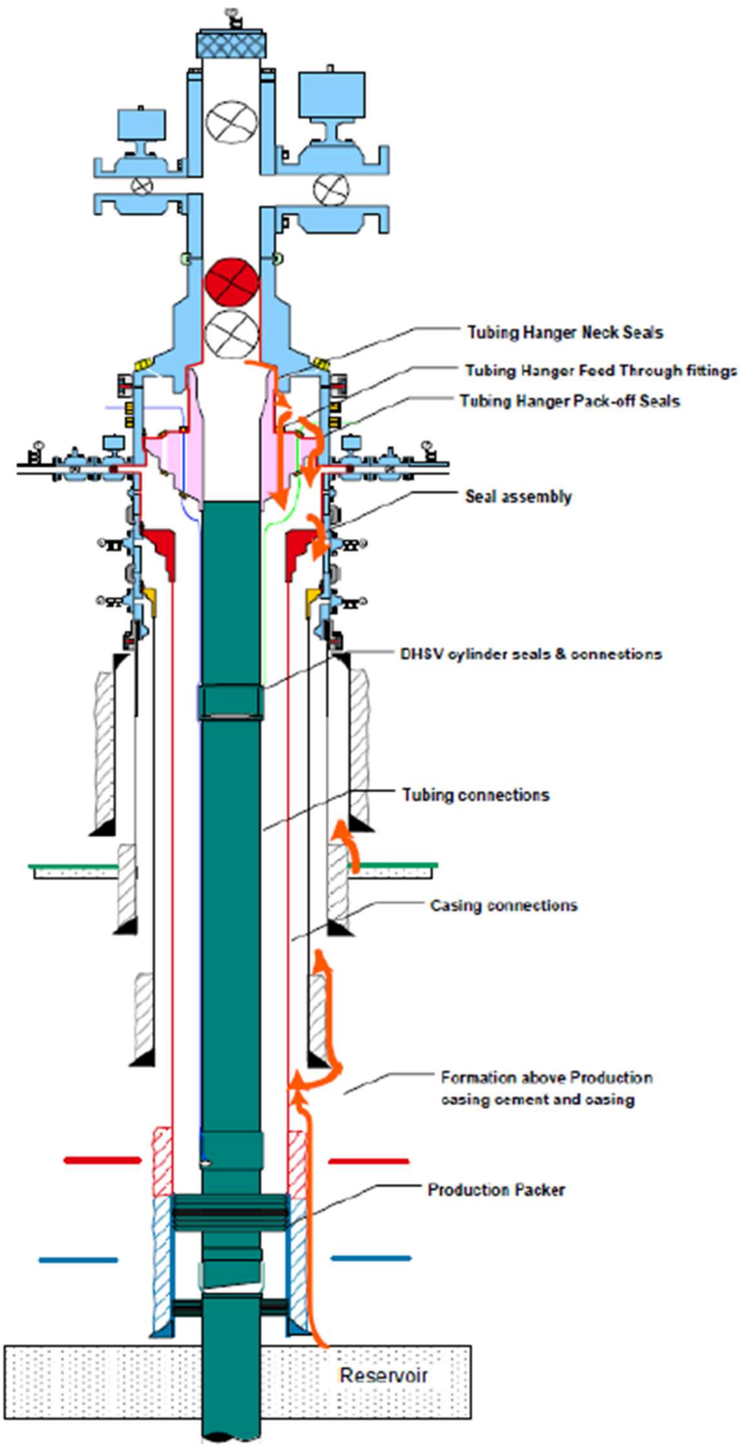
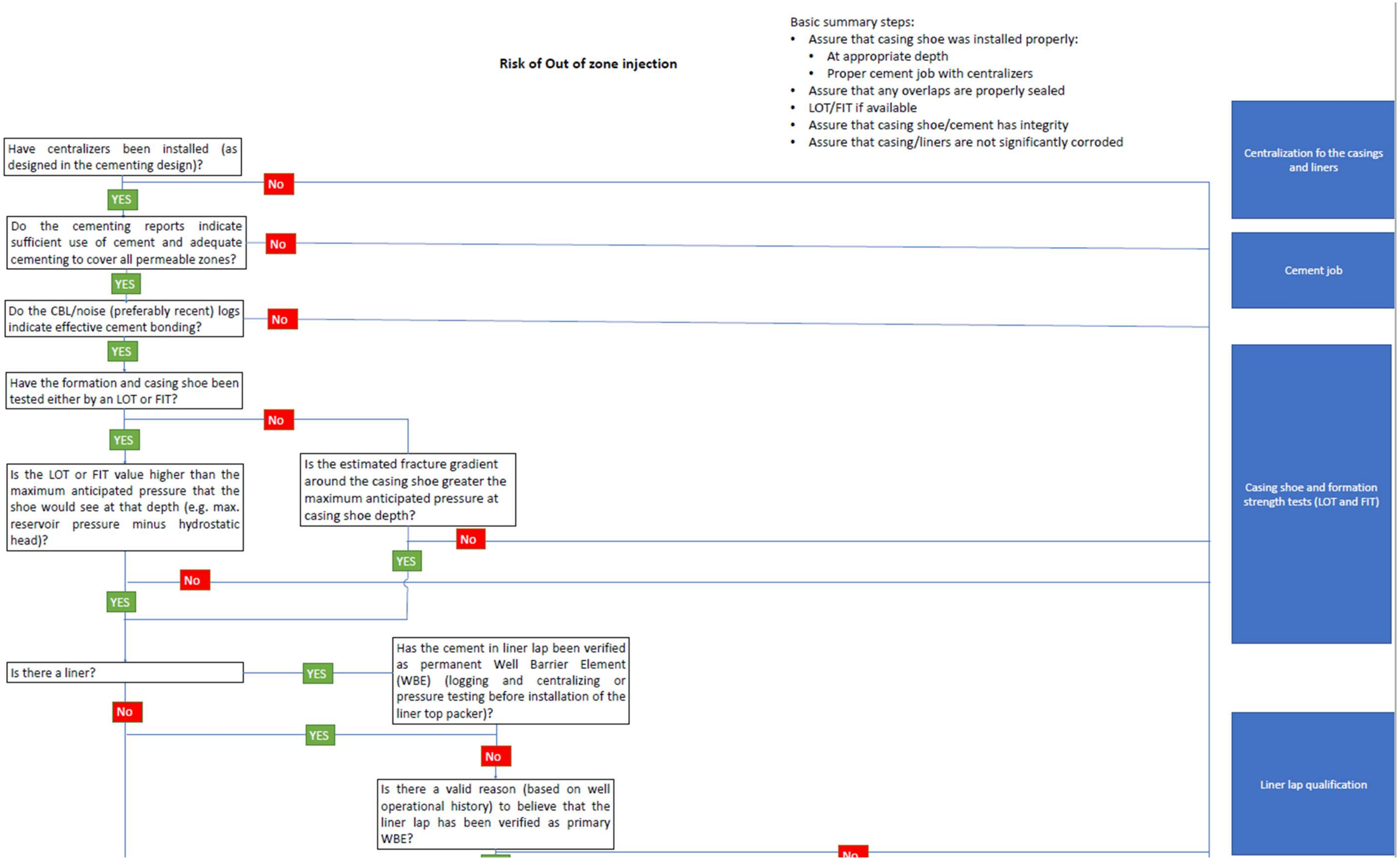


Figure 4. Out of zone injection conceptual diagram (IEAGHG, 2018b).


Risk of Out of zone injection
Basic summary steps:
• Assure that casing shoe was installed properly:
• At appropriate depth
• Proper cement job with centralizers
• Assure that any overlaps are properly sealed
• LOT/FIT if available
• Assure that casing shoe/cement has integrity
• Assure that casing/liners are not significantly corroded
Have centralizers been installed (as designed in the cementing design)?
No
YES
Do the cementing reports indicate sufficient use of cement and adequate cementing to cover all permeable zones?
No
YES
Do the CBL/noise (preferably recent) logs indicate effective cement bonding?
No
YES
Have the formation and casing shoe been tested either by an LOT or FIT?
No
YES
Is the LOT or FIT value higher than the maximum anticipated pressure that the shoe would see at that depth (e.g. max. reservoir pressure minus hydrostatic head)?
Is the estimated fracture gradient around the casing shoe greater the maximum anticipated pressure at casing shoe depth?
No
YES
No
YES
Is there a liner?
YES
Has the cement in liner lap been verified as permanent Well Barrier Element (WBE) (logging and centralizing or pressure testing before installation of the liner top packer)?
No
YES
No
Is there a valid reason (based on well operational history) to believe that the liner lap has been verified as primary WBE?
No
Centralization fo the casings and liners
Cement job
Casing shoe and formation strength tests (LOT and FIT)
Liner lap qualification

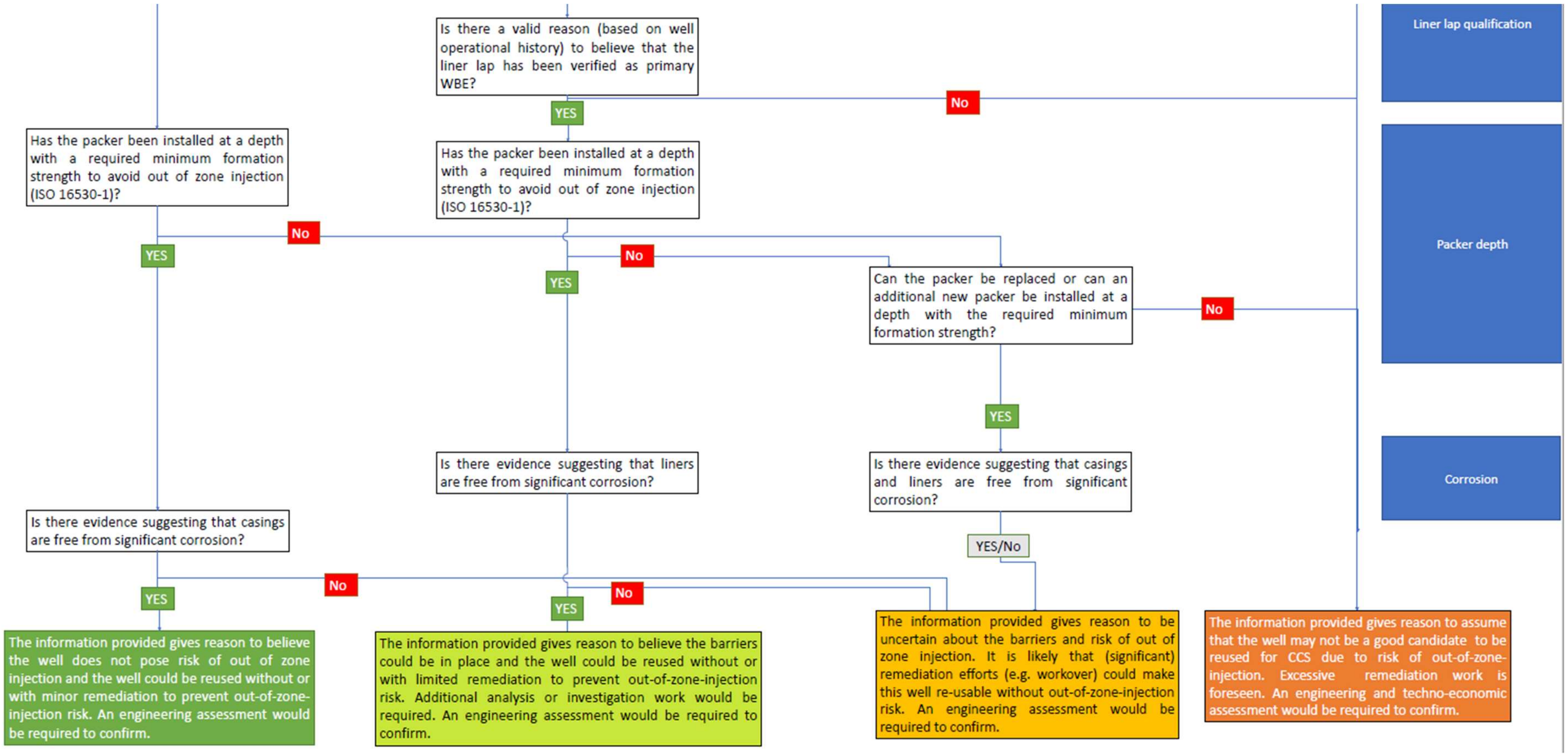
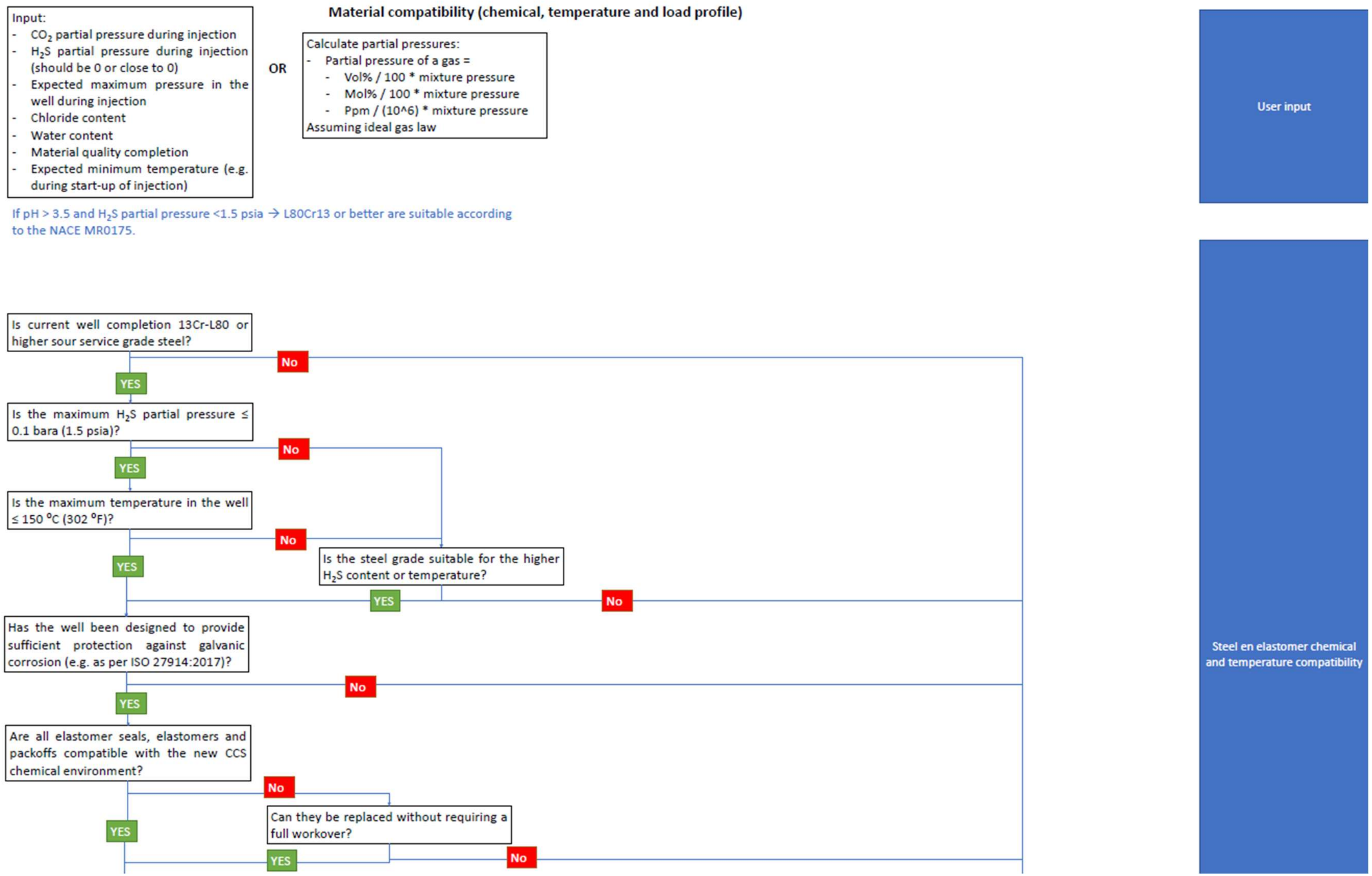


Figure 5. Detailed decision tree for assessing risk of out of zone injection.


Material compatibility (chemical, temperature and load profile)
Input:
- CO_2 partial pressure during injection
- H_2S partial pressure during injection (should be 0 or close to 0)
- Expected maximum pressure in the well during injection
- Chloride content
- Water content
- Material quality completion
- Expected minimum temperature (e.g. during start-up of injection)
OR
Calculate partial pressures:
- Partial pressure of a gas =
- Vol% / 100 * mixture pressure
- Mol% / 100 * mixture pressure
- Ppm / (10^6) * mixture pressure
Assuming ideal gas law
If pH > 3.5 and H_2S partial pressure <1.5 psia → L80Cr13 or better are suitable according to the NACE MR0175.
User input
Is current well completion 13Cr-L80 or higher sour service grade steel?
No
YES
Is the maximum H_2S partial pressure ≤ 0.1 bara (1.5 psia)?
No
YES
Is the maximum temperature in the well ≤ 150 °C (302 °F)?
No
YES
Is the steel grade suitable for the higher H_2S content or temperature?
YES
No
Has the well been designed to provide sufficient protection against galvanic corrosion (e.g. as per ISO 27914:2017)?
No
YES
Are all elastomer seals, elastomers and packoffs compatible with the new CCS chemical environment?
No
YES
Can they be replaced without requiring a full workover?
YES
No
Steel en elastomer chemical and temperature compatibility

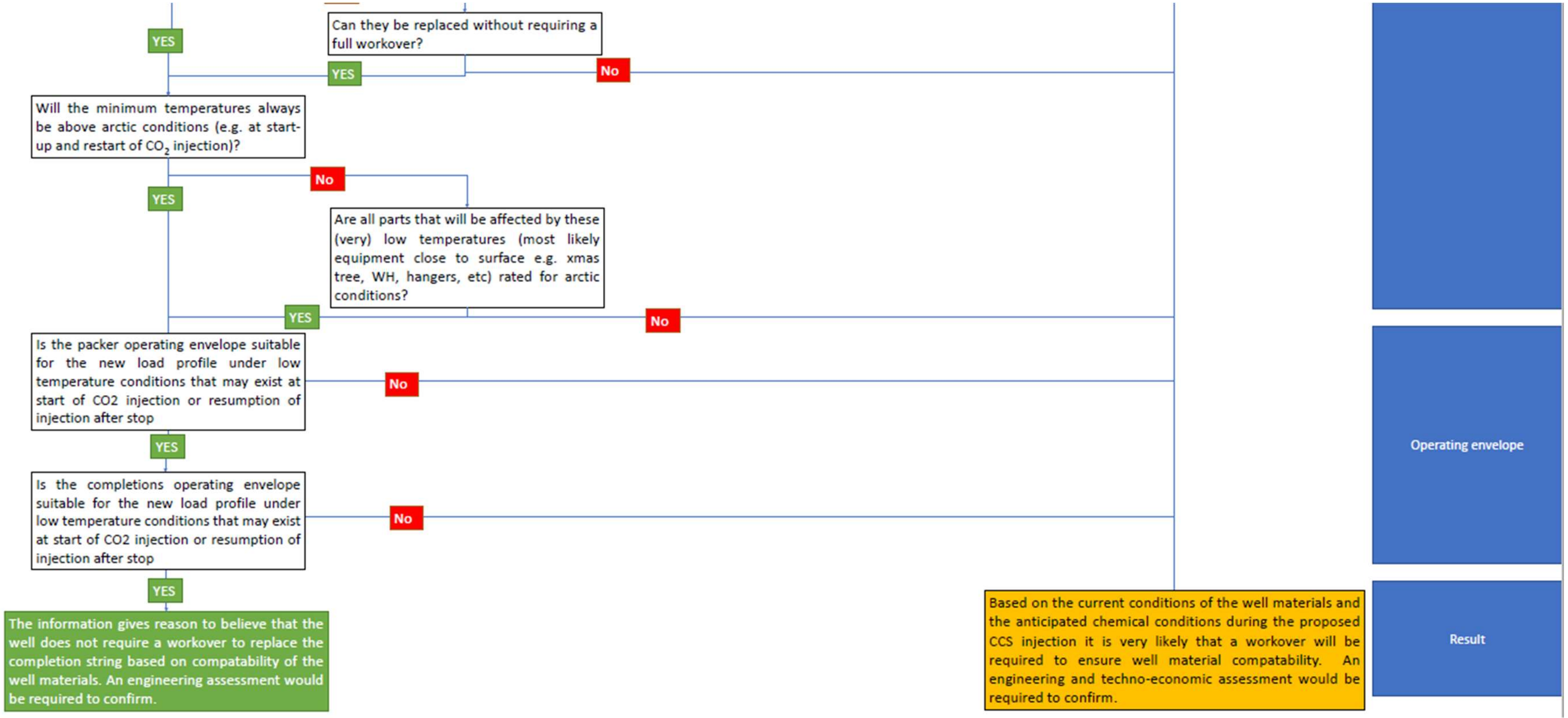


Figure 6. Detailed decision tree for assessment of material compatibility.

Assessment of chemical compatibility takes into consideration the chemical composition of injectate and in-situ temperature and temperature profiles. The steps are designed to:

- Verify that well materials are made of 13Cr-L80 or higher sour grade steel to withstand a CO_2-rich environment.
- Verify that well materials can withstand presence of H_2S if it is expected to be present
- Verify that the well was designed to offer protection against galvanic corrosion as recommended in ISO-27914.
- Verify that the well components such as elastomers and pack-offs can withstand the CO_2-rich corrosive conditions.

In addition to chemical changes a CCS well, especially a CO_2 injection well, may also experience extreme low temperature especially at the start of injection (or restart of injection if injection has been stopped for various reasons) due to the Joule-Thompson effect. The assessment steps include verification that the well materials are designed to withstand the low temperatures as well as resulting thermal stresses. Unlike the previous two assessments, results of material compatibility assessment include identification of need for workover to replace incompatible well components prior to well use and related techno-economic assessment.

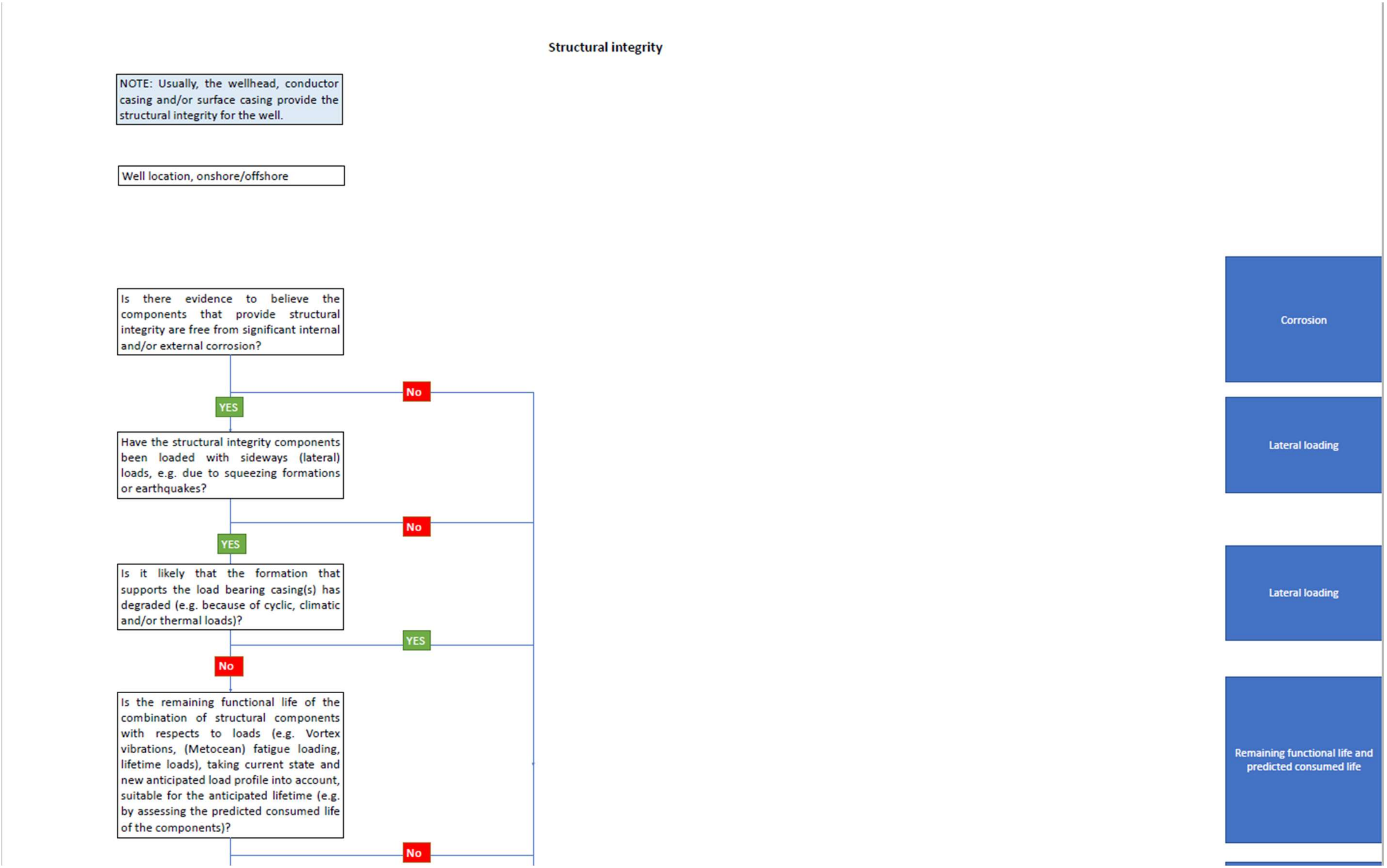
3.2.4. Structural integrity assessment

The final decision tree is for assessing the structural integrity of the well. The decision tree is developed by taking into consideration the recommendations described in ISO 16530 & NORSOK D010 standards as well as Oil & Gas UK guidelines. The decision tree is shown in Figure 7.

The structural integrity of a well is typically provided by the conductor casing, surface casing and the wellhead. The presence and type of these components will vary based on whether the well is onshore or offshore (Figure 8).

The potential failure modes for structural components can include metal corrosion, metal fatigue due to cyclic loads, degradation of soil strength, squeezing due to moving formations such as salt, etc. The assessment for structural integrity includes verification that the primary structural components will have enough strength to ensure structural integrity of the well over its expected lifetime under the anticipated operational conditions. Similar to the first two decision trees, the assessment will provide three possible recommendations.

The decision trees discussed above are designed to provide an assessment of the suitability of a well for a CCS project. In addition to this assessment we have developed an approach to predict cement integrity and CO_2 leakage in case cement fails.


Structural integrity
NOTE: Usually, the wellhead, conductor casing and/or surface casing provide the structural integrity for the well.
Well location, onshore/offshore
Is there evidence to believe the components that provide structural integrity are free from significant internal and/or external corrosion?
No
YES
Have the structural integrity components been loaded with sideways (lateral) loads, e.g. due to squeezing formations or earthquakes?
No
YES
Is it likely that the formation that supports the load bearing casing(s) has degraded (e.g. because of cyclic, climatic and/or thermal loads)?
YES
No
Is the remaining functional life of the combination of structural components with respects to loads (e.g. Vortex vibrations, (Metocean) fatigue loading, lifetime loads), taking current state and new anticipated load profile into account, suitable for the anticipated lifetime (e.g. by assessing the predicted consumed life of the components)?
No
Corrosion
Lateral loading
Lateral loading
Remaining functional life and predicted consumed life

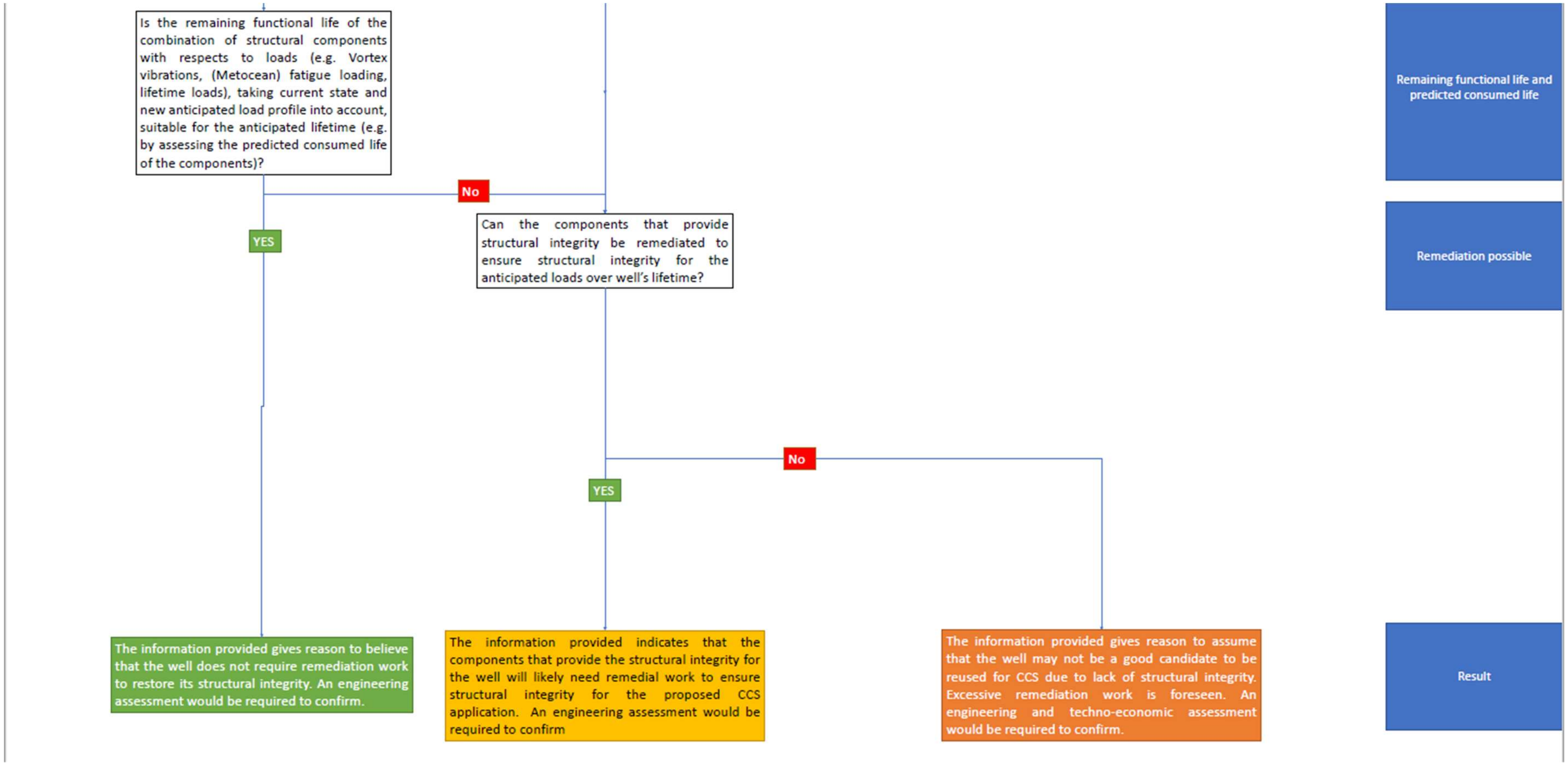


Figure 7. Detailed decision tree for assessment of structural integrity.

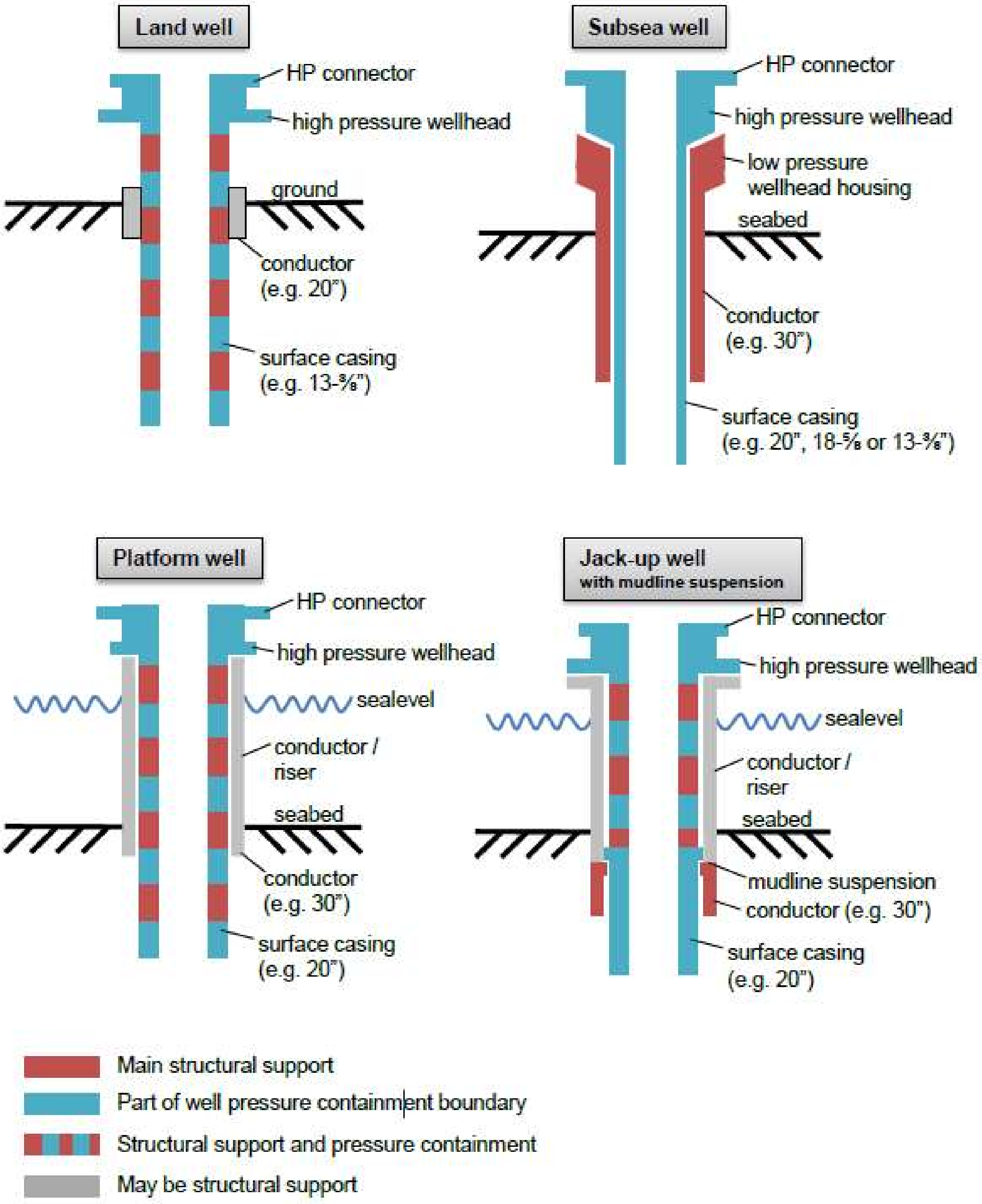


Figure 8. Differences in structural integrity components for different types of wells (Oil & Gas UK, 2012).

3.3. Cement integrity predictions

The primary focus of cement integrity predictions is to determine the probability of failure of integrity in the cement and primary caprock barriers and resulting CO_2 leakage. We take a two-step approach: first, we determine the probability of developing leakage pathways at the cement/caprock interface due to debonding of cement as well as the mean aperture of resulting micro-annuli. Next, we utilize the mean aperture and storage reservoir pressure to estimate the time-dependent CO_2 leakage rate and cumulative leakage over the lifetime of the project. For both these steps, we use fast, predictive models which are described below.

1. <u>Model to predict probability of debonding and micro-annuli:</u> We have developed a reduced order model (ROM) to perform fast predictions of cement debonding and the mean micro-annuli aperture. The ROM was developed using results of an extensive set of geomechanical modeling simulations (~ 4000 simulation runs) performed by TNO (Brunner et al., 2018). The geomechanical simulations were performed using the finite element analysis code DIANA and simulated evolution of geomechanical conditions in the cement/caprock environment behind wellbore casing as a result of changing pressure/stress conditions due to CO_2 injection through the wellbore. The extensive set of simulation runs were performed by sampling through four different uncertain parameters, including Young's modulus of cement, Poisson's ratio of cement, tensile strength of cement-rock interface, and injection temperature difference. The principal output of the geomechanical simulations was the aperture of the micro-annuli. The outputs of the 4000 simulation runs and corresponding inputs of the 4 uncertain parameters were used to develop the ROM that can be used to predict micro-annuli as a function of uncertain parameters. The ROM was developed using a two-step approach combining a "classifier" using Support Vector Classification (SVC) and a "regressor" using a Multivariate Adaptive Regression Splines (MARS) approach. The "classifier" is used to predict whether or not there will be debonding and the "predictor" is used to predict the aperture of micro-annuli in case debonding occurs. We generated four sets of ROMs for the predictions of maximum debonding under four different conditions: 1) soft cement property plus underbalanced well completion pressure; 2) stiff cement property plus underbalanced well completion pressure; 3) soft cement property plus balanced well completion pressure; 4) stiff cement property plus balanced well completion pressure. The predictive accuracy of the "classifier" and "regressor" is validated through cross validation as shown in Figure 9. As can be seen from the figure the "classifier" within all four ROMs can categorically identify the occurrence of debonding with 98% accuracy and the "regressor" provides a high-fidelity prediction on maximum debonding apertures with the coefficients of determination, R^2, over 0.99.

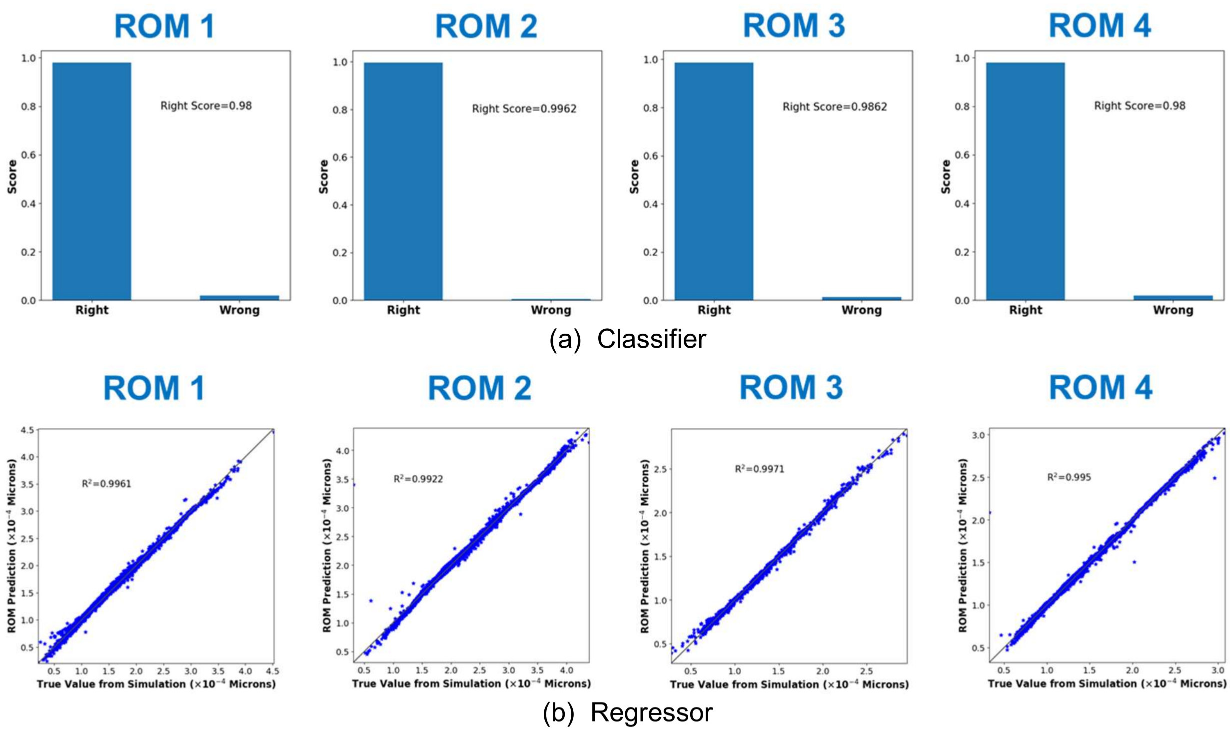


Figure 9. Validation of classifier (a), and regressor (b) for four sets of newly developed geomechanical ROMs.

2. Model to predict leakage rate: We plan to use the ROM developed by LANL for predicting CO_2 leakage through cemented wellbores as part the National Risk Assessment Partnership (NRAP) project (Harp et al., 2016). The ROM takes as input the effective cement permeability, depth of storage reservoir and pressure and saturation in the storage reservoir and predicts the CO_2 leak rate. We plan to use the predicted aperture of micro-annuli output from the geomechanical ROM and calculate an effective permeability for cement with the micro-annuli. Similar to the geomechanical ROM, the wellbore leakage ROM was developed using an extensive set of high-fidelity numerical simulations of CO_2 injection in a reservoir and its leakage through a cemented wellbore.

Using the combination of the geomechanical and leakage ROMs we will predict the probability of leakage and the total leakage in cases where leakage probability is non-zero. It should be noted that this approach will be used only to estimate the leakage potential through the primary caprock. We will not be estimating CO_2 movement beyond the primary caprock. We assume that the operator will utilize the predictions of leakage potential to determine mitigation approaches in order to ensure well integrity during the project lifetime.

4. Programming the assessment tool

In addition to development of the decision trees and models for estimating the leakage potential, we have also developed the overall programming framework/paradigm of the assessment tool, have implemented multiple decision trees in computational algorithms using the programming paradigm and have also developed multiple tool graphical user interfaces (GUIs) to input data and perform screening assessment.

4.1. Tool programming framework

The REXCO$_2$ Tool is leveraging the NRAP-Open-IAM software tool (https://gitlab.com/NRAP/OpenIAM) which provides an existing software framework for geologic CO_2 sequestration (GCS) risk assessment. NRAP-Open-IAM is an open source software package for performing integrated assessment model (IAM) risk analyses of geologic CO_2 sequestration (GCS) operations. The framework allows reduced-order GCS component models (e.g., reservoir, wellbore, aquifer, caprock stratigraphy, atmosphere models) to be integrated into a system model allowing rapid ensemble analysis of GCS leakage risk. The open-source framework is designed to allow new component models to be plugged in as needed and new risk assessment approaches to be implemented (Figure 10).

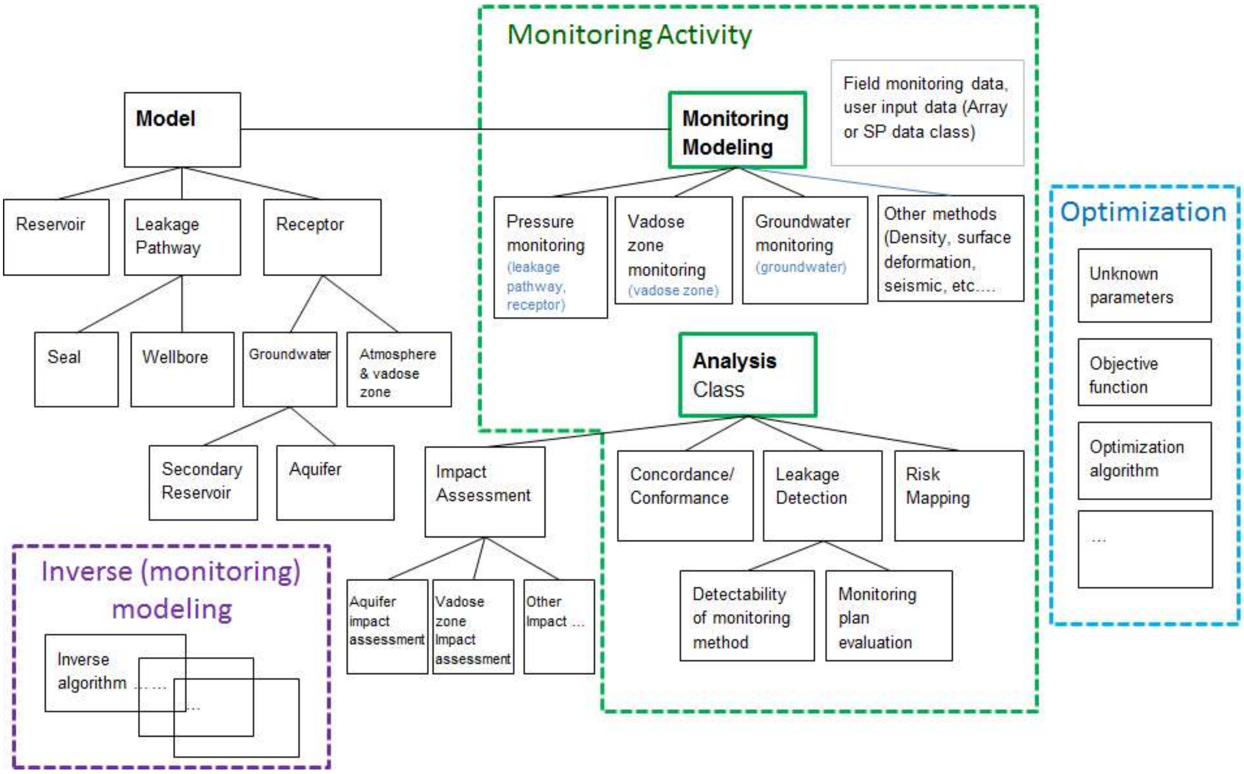


Figure 10. NRAP-Open-IAM integrated assessment model structure.

The core functionality of NRAP-Open-IAM is provided by the MATK (https://matk.lanl.gov) software package, which facilitates the development of component models and their integration into a system model, provides risk assessment tools (e.g., Latin Hypercube sampling, calibration, sensitivity analysis, etc.), allows ensemble realizations to be evaluated concurrently (i.e., use parallel processes for multiple simulations) across operating system platforms (Linux, MacOS, PC) and architectures (from laptop to high performance computing cluster). The REXCO$_2$ Tool will also derive this functionality via the MATK package through the NRAP-Open-IAM framework. In addition, the REXCO$_2$ Tool will be able to access all of the NRAP-Open-IAM component model ROMs because of their similar class structure.

4.2. Tool graphical user interfaces (GUIs)

The REXCO$_2$ Tool is leveraging the NRAP-Open-IAM GUI structure in order to fast-track its own GUI development. The NRAP-Open-IAM GUI utilizes the Tkinter python package (https://docs.python.org/3/library/tkinter.html) which provides a rich set of GUI features including text input boxes, dropdown menus, message boxes, and page tabs (Vasylkivska et al., 2018). These types of features are being integrated into the REXCO$_2$ Tool using the NRAP-Open-IAM as a template.

The GUI setup uses a component-based approach, where the main entry point for the user will call various components to perform the different parts of the assessment (such as well screening or the well leakage potential or integrity analysis). The general setup can be seen in **Error! Reference source not found.**, where the user will access the tool via a main Dashboard (**Error! Reference source not found.**). The first step is for the user to input relevant information about their site, field, and wells that they hope to assess (Figure 13). This is done in the Tool Initialization component, which will save the data for later use in the assessment.

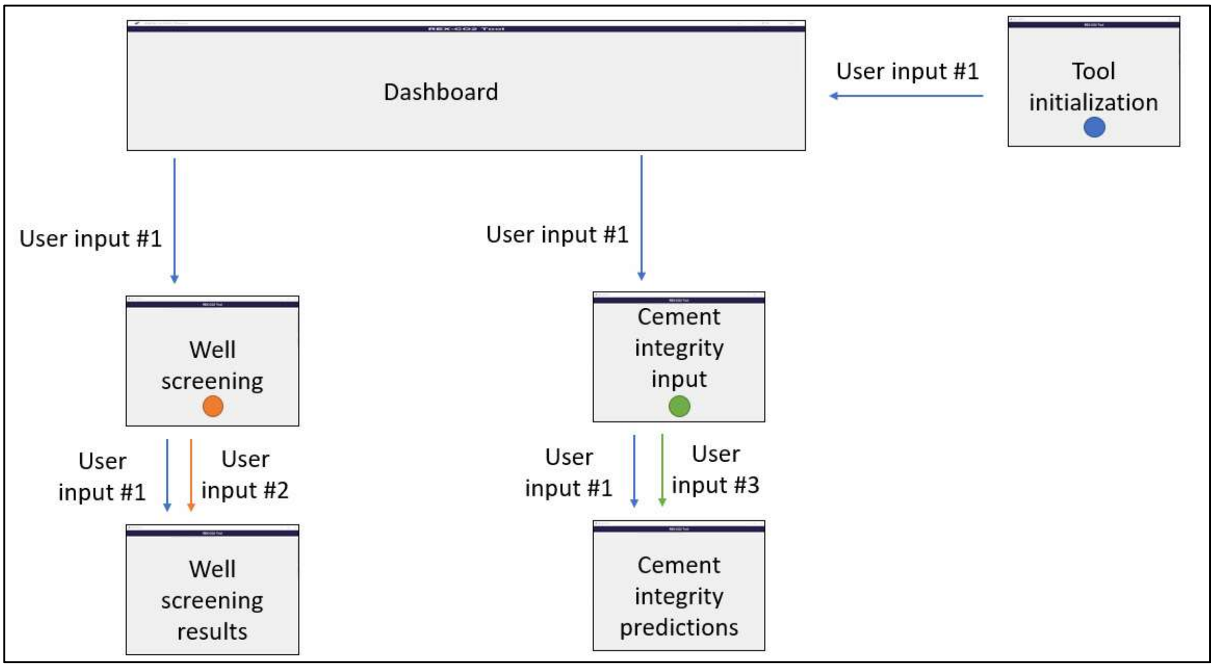


Figure 11. General REXCO$_2$ tool setup.

Once the user has completed the tool initialization, then the user will be able to access the Well Screening and the Cement Integrity Predictions aspects of the tool. The Well Screening component is the part of the tool that will guide the user through the four different decision trees mentioned in Section 3. The idea is that the user will complete all decision trees for each well desired for screening. The program will guide the user through the questions in the trees, resulting in an assessment of the well for that particular decision tree.

The final element of the tool is the cement integrity predictions, which performs lightweight calculations using pre-built ROMs discussed in Section 3.3. In this component, the tool will use the previously entered user input, along with some additional inputs, to run the ROMs and produce a probabilistic estimation of cement debonding and CO_2 leakage.

From each of these components, the user can navigate back to the Dashboard to access the other components.

Figure 12. Initial screen (Dashboard) a user will see at the beginning of REXCO2 Tool.

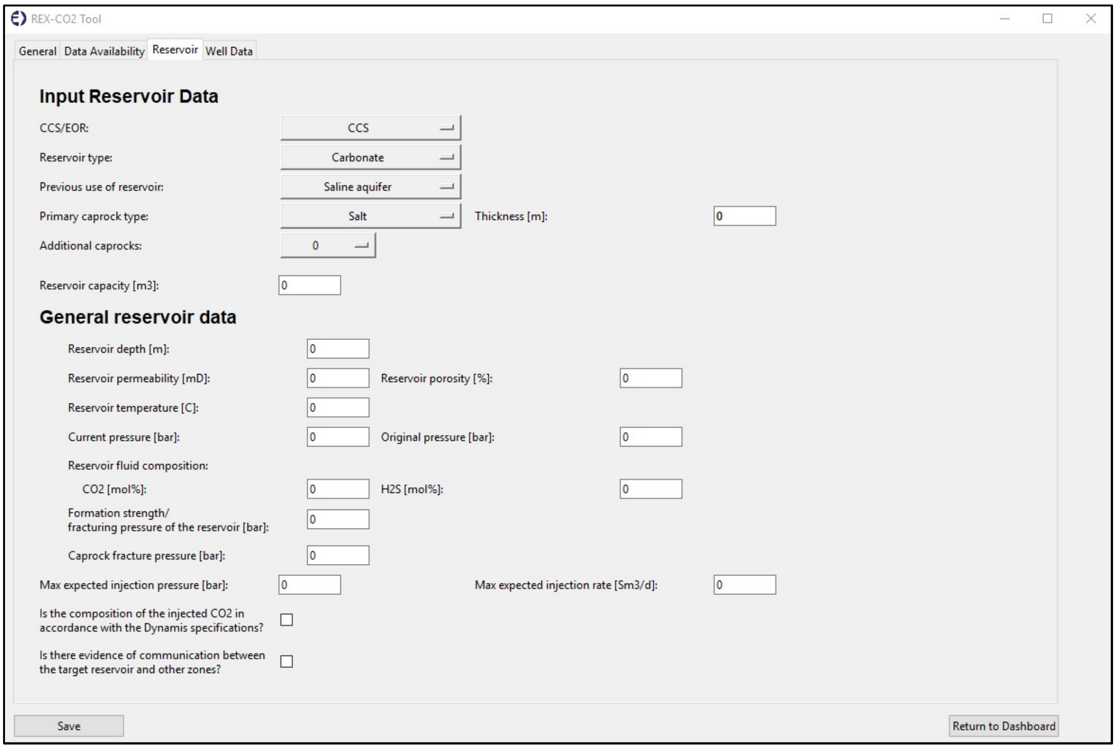


Figure 13. The tool initialization window to input reservoir data.

At the time of writing this report development of the tool is not complete. The examples of the dashboards shown in Figure 12 and Figure 13 are preliminary versions. These dashboards and the tool will be adapted and updated according to feedback from the industry partners as well as during testing and tool application to national case studies during the REX-CO_2 project.

5. Summary

We have successfully developed the principal components of the well screening tool. The different parts in the well screening tool include 1) Tool initialization 2) Well integrity assessment 3) Out of zone injection risk assessment 4) Well structural integrity assessment and 5) Well material compatibility assessment. We have developed detailed decision trees for each of these. We have used the ISO 27914 standard as well as US-EPA's Class-VI regulations both of which were specifically developed for CO_2 storage wells and ISO 16530 and NORSOK D010 standards to develop a reference well design used for development of the decision tree. We have also developed a modeling approach to estimate leakage potential of a well. The modeling approach combines a newly developed geomechanical ROM based on TNO's geomechanical simulations of cement debonding and a previously developed wellbore leakage ROM by LANL. We have developed a programming framework for the tool by leveraging NRAP's Open-IAM software framework. We have translated some of the decision trees using the programming framework and have developed initial versions of tool graphical user interfaces (GUIs).

Our next step will be to acquire feedback on the decision trees from industry partners and to update them as required. In addition, we will continue development of the tool and plan to complete development of the preliminary version of the tool by October 31, 2020. We expect the tool and underlying decision trees to be updated depending on lessons learned during tool development and from application to country- and field-specific tool applications.

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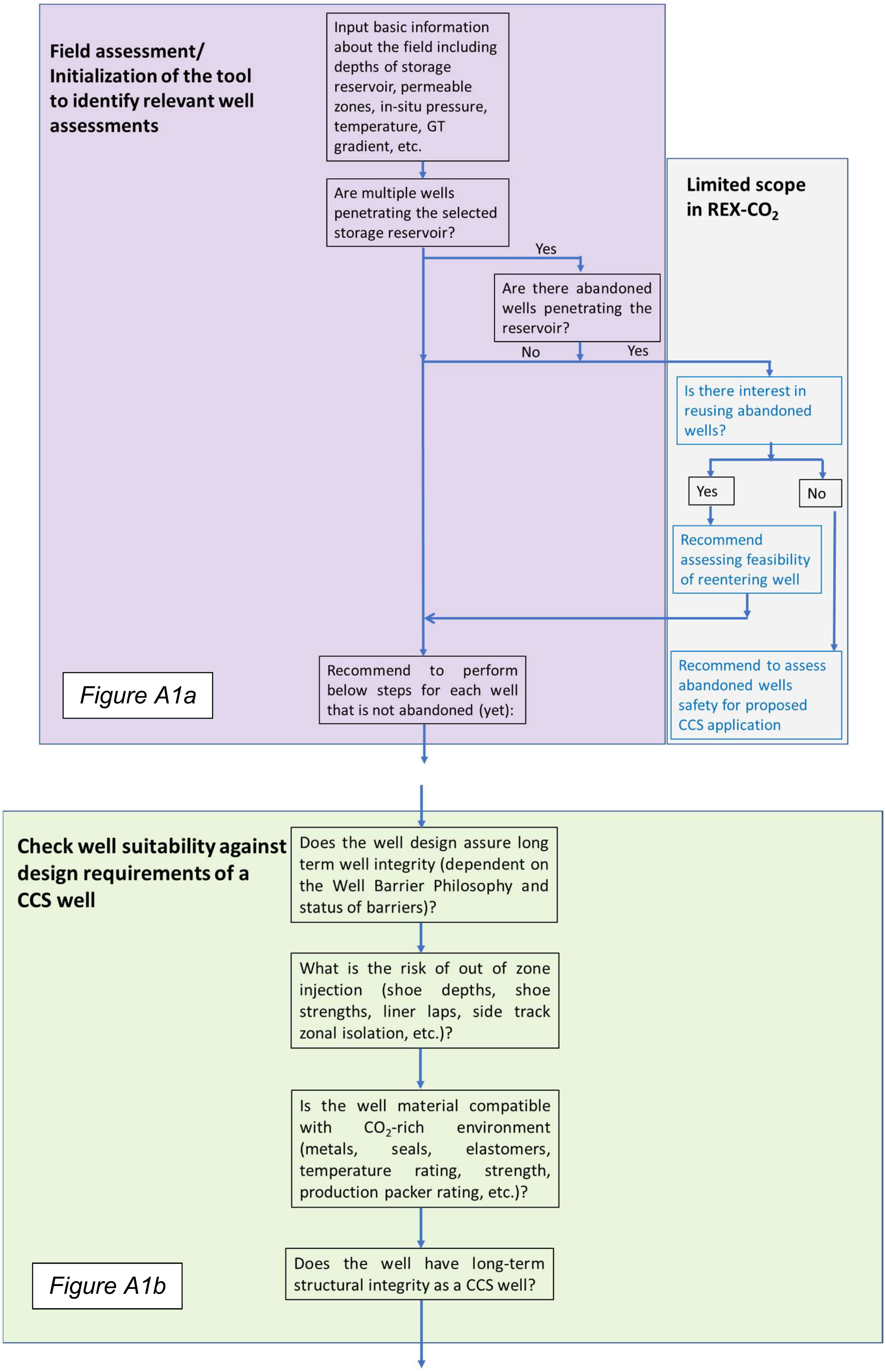
Appendix A. Well Assessment Framework



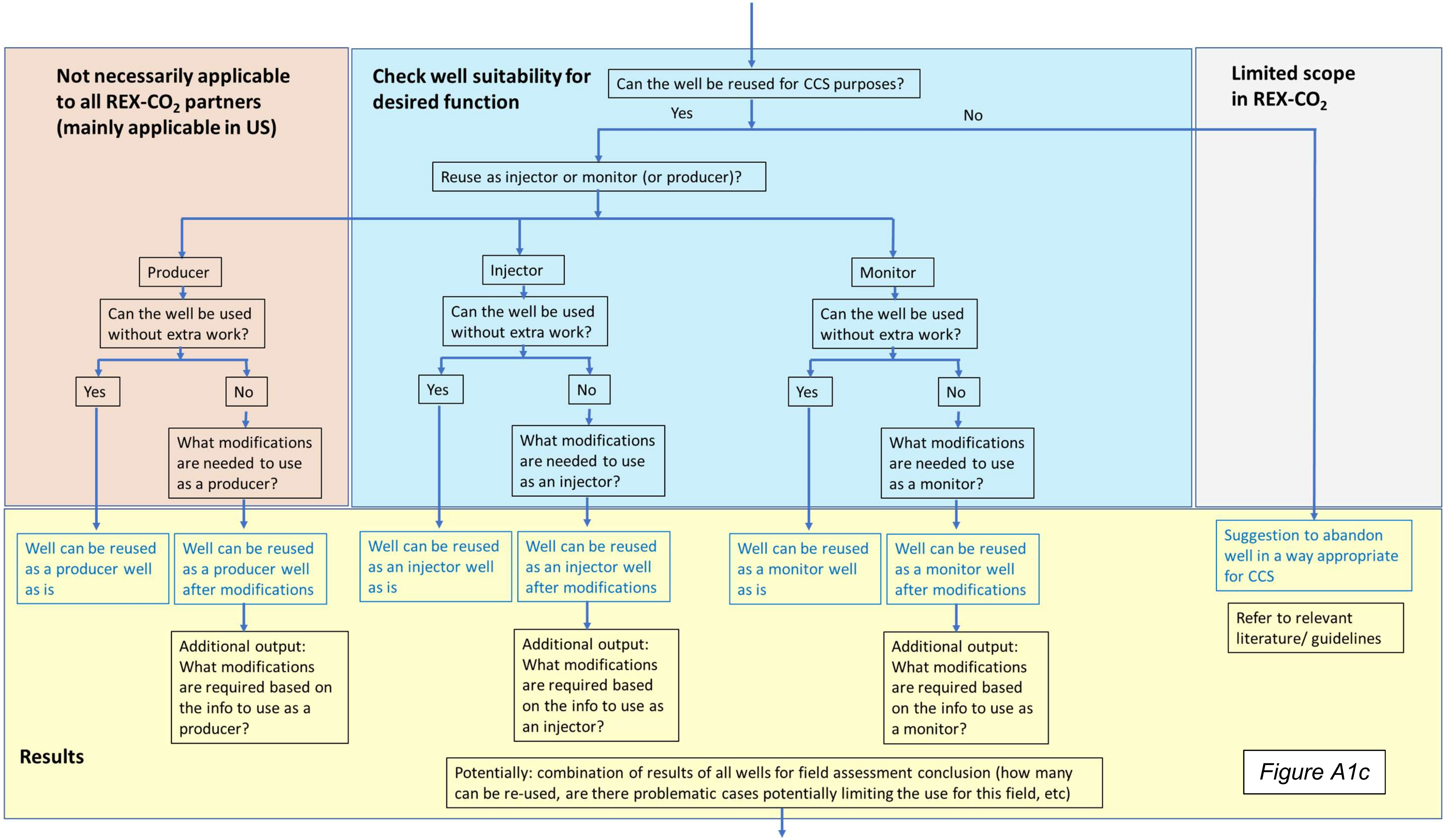

Not necessarily applicable to all REX-CO2 partners (mainly applicable in US)
Check well suitability for desired function
Limited scope in REX-CO2
Can the well be reused for CCS purposes?
Yes
No
Reuse as injector or monitor (or producer)?
Producer
Injector
Monitor
Can the well be used without extra work?
Yes
No
What modifications are needed to use as a producer?
What modifications are needed to use as an injector?
What modifications are needed to use as a monitor?
Well can be reused as a producer well as is
Well can be reused as a producer well after modifications
Well can be reused as an injector well as is
Well can be reused as an injector well after modifications
Well can be reused as a monitor well as is
Well can be reused as a monitor well after modifications
Suggestion to abandon well in a way appropriate for CCS
Refer to relevant literature/ guidelines
Additional output: What modifications are required based on the info to use as a producer?
Additional output: What modifications are required based on the info to use as an injector?
Additional output: What modifications are required based on the info to use as a monitor?
Results
Potentially: combination of results of all wells for field assessment conclusion (how many can be re-used, are there problematic cases potentially limiting the use for this field, etc)

Figure A1c

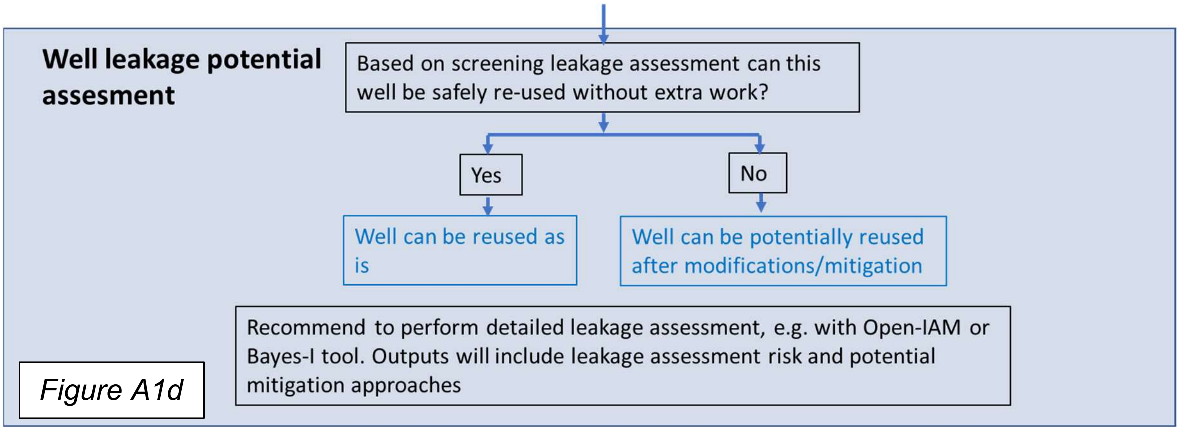


Figure A1. Conceptual well re-use assessment workflow. a) Initial check b) Check well design suitability, compatibility and structural integrity c) Check a well's functional suitability d) Leakage risk assessment.