sCO2-4-NPP: Innovative sCO2-Based Heat Removal Technology for an Increased Level of Safety of Nuclear Power Plants

D3.4 Requirements for testing and operation, including requirements for the preoperational and initial start-up test programmes for the system

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1 List of Acronyms

Abbreviation / Acronym	Description / meaning
ASN	Autorité de Sûreté Nucléaire (French Nuclear Safety Autority)
BNI	Basis Nuclear Installation
DEC	Design Extension Conditions
GOR	General Operation Rules
I&C	Instrumentation and Control
IAEA	International Atomic Energy Agency
LUHS	Loss of Ultimate Heat Sink
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
OLC	Operational Limits and Conditions
PSA	Probabilistic Safety Assessment
SAR	Safety Analysis Report
SBO	Station Black-out
SSC	Systems, Structures and Components
SUJB	Státní Úřad pro Jadernou Bezpečnost (State Office for Nuclear Safety)
TOS	Technical Operations Specifications
WENRA	Western European Nuclear Regulators Association

2 Introduction

The objective of this deliverable is to present the regulations related to the operation and testing of nuclear power plant equipment in the Czech Republic and France, with an extrapolation to the sCO2 system developed in the sCO2-4-NPP project.

The system is still under development, and therefore, some procedures or operating rules cannot be prepared in detail yet. However, it is important for the developers of the system to know what the expectations for a system providing safety functions are. Indeed, precise expectations on the capacity of the system to be controlled and to undergo regular tests will support certain development decisions.

First, some high-level requirements are presented, e.g. the most important WENRA and IAEA regulations, regarding the limits and conditions for nuclear power plants, modifications, maintenance and testing. These documents form the basis for both Czech Republic and French regulations.

Then, some specific rules are described regarding the safety systems operation and testing in these countries.

3 High level requirements

First of all, some international requirements regarding testing and operation of safety systems in a nuclear power plant should be considered. The rules given by WENRA and IAEA are valid for both France and Czech Republic as well as for all European countries.

The most important documents are listed below, and some selected parts are cited. For more details please check the referred publications.

3.1 WENRA requirements

"WENRA Safety Reference Levels for Existing Reactors", September 2014 (Issue H and K)

Operational Limits and Conditions (OLC) shall be developed to ensure that plants are operated in accordance with design assumptions and intentions as documented in the Safety Analysis Report (SAR).The OLCs shall define the conditions that must be met to prevent situations that might lead to accidents or to mitigate the consequences of accidents should they occur.

Each established OLC shall be justified based on plant design, safety analysis and commissioning tests. OLCs shall be kept updated and reviewed in the light of experience, the current state of science and technology, and every time modifications in the plant or in the safety analysis warrant it and changed if necessary.

The process for making modifications or temporary modifications of OLCs shall be defined. Such modifications shall be adequately justified by safety analysis and independent safety review. The licensee shall prepare and implement documented programmes of maintenance, testing, surveillance, and inspection of SSCs important to safety to ensure that their availability, reliability, and functionality remain in accordance with the design over the lifetime of the plant. They shall take into account operational limits and conditions and be re-evaluated in the light of experience. The programmes shall include periodic inspections and tests of SSCs important to safety in order to determine whether they are acceptable for continued safe operation of the plant or whether any remedial measures are necessary.

The extent and frequency of preventive maintenance, testing, surveillance and inspection of SSCs shall be determined through a systematic approach on the basis of:

- Their importance to safety,
- Their inherent reliability,
- Their potential for degradation (based on operating experience, research and vendor recommendation),
- Operational and other relevant experience and results of condition monitoring.

In-service inspections of nuclear power plants shall be carried out at intervals whose length shall be chosen in order to ensure that any deterioration of the most exposed component is detected before it can lead to failure.

Data on maintenance, testing, surveillance, and inspection of SSCs shall be recorded, stored and analysed. Such records shall be reviewed to look for evidence of incipient and recurring failures, to initiate corrective maintenance and review the preventive maintenance programme accordingly.

The maintenance programme shall be periodically reviewed in light of operating experience, and any proposed changes to the programme shall be assessed to analyse their effects on system availability, their impact on plant safety, and their conformance with applicable requirements. The potential impact of maintenance upon plant safety shall be assessed.

3.2 IAEA requirements

The IAEA safety standards in the domain of NPP operational safety include the Specific Safety Requirements publication IAEA SSR-2/2 [2] from 2016 and a number of Safety Guides. In this section the following Safety Guides are considered: IAEA NS-G-2.3 [3], IAEA NS-G-2.2 [4] and IAEA NS-G-2.6 [5]. According to document [21] these guides were published in the period 2000–2002 and represent the international consensus on operational safety which existed at that time, when design extension conditions had not yet been introduced (i.e. no guidance on DEC is given in below described IAEA guides). The guides would benefit from amendments to take into consideration revisions implemented in the other safety standards and, in particular, the IAEA SSR-2/2 Rev. 1 [2] and lessons from the Fukushima Daiichi accident.

In IAEA NS-G-2.2 [4] the Requirement 6 of IAEA SSR-2/2 Rev. 1 [2] being relevant for this deliverable should be implemented. Namely, the operational limits and conditions should be expanded to also cover design extension conditions (including equipment used for accident management and severe accident management, permanently installed and mobile).

In IAEA NS-G-2.3 [3] the Requirements 10 and 11 of IAEA SSR-2/2 Rev. 1 [2] should be implemented, dealing with adequately addressing configuration control and include guidance on Management of modifications for organizational changes, temporary modifications and modifications to computer based systems, which is of less relevance for this deliverable.

Finally, in IAEA NS-G-2.6 [5] the Requirement 13 of IAEA SSR-2/2 Rev. 1 [2] (being relevant for the sCO2-4-NPP project) should be implemented to address adequately Equipment Qualification in relation to activities needed during operation, including realistic performance targets under DEC conditions.

IAEA, SSR-2/2, Safety of Nuclear Power Plants – Commissioning and Operation, Rev.1, 2016 (Requirements 6, 25 and 31)

The operating organization shall ensure that the plant is operated in accordance with the set of operational limits and conditions. The OLCs shall form an important part of the basis for the authorization of the operating organization to operate the plant. The plant shall be operated within the operational limits and conditions to prevent situations arising that could lead to anticipated operational occurrences or accident conditions, and to mitigate the consequences of such events if they do occur.

The operational limits and conditions shall:

- be developed for ensuring that the plant is being operated in accordance with the design assumptions and intent, as well as in accordance with its licence conditions reflect the provisions made in the final design as described in the safety analysis report.

- be submitted to the regulatory body for assessment and approval before the commencement of operation, if so required by the regulatory body.
- be substantiated by a written statement of the reason for their adoption.
- be reviewed and revised as necessary in consideration of experience, developments in technology and approaches to safety, and changes in the plant include requirements for normal operation, including shutdown and outage stages, and shall cover actions to be taken and limitations to be observed by the operating personnel.

The operational limits and conditions shall include the following:

- Safety limits,
- Limiting settings for safety systems,
- Limits and conditions for normal operation,
- Surveillance and testing requirements,
- Action statements for deviations from normal operation.

The operating organization shall ensure that a commissioning programme for the plant is established and implemented.

The commissioning programme for the plant shall:

- cover the full range of plant conditions required in the design and the safety case. The results shall be used to demonstrate that the behaviour of the plant as built is in compliance with the design assumptions and the licence conditions. Special attention shall be paid to ensuring that no commissioning tests are performed that might place the plant in an unanalysed condition. Commissioning stages, test objectives and acceptance criteria shall be specified in such a way that the programme is auditable.
- provide the operating organization and the regulatory body with the means of identifying the hold points in the commissioning process at which approval may be required prior to continuing to the next stage.
- be divided into stages. A review of the test results for each stage shall be completed before commissioning is continued to the next stage. On the basis of the review, a judgement shall be made on whether the commissioning programme can proceed to the next stage. Judgements shall also be made on the basis of the review on whether the succeeding stages will be modified as a consequence of the test results, or because some tests in the stage had not been undertaken, or some tests had been undertaken but had not been completed. The results for some stages may be subject to approval by the regulatory body before commissioning can proceed to the next stage.
- include all the tests necessary to demonstrate that the plant as built and as installed meets the requirements of the safety analysis report and satisfies the design intent and, consequently, that the plant can be safely operated in accordance with the operational limits and conditions.
- be sufficiently comprehensive as to provide reference data to characterize structures, systems and components. Such reference data shall be retained as they are important for ensuring the safety of the plant and for subsequent safety reviews.

Operating and maintenance procedures shall be validated to the extent practicable as part of the commissioning programme, with the participation of future operating personnel. Suitably qualified operations personnel shall be directly involved in the commissioning process. Operating personnel and plant technical staff shall be involved in the commissioning process to the extent necessary to ensure proper preparation for the operational phase. All the functions of the operating organization shall be performed at the appropriate stages during commissioning. These functions shall include discharging responsibilities for management, training of personnel, the radiation protection programme, waste management, managements of records, fire safety, physical protection and the emergency plan.

Operating procedures and test procedures shall be verified to ensure their technical accuracy and shall be validated to ensure their usability with the installed equipment and control systems. Verification and validation of procedures shall be performed to confirm their applicability and quality, and to the extent possible shall be performed prior to fuel handling operations on the site. This process shall continue during the commissioning phase. Verification and validation shall also be carried out for procedures for overall operation.

From the commencement of commissioning, reviewed and approved arrangements for work control, modification control and plant configuration control shall be in place to meet the conditions of the commissioning tests.

Initial fuel loading shall not be authorized until all relevant pre-operational tests have been performed and the results have been accepted by the operating organization and the regulatory body. Reactor criticality and initial power increase shall not be authorized until all necessary tests have been performed and the results have been accepted by the operating organization and the regulatory body, as appropriate. The tests of the commissioning programme shall be successfully completed as a necessary condition for authorization, as appropriate, for normal operation of the plant to be commenced.

The operating organization shall ensure that the interfaces and the communication lines between different groups (i.e. groups for design, groups for construction, contractors, groups for commissioning and groups for operations) shall be clearly specified and controlled. Authorities and responsibilities shall be clearly specified and shall be delegated to the individuals and groups performing the commissioning activities. The operating organization shall be responsible for ensuring that construction activities are of appropriate quality and that completion data on commissioning activities and comprehensive baseline data, documentation or information are provided. The operating organization shall also be responsible for ensuring that the equipment supplied is manufactured under a quality assurance programme that includes inspection for proper fabrication, cleanliness, calibration and verification of operability.

During construction and commissioning, the plant shall be monitored, preserved and maintained so as to protect plant equipment, to support the testing stage and to maintain consistency with the safety analysis report. A comparison shall be carried out between the as built plant and its design parameters. A comprehensive process shall be established to address non-conformances in design, manufacturing, construction and operation. Resolutions to correct differences from the initial design and non-conformances shall be documented.

The operating organization shall ensure that effective programmes for maintenance, testing, surveillance and inspection are established and implemented.

Maintenance, testing, surveillance and inspection programmes shall be established that include predictive, preventive and corrective maintenance activities. These maintenance activities shall be conducted to maintain availability during the service life of structures, systems and components by controlling degradation and preventing failures. In the event that failures do occur, maintenance activities shall be conducted to restore the capability of failed structures, systems and components to function within acceptance criteria.

The operating organization shall establish surveillance programmes for ensuring compliance with established operational limits and conditions and for detecting and correcting any abnormal condition before it can give rise to significant consequences for safety.

The operating organization shall develop procedures for all maintenance, testing, surveillance and inspection tasks. These procedures shall be prepared, reviewed, modified when required, validated, approved and distributed in accordance with procedures established under the management system.

Data on maintenance, testing, surveillance and inspection shall be recorded, stored and analysed for the purpose of confirming that the operating performance is in accordance with the design intent and with requirements for the reliability and availability of equipment.

The frequency of maintenance, testing, surveillance and inspection of individual structures, systems and components shall be determined on the basis of:

- The importance to safety of the structures, systems and components, with insights from probabilistic safety assessment taken into account,
- Their reliability in, and availability for, operation,
- Their assessed potential for degradation in operation and their ageing characteristics,
- Operating experience,
- Recommendations of vendors.

IAEA, NS-G-2.3, Modifications to Nuclear Power Plants, 2001 (Modifications relating to plant configuration)

The detailed design of modifications should specify requirements for construction, installation, commissioning, equipment qualification, testing, including test acceptance criteria, and maintenance during operation. Operational limits and conditions should be reassessed and revised, as necessary, following any safety related modifications at the plant or any changes to the safety analysis report, and also on the basis of accumulated experience and technological developments. Results of routine tests or commissioning tests also necessitate analysis and consideration of the need for modifications to operational limits and conditions.

Where it is necessary to modify OLCs temporarily, for example, in order to perform physics tests on a new core, particular care should be taken to ensure that the effects of the changes are analysed. The modified state, although temporary, should undergo assessment and approval at the same level as for a permanent modification. Where a permanent approach is available as a reasonable alternative, this should be preferred to a temporary modification of operational limits and conditions. Modifications should be approved by the regulatory body where this is the national practice.

The ability to operate the modified plant safely should be verified through a testing programme which includes checks, measurements and evaluations prior to, during and on completion of the modification. Testing and commissioning, which may include pre-installation tests of equipment, including equipment qualification, should be aimed at demonstrating that modifications meet their design specifications for all anticipated operational occurrences and in design basis accidents (*it should be noted, that the design extension conditions were introduced at the IAEA after 2001, therefore they are not considered here*). For major modification projects, which may involve a staged programme approach with separate approvals at each stage, a more rigorous programme of testing and commissioning, together with appropriately approved commissioning schedules, may be appropriate.

The testing of equipment prior to installation in the plant should be considered. Tests should be planned as part of the initial design of the modification. Acceptance tests should include specific acceptance criteria based on performance criteria and testing requirements specified as part of the modification process. The test plan should be reviewed and approved by the plant management, and should also be submitted, if required, for review and approval by the regulatory body.

Arrangements should be made for the verification and validation of any changes to procedures, operational limits and conditions and process software, and this should be done in the commissioning phase. Validation can be done by testing on simulation models or by specially controlled operational tests to confirm that changes are operable and produce the desired results. When conditions do not allow testing to be conducted after execution of the modification, testing should be done in advance on specific test facilities. The ability to execute a programme successfully and efficiently may depend on the accessibility of the modified system for on-line measurements and may necessitate special provisions for measuring and testing. The necessity for such provisions should be assessed in the design stage of the modification.

IAEA, NS-G-2.2, Operational Limits and Conditions and Operating Procedures for Nuclear Power Plants, 2000

There will be safety system settings for a range of parameters. These are the parameters included in safety limits as well as other parameters, or combinations of parameters, which could contribute to pressure or temperature transients. Exceeding some such settings will cause the reactor to be tripped to suppress a transient. Exceeding other settings will result in other automatic actions to prevent safety limits from being exceeded. Some other safety system settings are provided to initiate operation of engineered safety systems (*the DEC safety features are also required, according to current approach*). These systems limit the course of anticipated operational occurrences in such a way that either safety limits are not exceeded or the consequences of postulated accidents are mitigated. Established safety system settings should ensure automatic actuation of safety systems within parameter values assumed in the safety analysis report, despite the possible errors that could occur adjusting the nominal set point. Appropriate alarms should be provided to enable the operating personnel to initiate corrective actions before safety system settings are reached.

In order to ensure that safety system settings and limits and conditions for normal operation are met at all times, the relevant systems and components should be monitored, inspected, checked, calibrated and tested in accordance with an approved surveillance programme. The surveillance programme should be adequately specified to ensure the inclusion of all aspects of the limits or conditions. The frequency of the surveillance procedures should be stated and should be based on a reliability analysis including, where available, a probabilistic safety assessment (PSA) and a study of experience gained from previous surveillance results or, in the absence of both, the recommendations of the supplier.

The surveillance requirements should be specified in procedures with clear acceptance criteria so that there are no doubts concerning system operability or component operability. The relationship between these criteria and the limit or condition being confirmed should be available in written form. The surveillance requirements should also cover activities to detect ageing and other forms of deterioration due to corrosion, fatigue and other mechanisms. Such activities will include non-destructive examination of passive systems as well as of systems explicitly covered by limits and conditions for normal operation. If degraded conditions were to be found, then the effect on the operability of systems should be assessed and acted upon.

IAEA, NS-G-2.6, Maintenance, Surveillance and In-service Inspection in Nuclear Power Plants, 2002

The maintenance programme for a nuclear power plant should cover all preventive and remedial measures, both administrative and technical, that are necessary to detect and mitigate degradation of a functioning SSC or to restore to an acceptable level the performance of design functions of a failed SSC. The purpose of maintenance activity is also to enhance the reliability of equipment. The range of maintenance activities includes servicing, overhaul, repair and replacement of parts, and often, as appropriate, testing, calibration and inspection.

While there are various conceptual approaches to maintenance, the relevant activities may be divided into **preventive and corrective maintenance**. A considerable part of all maintenance activity is performed while the plant is shut down; however, maintenance may be planned and executed under power operation provided that adequate defence in depth is maintained. For definitions of different types of maintenance, see the Glossary [5].

Preventive maintenance should include periodic, predictive and planned maintenance activities performed prior to failure of an SSC so as to maintain its service life by controlling degradation or preventing its failure.

- Periodic maintenance activities should be accomplished on a routine basis and may include any combination of external inspections, alignments or calibrations, internal inspections, overhauls, and replacements of components or equipment.
- Predictive maintenance should involve continuous or periodic monitoring and diagnosis in order to predict equipment failure. Not all equipment conditions and failure modes can be monitored, however; predictive maintenance should therefore be selectively applied where appropriate. Predictive techniques may include condition monitoring, reliability centred maintenance and similar techniques.
- Planned maintenance activities should be performed prior to unacceptable degradation or equipment failure and may be initiated on the basis of results of predictive or periodic maintenance, vendor recommendations or experience.

Corrective maintenance includes actions that, by means of repair, overhaul or replacement, restore the capability of a failed SSC to perform its defined function within the acceptance criteria.

Structures, systems and components important to safety should be included in the preventive maintenance programme. The operating organization should review the programme as appropriate in order to ensure that items important to safety have been properly identified and classified, and that the applicable requirements of the regulatory body have been met.

Maintenance actions can have significant effects on reliability and risk, but they can also entail a significant expenditure of resources. In order to reconcile potentially conflicting demands, individual maintenance actions should be prioritized according to their importance, and their probable effects on reliability and risk should be quantified. Different approaches can be used for this, all of which are based firstly on the selection of SSCs important to safety and secondly on specifying risk and performance criteria to ensure that the SSCs remain capable of performing their intended functions. The maintenance work that is most important for ensuring the reliability of components and controlling risks should be identified by these means.
The use of risk informed maintenance strategies should be considered, to provide a reasonable balance in the mixture of corrective, preventive and predictive maintenance and to facilitate proactive maintenance rather than exclusively reactive maintenance.

Preventive maintenance should be of such a frequency and extent as to ensure that the levels of reliability and functionality of the plant's SSCs important to safety remain in accordance with the design assumptions and intent. It should also ensure that the safety status of the plant has not been adversely affected since the commencement of operation. In establishing the frequency and extent of preventive maintenance, the following aspects should be considered:

- the importance of SSCs to safety,
- designers' and vendors' recommendations,
- relevant experience available,
- results of condition monitoring,
- the probability of failure to function properly,
- on-line maintenance,
- the necessity of maintaining radiation doses as low as reasonably achievable (the ALARA principle).

The frequency with which SSCs not normally in use are maintained should be optimized to prevent possible wear-out due to subsequent overtesting, but also to provide confidence that they will perform their functions satisfactorily when called upon and to reduce the probability of errors in their reinstatement.

A **surveillance programme** should be established by the operating organization to verify that provisions for safe operation that were made in the design and checked during construction and commissioning continue in effect during the operating lifetime of the plant and continue to supply data to be used for assessing the residual service life of SSCs. At the same time, the programme should verify that the safety margins are adequate and provide a high tolerance for anticipated operational occurrences, errors and malfunctions. Particular attention should be paid to the following aspects:

- integrity of the barriers between radioactive materials and the environment (such as fuel cladding, primary pressure boundary and containment),
- availability of safety systems (note: *the DEC safety features, required according to current approach, have not yet been considered in 2002*) such as the protection system, the safety system actuation systems and the safety system support features,
- availability of items whose failure could adversely affect safety.

The surveillance programme should fulfil the following functions:

- delineating in sufficient scope and depth the aims of surveillance in accordance with operating limits and conditions and other requirements that are applicable to SSCs important to safety,
- specifying the frequency of surveillance and providing for the scheduling of surveillance activities,

- specifying standards to be applied and providing for appropriate procedures to be followed in the conduct and assessment of each surveillance activity,
- verifying that SSCs important to safety remain within the operational limits and conditions,
- specifying the authorities and responsibilities assigned both to individuals and to on-site and off-site organizations involved in deciding on and carrying out surveillance activities,
- specifying the qualifications of personnel performing surveillance activities,
- indicating the points at which tests are required and deficiencies, if any, are rectified,
- specifying the requirements for records to be kept and for the retention and retrievability of such records,
- providing cross-references to other documents relevant to the surveillance programme,
- ensuring that regular or periodic reviews of surveillance programmes are carried out.

4 Czech Republic regulations for operation and maintenance

There are several levels of requirements regarding the testing and operational procedures for the safety systems in Temelín NPP (figure 1).

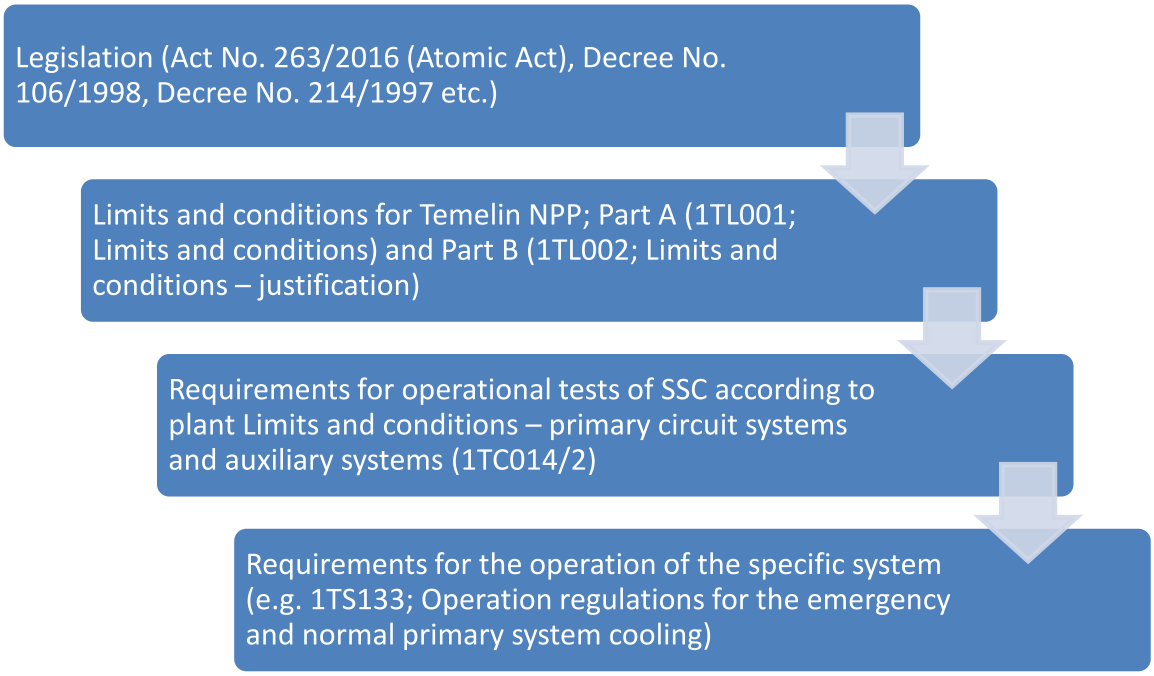

Figure 1. Requirements for testing and operation of NPP systems in Czech Republic

4.1 Legislation

Act No. 263/2016 (Atomic Act), states that "limits and conditions mean a set of requirements, compliance with which means that the performance of activities [related to the use of radioactive materials] is considered safe".

Limits and conditions for Temelín NPP must meet the legislative requirements given in particular by Act 263/2016 and Decree 106/1998 [7]. The requirements for testing are given in Decree 358/2016 [8].

Safety functions derived from the criteria and classification of selected SSC are specified in Decree No. 214/1997 [9] (Decree on quality assurance in activities related to the use of nuclear energy and activities resulting in radiation exposure and the establishment of criteria for classification of selected devices into safety classes).

The philosophy of plant operation limits and conditions is consistent with NUREG 1431 [10], [11].

Some basic requirements for testing and operation of the sCO2 system resulting from the legislation were already described in the previous deliverable, *D3.3 Design bases and safety analyses for system and components (p. 4.13.2 and 6.1).*

4.2 Limits and conditions for Temelín NPP

The set of Limits and conditions for Temelín NPP must be clear and the internal structure of the documentation must guarantee unambiguous interpretation. This requirement is achieved by the use of NUREG 1431. Therefore, the requirements for Temelín NPP are divided into two volumes: Part A (TL001): Limits and conditions and Part B (TL002): Limits and conditions - justification. Content of both volumes corresponds to NUREG 1431 to the applicable extent.

Limits and conditions, Part A contains the conditions for the safe operation of the safety systems of Temelín NPP based on safety analyses that demonstrate the accidents mitigation within abnormal operation and emergency conditions. This part forms clearly defined conditions within which the safety of the Temelín NPP is maintained. Failure to comply with the conditions set out in Part A, means immediate disruption of the safe operation of the power plant.

Limits and conditions, Part B describes the conditions for the safe operation of the systems related to nuclear safety, during normal operation of Temelín NPP. Violation of the conditions set in Part B does not cause an immediate threat to plant safety, however, long-term power operation is not possible without their fulfilment.

In accordance with the basic principles and criteria of the design of a nuclear installation, its safe operation should be ensured by the fulfilment of the following general safety criteria:

- the ability to shut down the reactor safely and to maintain it in safe shutdown conditions,
- the ability to remove residual heat from the core,
- the ability to limit releases of radioactive substances so that the releases do not exceed specified limits.

The NPP must be designed so that these general safety criteria are met in all design conditions. It is safe as long as its equipment is able to meet these general safety criteria. Adherence to these criteria is achieved by the principles of defence in depth and ensuring the fulfilment of safety functions.

The sCO2 system is formally not a safety system. It serves to mitigate an accident’s consequences as an alternative system and therefore it can have an impact on plant safety.

During normal operation of the unit all power levels, the sCO2 system is not utilized and should be in a standby mode. Normal operation includes all plant operating regimes (table 2). The system should be actuated automatically in case of an SBO, LUHS and combinations of the above if other means for the decay heat removal fail.

Table 1. Plant operating regimes

Regime		Thermal power	Average primary circuit coolant temperature (T_{av})	k_{ef}
1	Power operation	≥ 2% P_{nom}	> 260 °C	≥ 0.99
2	Start-up	< 2% P_{nom}	> 260 °C	≥ 0.99
3	Hot standby	Decay heat	≥ 260 °C	< 0.99
4	Hot shutdown	Decay heat	260 °C > T_{av} ≥ 150 °C	< 0.99
5	Cold shutdown	Decay heat	150 °C > T_{av} ≥ 70 °C	< 0.99
6	Outage/ refuelling	Decay heat	< 70 °C	≤ 0.98

k_{ef} – effective neutron multiplication factor

The operability of all modules of the sCO2 system is required to ensure the sufficient heat removal in accident conditions after the reactor shutdown. The pre-commissioning test (final test) requirements and the expected supervision by an authorized person were already described in the previous deliverable, *D3.3 Design bases and safety analyses for system and components.* During the lifetime of the plant, the system should be controlled in a regular manner to prove its operability. The required frequency of the tests is shown in table 2.

Table 2. Requirements for test frequency

Test requirement	Frequency
Check of the valves, fans, pumps	31 days; part of the cyclic control (together with safety systems)
Test of I&C	31 days; part of the cyclic control (together with safety systems)
Test of the whole system operability	18 months; during first stages of outages*

*) when parameters of steam in main steam line are sufficient for these tests

The regular check is required to ensure the operability of the system. Verification includes testing of the operation of valves, fans and pumps (if there are any) of the system and its auxiliary systems. The control is performed by a physical check. This control is part of the program of so-called cyclic controls.

These requirements are derived from control requirements for safety systems and the tests will be performed together. For the systems, which are redundant according to the principle 3 x 100% each division will be verified once every 3 months. If the system is redundant, it should be controlled every 31 days. For testing of the individual valves of the system, the operator has the means to break normal procedure and adjust the valve to a position opposite to its state given by the procedure. At the end of the test, the position from the normal procedure is restored. It should be ensured (by the I&C system and administratively) that the operator does not have the possibility to test more than one system module at once and in the event of an emergency the relevant valves automatically take a position required to perform their safety function. The performance of pumps and fans is tested for 5-30 minutes. If the repair or replacement of the component is needed, it should be tested for 1 hour to ensure its operability.

The aim of the regular check is to control if valves are opened by appropriate I&C signals, fans start their operation and reach the required speed and pumps start operation and reach proper parameters.

For testing of I&C system, its design must contain special connections and equipment, enabling to test its performance during normal unit operation (e.g. without activation of safety systems).

The second type of test, conducted once every 18 months, should demonstrate that the sCO2 system *as a whole* is operational. This inspection will be performed at the time of first stages of outages, when parameters of steam in the main steam line are sufficient for these tests. As part of this control, the operation of the instrumentation and control of the system components is also checked. The operational test demonstrates the capability of the control system response to all input states with the expected result.

During this test it should be checked if the system is capable of removing heat from the steam generator to the ultimate heat sink (atmosphere). The performance of the system will be verified by thermohydraulic calculation basing on differences in temperatures and mass flow values in the CO_2 loop. The heat capacity of the system must be extrapolated to reduced steam parameters during the tests, because it will not be possible to reach the design pressure in the steam lines during the tests.

The system must be equipped with a device for consumption/ dissipation of the electricity produced during the test.

The requirement of each test frequency is met if the control is performed within 1.25 times the expected interval. If it is found that the inspection has not been carried out within the specified frequency, then it must be carried out within next 24 hours. If the check is not performed even within the prolonged interval, then the operation requirements must be immediately declared not met. If the check is performed within a prolonged interval, but success criteria are not met, then the operation requirements must be immediately declared not met.

4.3 Requirements for operational tests of systems, structures and components

The next level of the requirements is the document "Requirements for operational tests of SSC according to plant Limits and conditions – primary circuit systems and auxiliary systems" (1TC014/2, parts A and B). All the important systems and components and their testing procedures are described in two parts of this document.

The following elements are considered for each SSC:

- Explanation

This point contains the general explanation of the test requirements and procedures for the considered system

- Test objective

The purpose of testing the condition of the components and their operability is to verify that safety (and safety-related) systems are maintained in a state that guarantees their readiness to perform the required safety functions.

- Testing frequency

The required frequency of the tests is described in the plant documentation as stated before. For the sCO2 system, the frequency will be:

  - 31 days for valves, fans etc.
  - 18 months for the whole system operation

- Initial state

In all plant operating regimes (regimes 1-6, as described before), the sCO2 system should be in the stand-by mode, operable and ready for the actuation.

- List of monitored parameters

This point contains the list of all the important system parameters that are measured (temperatures, pressures, fluid levels, valves positions and setpoints etc.), specifying the location of the measurement and used measurement instruments.

- Test procedure

Here, the actions to be taken during the control are described, one by one. This can be done once the final design of the system is ready.

- Final state of the unit and considered system

After the test, the unit should be in the same operating regime as before the test. The system should be again ready for the operation.

- Success criteria and test evaluation

All the controlled components of the system are operable, maintained in the required state and with expected parameters.

4.4 The requirements for the operation of the specific system

Finally, there are separate documents for each system. Such detailed description will have to be prepared for the sCO2 system if it is to be installed in one of the Czech NPPs.

This document consists of the following chapters:

- Introduction
    - System objective
    - Influence on other systems
    - Technological restrictions, safety and hygiene principles and measures, special requirements on equipment and emergency mitigation
    - Related documents
- System description
    - Arrangement of the system components in the NPP
    - Description of the functions
- System components
- System operation
    - Commissioning of the system
    - System operation in different plant regimes
    - Standard handling
    - Decommissioning
    - System repairs
- General system requirements
    - Testing and controls
    - Division of the components between the plant units

5 French regulations for operation and maintenance

The large number of nuclear reactors in France and the need to maintain a high level of safety have enabled the safety authorities and the operator (EDF) to set up an iterative process based on regulations and the taking into account of feedback at different levels: for all the power plants, for each level of power plant and for a particular power plant.

In the following paragraphs, we present these regulations and their application to power plants, both during operation and during shutdowns.

5.1 Legislation

Legislation on operational safety and testing of safety-related equipment in nuclear power plants in France is derived from the international texts presented in paragraph 3.

In France, it is set out in the following texts:

- Environment French Code [16]
- BNI Decree [17]
- Order of 10 November 1999 [18]
- ESPN Order [19]

Based on these texts, the operator will apply the regulations through internal documents specifying the characteristics and parameters to be respected for the systems, the operating rules (GOR) and the maintenance and test procedures. These internal documents are also based on the principles of nuclear safety at the design stage (presented in documents D3.2 and D3.3).

The following figure presents a summary of the safety approach adopted by EDF for the operation of the nuclear plants.

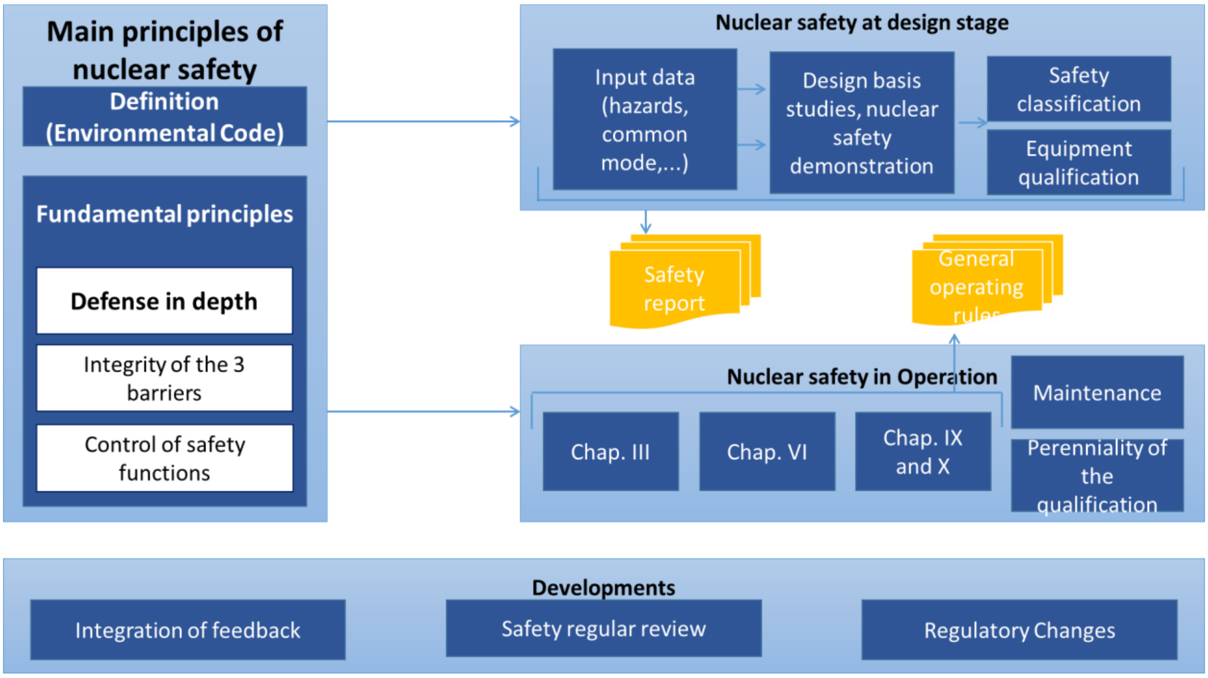

Figure 2: Principles of safety in operation for EDF

Figure 2 shows that the French regulatory texts (presented in D3.1 and D3.2) are used by the operator and the constructor to determine the safety rules necessary in the design phase of the plant and/or the plant system. These rules allow the manufacturer to establish the criteria to be met by the developed system, the studies necessary for the demonstration of safety for the whole plant, the SSC classification of the system and also the qualification procedures (see D3.3). For the operator, these rules will be used to define the Safety Reports that will accompany the dossier to the safety authorities and the plant operators and the General Operating Rules (GOR).

5.1.1 Safety Report

The "safety report" is the document that the operator must submit to the ASN in support of an application for authorisation to create, commission or dismantle a basic nuclear installation (BNI). In order to obtain authorisation to create and then operate a BNI, the operator must provide all the information required to justify that the technical and organisational measures that it will implement are sufficient to prevent or limit the risks of incident or accident posed by the BNI.

Since the challenge of the safety report is for the operator to demonstrate the safety of the BNI, the ASN has decided to specify its content in a regulatory decision. This decision concerns all BNI (nuclear power plants, research facilities, fuel cycle facilities, radioactive waste storage facilities, etc.) and sets out a series of requirements for the preparation and content of the safety report (see D3.3).

The safety report is analysed by the ASN at various stages in the life of a BNI, in particular:

- during the procedures for authorisation of creation, authorisation of commissioning, authorisation of final shutdown and dismantling or transition to the surveillance phase, in order to assess the nuclear safety of the BNI and to prepare the authorisation and associated requirements;
- during the examination of modifications to the BNI;
- during inspections of the nuclear facility.

5.1.2 General Operating Rules

The same regulatory texts are used by the operator to determine the General Operating Rules for the plant. These are a collection of rules approved by the ASN which define the authorised area of operation of the installation and the associated control prescriptions. This collection is strictly confidential and specific to each reactor operated. Documentary modifications, whether temporary (referred to as an exemption) or definitive (referred to as an amendment), whether they concern a single reactor (local modification) or several (generic modification), are subject to examination by the ASN when they affect chapters III, VI, VII, IX or X of the GOR.

These chapters of the GOR are the most important for safety and are carefully examined by the ASN.

- Chapter III describes the "technical operating specifications" (TOS), which delimit the normal operating range of the reactor, in particular the permissible range for operating parameters (pressures, temperatures, neutron flux, chemical and radiochemical parameters, etc.).
  The TOS also specify the behaviour to be taken if these limits are exceeded. The TOS also define the equipment required according to the state of the reactor and indicate the actions to be taken in case of malfunction or unavailability of this equipment.
- Chapter VI consists of procedures for operating the reactor in the event of an incident or accident. It prescribes the reactor operation to be implemented in these situations to maintain or restore the fundamental safety functions (reactivity control, core cooling, containment of radioactive products) and to bring the reactor back to a safe state.
- Chapter IX defines the periodic inspection and test programmes for equipment and systems important to safety, implemented to verify their availability. In case of unsatisfactory results, the action to be taken is specified by the TOS. Such situations may sometimes require the operator to shut down the reactor to repair the failed equipment.
- Finally, Chapter X defines the physical test programme for the reactor core. It contains the rules that define the programmes for core verification during restart and core surveillance during reactor operation.

We can also mention GOR chapter VIII on maintenance which is related to Defence-in-depth level: 2. This chapter specifies the operational objectives sought, the description of the process of prescribing the domain, the approach adopted, and the quality requirements relating to the activities covered by this chapter. It is an exhaustive and prescriptive document. All possible events during operation are listed and the processes to be followed are detailed. The operators of the plant must follow these instructions and not deviate from them. The GOR maintenance chapter concerns all the Elements Important for the Protection of Interests (important for Safety).

This chapter specifies in particular for the field of maintenance:

- The policy,
- The maintenance repository (overall presentation, objectives of the maintenance programmes, scope of application of the maintenance of application of the maintenance programmes, products of the maintenance standard applicable to the plant, requirements for monitoring chemical parameters),
- Requirements relating to maintenance activities (scheduling of interventions and control of the performance of important activities, including requalification after intervention, trend monitoring, durability of the qualification, special provisions and means),
- Management of materials and spare parts,

- Reliability control.

The other chapters correspond to:

- Organisation of the operation (Chapter - I),
- Hazards (Chapter - II),
- Radiation Protection (Chapter - IV),
- Control of risks to man and the environment (Chapter - V),
- Serious accidents (Chapter VII),
- Control of inconveniences in normal operation and in degraded mode (Chapter XI)

5.2 Requirements during operation

5.2.1 Limits and conditions

The operating boundary conditions of a plant are given in the GOR. For each power plant operated by EDF, these boundary conditions were calculated on the basis of the type of power plant when the safety report was initially written. Then, during the life of the plant, and depending on the modifications and new regulations, these boundary conditions may be recalculated.

For the sCO2 system, boundary conditions will also have to be calculated so that they can be integrated into the system monitoring parameters in the control room. It will therefore also be necessary to ensure that the control system can be integrated into the control room of the power plant and to provide the necessary measurements for monitoring the system when it is operating.

5.2.2 Maintenance during Operation

In terms of maintenance, the objective is to keep all the functions necessary for the safe and economical operation of reactors available and reliable. In essence, maintenance makes it possible to monitor the abnormal behaviour of equipment, particularly following inspections or visits during operation, and, if necessary, to bring them back into conformity by corrective action (repairs, adjustments, replacements, renovations).

The EN13306 standard [20] defines the main types of maintenance performed on a nuclear power plant:

- Corrective maintenance: maintenance performed after detection of a failure and intended to restore an equipment to a state in which it can perform a required function.
- Preventive maintenance: maintenance performed at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or degradation of the operation of an equipment. Preventive maintenance can be broken down into:
    - conditional preventive maintenance: preventive maintenance based on monitoring the operation of the asset and/or the significant parameters of this operation, including the resulting actions (this includes predictive maintenance which links the evolution of one or more parameters of an operating asset to that of a given type of degradation, for example:

monitoring the vibrations of a rotating machine). It is therefore a maintenance that depends on the appearance of indicators that reveal the condition of the equipment,
  - systematic (periodic) preventive maintenance: preventive maintenance carried out at pre-established time intervals or according to a defined number of usage units but without prior control of the condition of the asset.

The chapter related to the maintenance of GOR (Chapter VII) is completed by the Requirements for Qualified Materials (RQM) and Rules for the Supervision in Operation of Mechanical Equipment (RSOME).

The RMQ and the RSOME complement the requirements of the GOR, respectively, with :

- specific preventive rules (RMQ), during interventions carried out on equipment important to safety, ensuring that their qualification to accident conditions is maintained in operation,
- an industrial code (RSOME) presenting the basic operations and methods of monitoring mechanical equipment and pressure vessels during operation: in practice, these monitoring requirements, derived from the RCC-M design code and the operating experience, are carried out by dedicated Basic Preventive Maintenance Programmes (periodic inspections, hydraulic tests, non-destructive testing, replacement or repair rules, etc.).

When the plant is in operation, maintenance will mainly be carried out during daily rounds, such as the detection of visible leaks. Maintenance during operation is possible and subject to analysis by the ASN.

These maintenance-related documents are specific to each plant (as they are established for each of the plant components). In the framework of the sCO2 system, it will also be necessary to define these rules to integrate them into the different documents (GOR, RMQ and RSOME). As the system is not yet precisely and definitively defined, it is difficult to establish these rules at this stage.

The industrialists who develop the components will nevertheless have to take into account the need to establish at the time of qualification, and for any significant modification of the components, the various recommendations relating to maintenance. Certain procedures (cold start, stand-by, etc.) will also require maintenance recommendations because the deterioration of certain parts, and the failure rates during start or operation may depend on them.

5.2.3 Tests during Operation

When the plant is in operation, some components, such as diesels, may be subject to periodic testing (as defined in the GOR) to verify their correct start-up.

In the context of the sCO2 system, start-up tests may be planned (in addition to more tests during the plant's shutdowns) and will then be integrated into the plant's GOR.

5.3 Requirements for Maintenance, Tests and Shutdown

5.3.1 Plant Shutdowns

Reactors have to be shut down periodically to renew the fuel, which is gradually depleted during the operating cycle. At each shutdown, one third or one quarter of the fuel assemblies are renewed. The length of the operating cycles depends on the fuel management adopted.

These shutdowns make parts of the plant temporarily accessible that are not accessible during operation. They are therefore used to check the state of the installation by carrying out inspection and maintenance operations and to implement planned modifications to the installation.

These stoppages can be of two types:

- simple refuelling shutdown and **partial visit** shutdown: lasting a few weeks, these shutdowns are devoted to renewing part of the fuel and carrying out a verification and maintenance programme.
- 10-yearly and **complete visit** shutdown: this is a shutdown that is subject to a particularly important verification and maintenance programme. This type of shutdown, which takes place every ten years, is also an opportunity for the operator to carry out major operations such as a complete inspection and hydraulic test of the primary circuit, a test of the containment or the integration of design changes decided upon after periodic safety reviews.

These outages are planned and prepared by the operator several months in advance. The ASN checks the measures taken to guarantee safety and radiation protection during the outage, on the one hand, and safe operation for the next cycle or cycles, on the other.

The main points of the ASN's inspection concern

- during the shutdown preparation phase, on the compliance of the reactor shutdown programme with the applicable standard; the ASN takes a position on this programme.
- during the shutdown, during regular briefings and inspections, on the handling of problems encountered.
- at the end of the shutdown, when the operator presents the outage report, on the state of the reactor and its suitability for restarting; at the end of this inspection, the ASN authorises the restart of the reactor.
- after the divergence, on the results of all the tests carried out during the outage and after restart.

5.3.2 Maintenance during Shutdowns

The maintenance carried out during plant shutdowns is mainly preventive maintenance (corrective maintenance operations must be carried out as soon as possible to allow the component or system to function).

This maintenance may involve the replacement of certain parts on a periodic basis (regardless of whether or not they are in a degraded state), such as valves and seals. But it will also be during shutdowns that heavier preventive maintenance operations will be carried out, such as non-destructive testing of the entire system, in order to determine whether certain components (requiring, for example, the dismantling of a part of the component) need to be changed.

The Initial Complete Visit of the Primary Circuit is the zero point of the Complete Visits (CV) and Partial Visits (PV) of the operating surveillance. From this visit, the schedule of plant shutdowns for partial or complete visits will be defined (see 5.3.1). This Initial Complete Visit consists of a set of non-destructive tests, such as eddy current testing of all steam generator tubes, inspection of the vessel by the In-Service Inspection Machine, etc.

The results of these checks give the state of the equipment before the installation is commissioned (defects left unchanged, for example), which makes it possible to monitor their development during operation. From then on, when the plant is shut down, new non-destructive tests will be carried out to enable this monitoring for all the plant's circuits.

Depending on the function of the component, its safety classification and the difficulty of implementing the non-destructive test, these tests are mainly carried out during the ten-yearly inspections (complete visit). Some non-destructive testing will be carried out during shutdowns for partial visits. The results of these inspections will lead to more extensive maintenance operations (plugging of steam generator tubes, repair of welds, changing of turbine seals, etc.).

The sCO2 system will also be affected by these maintenance operations. The developers of the main components should therefore consider possible non-destructive testing in parallel with the development of the component. Some components, such as the turbocharger, will probably be able to benefit from technologies already used for components of the same type, but for other components, such as the compact heat exchanger between the secondary loop and the sCO2 system, these non-destructive tests will have to be precisely defined and the means of carrying them out will also have to be qualified.

The preventive maintenance operations will also have to be determined in order to be integrated in the various documents related to the operation of the plant.

5.3.3 Test during Shutdowns

The shutdown period is used, in addition to the maintenance that cannot be done during operation, to carry out various regulatory tests on the plant's equipment. In this section, we will not present in detail all the tests performed in a nuclear power plant but the types of tests to which the sCO2 system may be subjected.

5.3.3.1 Commissioning tests

Any equipment subjected to pressure must pass, after its assembly and before its operation, a series of tests to verify the good conformity of the assembly and that it did not deteriorate the integrity of the system or component.

Thus, pressure equipment undergoes a hydraulic test at a pressure higher than the operating pressure. It allows checking their tightness and their resistance. We can mention in particular the test of the containment (3rd barrier) which is carried out at the design pressure. These tests will be carried out again during the life of the plant.

During the acceptance of the installation work, the Development agents carry out a “stocktaking” (inspection visit with the constructor or service provider, which makes it possible to check the conformity of the installation with the plans). They also carry out completion reviews (state of the retaining walls, integrity of the fire sectors, common wiring points, etc.).

The manufacturer draws up the Installation Completion Report which certifies the final quality of the installation. It defines the state of the equipment at the end of the installation: results of the readings, controls, tests or hydraulic tests carried out during and after the installation.

For the sCO2 system, commissioning tests will have to be performed to validate the proper installation and operation of the system after its installation.

5.3.3.2 Periodic tests

In addition to the design and qualification requirements applied to classified safety equipment, the periodic tests imposed on this equipment make it possible to guarantee, during operation of the unit, that there is no unfavorable change in the performance required to comply with the assumptions made in the accident studies of the safety report.

The equipment may suffer damage of various origins during operation (human intervention: maintenance, lining, adjustments, control and operating operations, accidental failures, wear and tear, ageing, etc.), which must be detected so that it remains available in the event of an incident or accident.

To this end, a Periodic Test completeness analysis note is written at the design stage, based on the TOS and the studies, in order to determine the nature and completeness of the tests required during operation, with regard to the safety missions assigned to the equipment and systems important to safety. It must identify:

- all the safety missions relating to the equipment and systems examined,
- the nature of the tests with respect to these missions, and the possible justifications for not performing them,
- the feasibility and representativeness of the tests, their acceptability from a safety and security point of view, their possible grouping,
- the safety criteria to be verified in order to decide on their availability (required performance of the equipment: injection rates, maneuverability and execution time of the actuators, heat exchange capacity, etc.), including, if necessary, an extrapolation between the conditions under which the test is performed and the safety requirements to be verified, their classification as criterion A (blocking) or B (non-blocking), and the frequency of the tests chosen.

Some of these periodic tests are carried out during partial outages (during outages for refueling, which take place about every 18 months) and ten-yearly outages. But most of the periodic tests have a higher calendar frequency. In addition, a tolerance of 25% on the periodicity of calendar frequency tests (daily, weekly, monthly, annual, etc.) is allowed, but the use of this tolerance must not lead to a shift in the programming of the next test. This tolerance does not exist for event-driven tests. In many cases, the very performance of a Periodic Test causes the unavailability of the tested equipment (or even other related equipment): Chapter IX of the GOR authorizes this performance because it is in essence a derogation from the TOS. However, it is forbidden to carry out a Periodic Test if a group 1 event (anomaly observed on the INES scale) is already in progress and in all cases, the operator must respect the time limits for unavailability mentioned in the associated test rule.

When they are carried out, Periodic Tests will make it possible to guarantee:

- the absence of unfavorable evolution compared to the design basis,
- compliance with the hypotheses chosen for the dimensioning operating conditions described in the accident studies of the Safety Report as well as the studies of the complementary field,
- checking the availability of the equipment and associated fluids constituting the safety functions required by the TOS,
- control of the availability of the means essential to the operability of incidental or accidental control procedures.

The periodic tests described in Chapter IX of the GOR concern all the elementary systems classified as important for the safety of the nuclear installation.

In the operation of the sCO2 system, it will be necessary to define the list of periodic tests that the system must undergo. Some elements (such as valves or equipment that allow the system to start working properly) will have to be tested with a higher frequency than other components (such as the sCO2/external heat exchanger for example).

6 Conclusions

This report presents the main requirements to ensure a maximum level of safety during the operation of a nuclear power plant. This safety approach is ensured by controlling the optimal operating conditions, maintenance of the safety and reliability levels at their maximum, and a program of regular tests and trials of the plant equipment. The regular reassessment of the safety systems shall guarantee that, throughout the life of the plant, this safety is maintained.

The recommendations on the maintenance and tests to which the sCO2 system will be subjected, cannot be established in detail yet, because of the ongoing development of the system (and therefore the fact that the main components are still at a design stage). However, some basic rules are presented, in order to take into account as much as possible the future constraints in this development phase.

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