RESEARCH REPORT

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Codes of practice guiding qualification of components in NPP

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Summary

This report is deliverable for 2012 of Subproject 3 in the project SESA "Seismic Safety of Nuclear Power Plants – Targets for Research and Education", part of the SAFIR 2014 program on nuclear safety.

2012 was the startup year of activity in Subproject 3.

Seismic qualification is more fragmented field compared to design of structures. The available methods, especially for the qualification of installed equipment (may be relevant for the Stress Test), require the use of large sets of criteria and databases – hence allowing for much larger margin of interpretation.

The aim of the work in this year is to summarize available component qualification databases and qualification procedures available in codes of practice (IEEE 344, ICE 68-3-3and RCC-E).

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Preface

The decisions to increase the number of nuclear power plants (NPP) in Finland, and especially the positioning of one NPP in the northern part of the country, called for reassessing the potential effect of earthquakes on plant safety requirements.

As a response to this need, the project SESA - ***Seismic Safety of Nuclear Power Plants – Targets for Research and Education*** was included in the Finnish Research Program on Nuclear Power Plant Safety, SAFIR 2014, under the umbrella of Reference Group 7 - Construction safety. SESA is in its first year of financing in 2011, and it has 3 Subprojects:

- Subproject 1. Earthquake hazard assessment,
- Subproject 2. Structural assessment,
- Subproject 3. Equipment qualification procedures,

This report is a deliverable of Subproject 3 for the 2012.

The work in SESA has been supervised by the Reference Group 7 and the Ad-Hoc group specifically named for the SESA project.

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1 Introduction

The design for earthquake loads is a challenging task both for ordinary buildings and Nuclear Power Plants. While design of buildings is a field interesting from a broad engineering perspective, qualification of components is a more specialised area. In fact, in ordinary building design, the question of component behaviour an performance is secondary, so the question is crucial only in some industrial applications and in the nuclear industry.

Seismic qualification is more fragmented field compared to design of structures. The available methods, especially for the qualification of installed equipment (may be relevant for the Stress Test), require the use of large sets of criteria and databases – hence allowing for much larger margin of interpretation.

The aim of the work in 2012 was to summarize available component qualification databases and qualification procedures available in codes of practice (specifically IEEE 344, RCC-E and CEI/IEC 68-3-3).

2 Goal

The aim of this document is to, is to review/summarize the seismic qualification procedures accepted primarily in:

- *IEEE Recommended Practice for Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations, IEEE Std 344-2004*

And supplement this data with references from:

- *IEC 60980: Recommended Practices for Seismic Qualification of Electrical Equipment of the Safety System for Nuclear Generating Stations*
- *RCC-E; Design and construction rules for Electrical Components of nuclear islands; AFCEN 2005*

The description is generic, given the limitation that the type of component is not defined in advance.

3 Measures for qualifying equipment according to IEEE 344

The scope of IEEE 344 is to give guidance on how to qualify equipment for a scenario with “a number of” OBE (Operating Base Earthquake) shakings followed by a SSE (Safe Shutdown Earthquake) shaking (§1.1).

As a rule IEEE 344 acknowledges that earthquakes create at ground level (§4.1):

- simultaneous shaking in all 3 directions of space
- the components of the shaking are statistically independent
- the strong motion part is 10-15s
- the significant frequency content is 1-33Hz

Duration, independence and frequency content arriving to a component may be affected/changed by the filtering effect of its support, be it building or other equipment (§4.2, §4.3).

In IEEE 344 the seismic environment for a component may be specified as (§4.4):
- response spectrum;
- time history (shaking);
- power spectral density (PSD);

3.1 Qualification approaches

"*Component qualifies*" means in IEEE 344 that the component is able to perform its safety function during and/or immediately after the SSE event. It is understood that the component must be able to withstand "a number of" OBE's in advance to be able to qualify for the SSE (§5).

Qualification can be demonstrated by:
- analysis
- testing
- analysis and testing
- experience data

As emphasized in IEEE 344 (§5) the safety functions are provided as part of the components specification. The seismic review should concentrate on the "seismic scenario" only, i.e. the OBE shakings followed by the SSE shaking. In the seismic case the qualification concentrates on a limited period of time during, and immediately following, the SSE event. This is very different from qualifying the components for normal operation, when the time span is much longer. Nonetheless, aging mechanisms have to be identified, and taken into account before the "seismic scenario" is applied.

3.1.1 Qualification by analysis

Qualifying by analysis is not recommended for complex equipment where the prediction of the response may be inadequate (IEEE 344 §7)

For dynamic analysis, IEEE (§7.2) recommends distinguishing between rigid and flexible equipment. Rigid equipment are the ones which have fundamental frequency larger than the cut-off frequency of the RRS (required response spectra).

The RRS expresses the load/shaking requirement on the component. It can be ground level spectra, floor spectra or spectra defined from the shaking of the location where the component will be fixed. Because the components have to be qualified for 3D shaking, the RRS is a set of 3 spectra in the 3 directions. The cut-off frequency of the RRS "where the ZPA asymptote begins"; beyond it an SDOF oscillator's response is not amplified.

Most NPP equipment are supposed to behave in the linear range; however if significant non-liberalities exist in the response (e.g. closing of gaps, localized yielding etc.) they have to be taken into account in the model.

Special classes of loads are hydrodynamic loads; they can also be treated using the analytical procedures.

A more conservative option accepted in IEEE 344 is the static coefficient analysis (§7.2). In this case the calculation of vibration modes are not needed, forces are calculated presuming acceleration response corresponding to the maximum amplification peak of the RRS.

3.1.2 Qualification by testing

The aim of the test should be clarified: (1) if the location of the component is known/fixed it is a proof testing for that location, (2) if the location can change, or many identical components are qualified for numerous locations it is generic testing, and (3) if the limits/capacity of the component is searched it is fragility testing.

In all cases the 3D effect should be taken into account conservatively. Some components can be tested simulating operational conditions (e.g. relays, motors, sensors etc.), while others may be tested while not in operation, but correct location/fixing/position etc. In this second case, the shaking of the component from earthquake is measures, and operation is proven for this input in later stage (separate qualification for operation).

The tested component should not be used in an NPP, unless it can be proven that the testes did not affect its ability to carry out its safety-functions.

Often visual/analytical inspection is not enough for categorizing components with respect to dynamic properties making it difficult to draft a suitable testing plan. In these cases exploratory/preliminary testing may be used to improve understanding of the dynamic behavior of the equipment. Two additional aspect complicate shake-testing of some components: (1) aging, including vibration aging and (2) accompanying loads.

Fragility testing is designed to map the limits of applicability of a component, being more recommended for components believed to be resilient to shaking.

3.1.3 Qualification by testing and analysis

Some equipment may be impractical to qualify by testing because of their size, but also impractical by analysis alone because of the complexity of the safety functions they carry out. In such cases the qualification by analysis & testing option becomes attractive (§9 – IEEE 344).

During the combined qualification, the analyses and tests can interact in two ways: (1) test data can be used to confirm validity of analytical model e.g. in terms of resonance frequencies, mode shapes, damping etc. (2) or analysis results can supply input response requirements for sub-components that are later tested (§9.2.4 – IEEE 344). In §6.2.1 this document, more emphasis is given to the second option of using analysis and then test.

3.2 Test methods

The testing signal used can be: (1) single-frequency and (2) multi-frequency. The main aim is (1) to cover the RRS with the TRS signals spectra (2) to have no less acceleration then the ZPA of the RRS, (3) to not include frequency above the RRS cut-off frequency and (4) to have sufficient duration as required by §8.6.5 of IEEE 344. The first 3 points refer to the "strength" of the shaking, while the 4th point is related to prescribing a signal with sufficient damage potential.

Some notes on testing signals: (1) If the RRS is dominated by a certain frequency it may be required to broaden the spectra. This is because there may be doubt concerning the correctness of the dominating frequency (i.e. doubt concerning the stiffness of the support). - §8.6.1.1 (2) The signal reaching the shake table has to be measured and its spectra, the TRS calculated (§8.6.1.2). (3) The RRS corresponding to proper damping values should be used (generally 5% is recommended). (§8.6.1.3).

In terms of input signal type, two types can be use:

- Single frequency signal – justified when the support of the component is reached by a strongly filtered motion, characterized by a single frequency peak. In this case the following tests are recommended:
  - continuous-sine test
  - sine-beat test
  - decaying-sine test
  - sine-sweep test
- Multiple-frequency signal – in the general case, as it is recognized that, unless strongly filtered, earthquakes produce a broadband shaking (0-33Hz). The multiple frequency tests are designed to activate all modes of the tested component simultaneously, and they are less conservative. The following test are recommended:
  - time-history test
  - random motion test
  - complex-motion test
  - random motion with sine dwells
  - random motion with sine beats
  - combination of multiple sinusoids
  - combination of multiple sine beats
  - combination of decaying sinusoids

The signals, used both for single frequency testing, and multiple frequency testing have to fulfill a series of criteria, as mentioned at the beginning of this chapter. Testing reports must state/discuss how the chosen testing procedure (1) is justified, (2) fulfills the IEEE 344 criteria and (3) if there are deviations from the IEEE 344 criteria, why they appear and how they are justified.

It is known that earthquake shaking is three-directional, for convenience tests can be carried out as:

- Single-axis tests
- Biaxial test
- Tri-axial test

Single and bi axial test must have a certain level of conservativeness, compensating for the lack of simultaneous shaking in other direction. The measures to achieve this level of conservativeness are specified in IEEE 344.

3.3 Extrapolation from similar equipment & multi-cabinet assemblies

Another option is to qualify equipment by reference to (1) already qualified equipment which (2) is judged to be similar to the one under consideration. Both the conditions for "similarity" and the methods for acceptable extrapolation are defined by IEEE-344 (§9.3).

A special case of qualification is the case when repetitive cabinets are to be qualified. IEEE 344 acknowledges the difficulty to test such assemblies because of their size, but warns against qualifying one individual unit and trying to extrapolate the results for the whole assembly. The core argument is that individual units do behave differently than whole assemblies because of (1) interaction, (2) torsional effects etc. – therefore, a more sophisticated justification is needed for the extrapolation from one unit to the whole.

3.4 Qualification by experience

This option of qualification is based on the analysis of the response of equipment to:

- (1) previous earthquake exposure or
- (2) previous test experience data.

The method has severe limitations. When it comes to qualifying by previous earthquake exposure, considerations like (1) the severity of shaking, (2) the damage potential of the shaking, (3) effect of aging, e.g. previous vibration aging, (4) the interaction with simultaneous loads like pressure, etc. narrow down the applicability of the method.

The following conditions should be fulfilled to qualify equipment, based on the earthquakes experienced by a "reference equipment class" (REC). The experience data can be supplemented by further tests and analysis if necessary, but the basic steps to be taken are:

- Characterize the motion experienced by the equipment in a reference equipment class
- Establish experience based seismic capacity of the reference equipment class
- Comparing the candidate equipment to the reference equipment class
- Documentation of the qualification process

The reference equipment class (REC) is a group of equipment with similar physical, functional and dynamic properties to the one needed to qualify. The equipment in the REC must have demonstrated good performance in previous earthquakes.

Equipment belong to the REC can feature on inclusion rules and prohibited features (§10.2.3.1). A minimum number of equipment, performing satisfactorily in independent circumstances, needs to be available in the REC (§ 10.2.3.2). Independent items need to have (1) different physical characteristics, (2) experience different earthquake load, (3) be in different locations (e.g. inside a building) for the same earthquake load, or (4) have different orientation.

The minimum required independent items for a REC are 15 (with penalty of 30% on the loads) and 30 with no penalty.

The accepted load level for qualification for the REC is defined by the earthquake experience spectrum, or EES. The EES is the weighted average response spectra experienced by- equipment. Weighting is done to the number of independent equipment items in each location:

$$SA_{EES} = \frac{\sum_{n=1}^{m} N_n \cdot SA_n}{\sum_{n=1}^{m} N_n}$$

Where:
SA_{EES} – is the earthquake experience spectrum;
N_n – is the number of independent items in reference site n
SA_n – is the spectra experienced by the independent equipment in reference site n

In order to qualify the candidate equipment, the RRS (required response spectra) must be enveloped by the EES in the frequency range of interests (§10.2.4). Failure to envelope the RRS must be justified. The RRS for typical equipment is in-structure, horizontal, medial centered, 5% damped floor spectra resulting from the SSE (safe-shutdown earthquake).

The candidate equipment must be verified to possess the inclusion rules of the REC and exclude the prohibition rules of the REC. The mounting of the candidate equipment must be evaluated in accordance with the qualification requirements (§10.2.4.f), and any significant design changes from the vintage of the equipment in the REC and the candidate equipment must be assessed if they could reduce seismic capacity.

3.5 Shock testing

IEEE 344 specifically warns against using results from shock test in earthquake qualification, citing the differences in (1) frequency content and (2) load duration.

4 Qualifying equipment according to CEI/IEC 68-3-3

The scope of ICE 68-3-3 is restricted to electro technical equipment (§1), and only has the ambition to guide the verification of the equipment by testing. Therefore only equipment size to be placed to a shake table can be considered. Fragility testing is also excluded from the focus of IEC 68-3-3.

The equipment qualification can be carried out using the (1) general seismic class or the (2) specific seismic class. General seismic class is to be used when the seismic loads are not known form a study dedicated for the specific equipment location. This is usually not the case in safety related NPP components. The specific seismic class provisions are to be used, when the seismic environment has been defined for the specific equipment location. For the specific seismic class the seismic loads are defined by response spectra or time history.

4.1 Qualification consideration and general procedures

One condition for testing equipment is that service conditions should be replicated as closely as possible. IEC 68-3-3 classifies qualification to:

Criteria 0: subjected to seismic test, experienced no malfunction

Criteria 1: experienced malfunction during test but recovered function post-shaking

Criteria 2: experienced malfunction, required resetting or adjustments to restart, but became functional without replacement or repair

The mounting of the equipment should be according to IEC 68-2-47 and must take into account the connections, piping and cables. The “in service” mounting structure of the equipment should be included in the test.

Vibration of the shake table should be measured to make sure that correct level of vibration is transmitted to the specimen. Vibration measurements may be taken form the specimen/equipment if they are required for the qualification process, but they are not part of the test requirement.

Usually, the range of frequencies for testing is 1-35Hz. Deviation from these values should be justified (§5.3).

4.2 Loads for testing of specific seismic class equipment

For the specific seismic class equipment (NPP case), the prefer test waves are:

- sin sweep for vibration response investigation
- sin beat
- time-history
- continuous sine for endurance at fixed frequency

Both the use of multi-frequency and single frequency waves is permitted. The main condition is that the test response spectrum (TRS) of the wave envelopes the required response spectrum (RRS), and the strong motion part of the signal is appropriate.

For evaluating seismic risk at the particular site allowance has to be made for a five S1 earthquakes, corresponding to OBE in NPP applications, followed by and S2 earthquake, corresponding to SSE in NPP applications (§13.1.2). Deviation for this loading protocol must be justified.

In certain cases the S1 loading sequences can be replaced by S2 loading, with the condition that the equivalency covers the vibration aging effects of the replaced S1 sequences (§13.1.2).

The test waves can be applied as “wave sequences”, with waves spaced at least at 2s, in order to avoid superimposing shaking effects from each sequence.

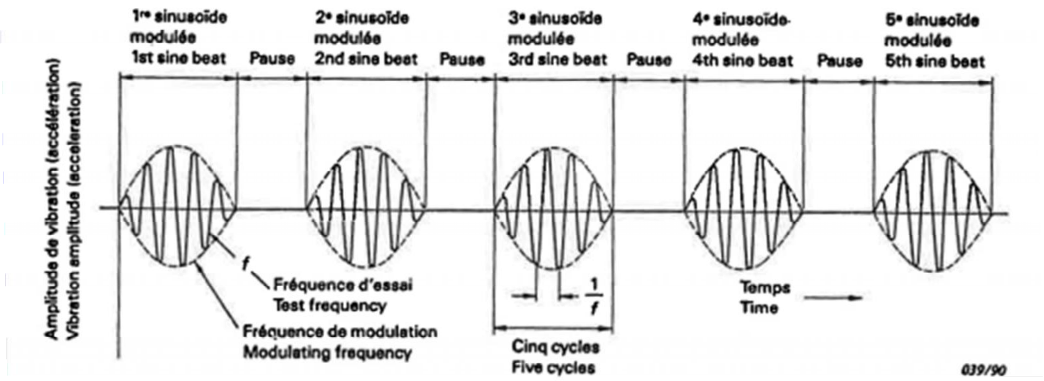
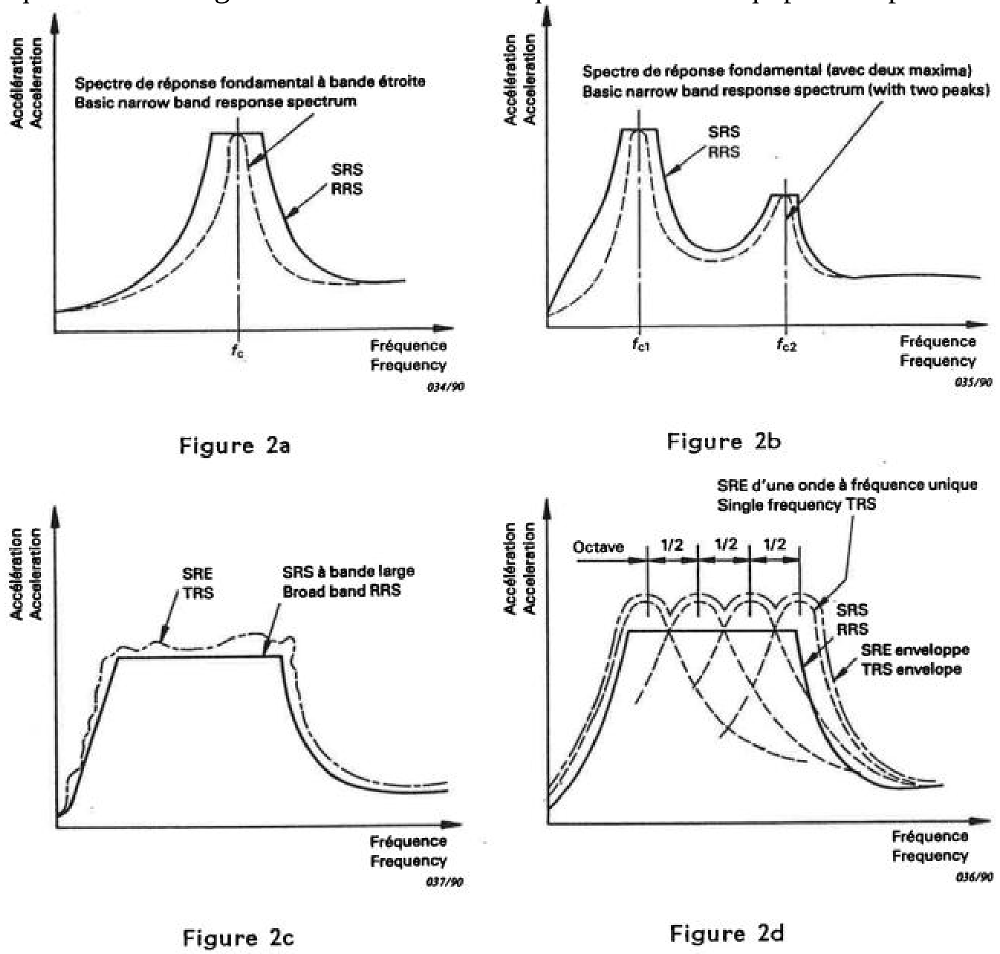


Figure 1. Sequence of five sine beats with five cycle

In case of multi-frequency wave being used as load, it should be ensured that the RRS is enveloped by the TRS (§13.2). In case of using time-history records as loads, the accelerograms may be overlapped with e.g. sine-beat signals, in order to produce a testing signal with spectra close to the RRS, and ZPA not much exceeding the target ZPA. The TRS should envelope the RRS in the range of frequencies starting from the resonance frequencies of the equipment up to 35Hz.



SRE = spectre de réponse d'essai
SRS = spectre de réponse spécifié

TRS = test response spectrum
RRS = required response spectrum

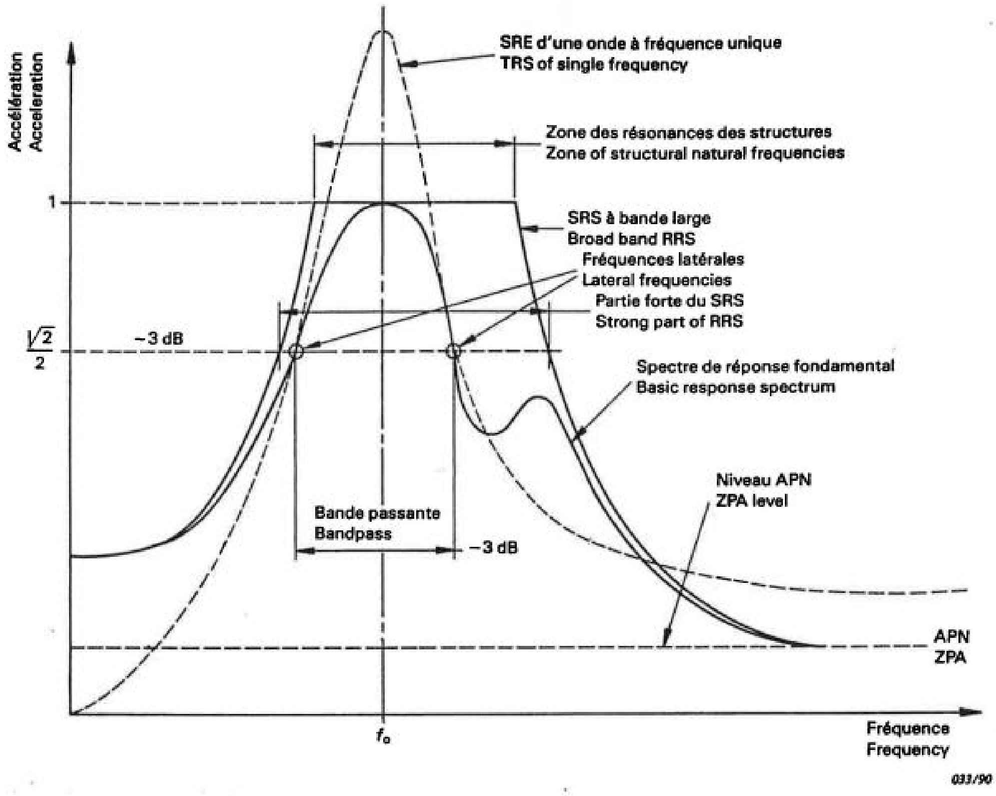
Figure 2. Types of response spectrum envelope

Besides multi-frequency testing described above, single frequency testing i.e. sin-sweep test, sine-beat tests, continuous-sine test are also permitted (§13.2).

4.3 Testing conditions and methods

The difficulty of defining loading signal for qualification test is highlighted with regards to aspects like:

- Weather the equipment is used in a particular location, or qualification is required for a generic location;
- How much broadening of the RRS is required because of uncertainties related to e.g. natural frequencies of the building. The broadened RRS is called the broad band RRS (Figure 3);
- The multi-directionality of the shaking;
- Simulating operating conditions for complex equipment assemblies;



SRE = spectre de réponse d'essai
SRS = spectre de réponse spécifié
APN = accélération à période nulle

TRS = test response spectrum
RRS = required response spectrum
ZPA = zero period acceleration

Figure 3. Typical envelope response spectrum

Vibration response investigation is normally carried out using a single direction sinusoidal excitation logarithmic sweep cycle in the range of 1-35Hz (§14.2). The excitation amplitude is normally $2 m/s^2$ or $1 m/s^2$ in cases when sharp resonance peeks are expected.

Test methods in CEI/IEC 68-3-3 distinguish between:

- Elements without critical frequencies below 35Hz;
- Elements with critical frequencies below 35Hz;

If critical frequencies are detected, the damping level has to be chosen. The damping of 5% is believed to be appropriate to stress levels close to the yield in most materials. More detailed recommendation are presented in Table 1.

Table 1. Recommended damping factors

Item	Stresses corresponding to		
	1/4 yield	1/2 yield 1)	At yield 2)
Welded steel structures	0.5 - 1	2	4
Bolted steel structures	0.5 - 1	4	7
Reinforced concrete structures	0.5 - 1	4	7
Cabinets and panels	0.5 - 1	2	5
Assemblies	0.5 - 1	2	7
Large equipments, steel pipes > 300 mm dia.	0.5 - 1	2	3
Small pipes ≤ 300 mm dia.	0.5 - 1	1	2

1) Often used for S1-earthquakes.
2) Often used for S2-earthquakes.

Test loads may be applied:

- Successively in a single directions (§15.1);
- Bi-directionally:
    - Two horizontal axes simultaneously (§15.2.1);
    - One horizontal and one vertical axis simultaneously (§15.2.2);
- Tri-axially;

5 Qualifying equipment according to RCC-E

RCC-E, like CEI/IEC 68-3-3 is a standard exclusively focusing on electrical equipment and systems, more specifically to safety classifies equipment. In fact RCC-E is referencing methods from CEI/IEC 68-3-3 to a large extent.

One particularity setting aside RCC-E from the other reviewed documents is its much broader focus. RCC-E is concerned with:

- General and quality requirements (Section A);
- Qualification and approval (Section B);
- Functional system design (Section C);
- Installation (Section D);
- Constituent parts of equipment (Section E);
- Verification and testing methods (Section MC);

From these only Section B, can be seen to outline specifically engineering requirements for the equipment. Section B is divided into:

- General introduction (B1000);

- Basic rules governing the qualification procedure (B2000);
- Qualification procedure for normal ambient operating conditions (B3000);
- Qualification procedure K3 (B4000);
- Qualification procedure K2 (B5000);
- Qualification procedure K1 (B6000);
- Qualification procedure for severe accident condition (B7000);

From the above segment only B4000-B6000 is strictly dedicated to methods of seismic qualification.

5.1 Qualification procedure K3

The procedure is meant to ensure that equipment located outside of the containment is capable to perform its specific functions under normal ambient and under seismic loading.

5.1.1 Testing procedures

The aim of the testing is to verify the performance of equipment for S2 level earthquake loads, corresponding to SSE earthquakes. The verification can be carried out by (1) testing (2) analysis or (3) combined testing and analysis. When testing is used, the accelerogram corresponding to the SSE should be applied to the anchoring points of the equipment.

Aging of equipment can be taken into account by testing for earthquake the same equipment as tested in B3000 (qualification procedure for normal ambient operating conditions), or by showing that the normal ambient aging mechanisms have no effect on seismic performance.

The acceptable test methods include:

- Single axis sine-beat or sine-sweep test;
- Single-axis time history tests;
- Two-axis time history tests;

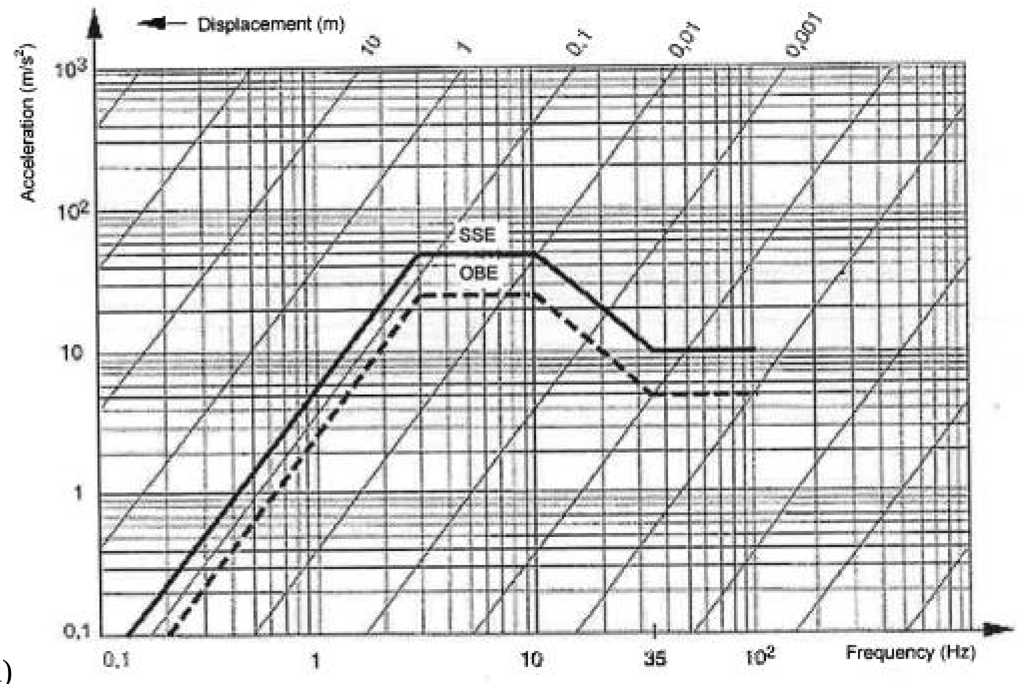
CEI/IEC 68-3-3 is specifically referenced for limitations and specific measures of implementation for these test types.

5.1.2 Details of implementation

In case of single-axis time history and two-axis time history test the following specific measures are imposed:

- Minimum duration of strong signal portion (25% of maximum value and above) 10s;
- Total signal duration 20s;
- At least:
    - 6 (positive or negative) peaks exceeding 70% of maximum ZPA for single axis;
    - 8 (positive or negative) peaks exceeding 70% of maximum ZPA for two axis;

Il all cases the S2/SSE level test has to be preceded by 5 S1/OBE level seismic tests. If no other data is available, the electrical equipment should be qualified for all floor spectra where electrical equipment may be installed. The recommended general RRS spectral shapes are presented in Figure 4.



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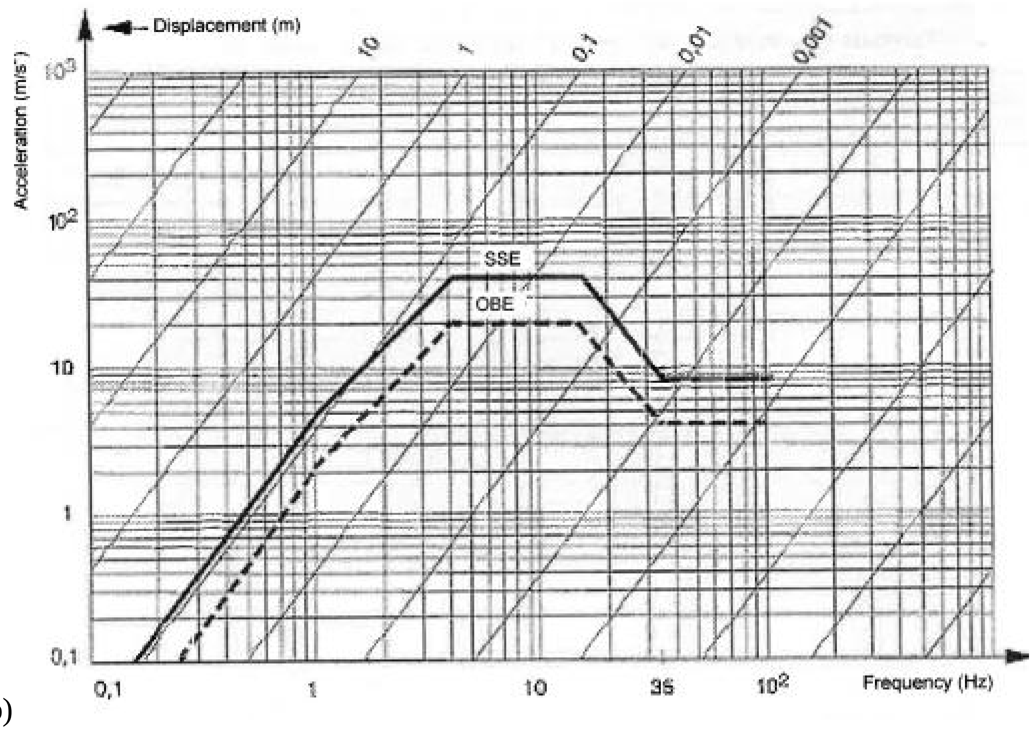

b)

Figure 4. General purpose (a) horizontal and (b) vertical RRS spectra

5.2 Qualification procedure K2

K2 is the seismic qualification procedure dedicated to electrical equipment inside the containment. The aim is to show that equipment is capable to perform its specific functions under ambient and seismic conditions.

The main difference with K3 refers to the treatment of radiation aging affecting the equipment.

5.3 Qualification procedure K1

K1 is dedicated to equipment insulated inside of the containment, with the purpose of showing that they are capable to perform their functions under seismic loading and under normal, accidental and post accidental ambient conditions.

Besides the seismic qualification measures for K1 equipment, the recommendations of NF M64-001 *"Procedure For Qualification Of Electric Equipment Installed In Containments For Pressurized Water Reactors Subject To Accident Conditions"* have to be followed. The supplementary measures refer to spectral shapes and OBE/SSE loading specifications:

Table 2. NF M64-001 supplementary recommendations for K1 equipment qualification

Information	Refers to paragraph number (of the standard)	Value assigned by the Standard
Seismic loading – horizontal spectrum (and damping)	Appendix A – Fig. A1	Assemblies spectrum (all plants) - 5 % damping
Seismic loading – vertical spectrum (and damping)	Appendix A – Fig A2	Assemblies spectrum (all plants) - 5 % damping
Seismic loading – OBE and SSE spectra	7.5.2	OBE imposed prior to SSE and number of OBE chosen equal to 5

6 Conclusions

The following preliminary conclusions and recommendations can be formulated:

- Equipment qualification is characterized by very diversified regulatory background. Fundamentally, these regulations are based in sound engineering principles, so they should not result in assessment leading to very different level of safety;
- It is important to closely assess the application area of the standard used for qualification. E.g. two of the standards reviewed here are explosively dedicated to electrical equipment;
- It appears to be generally accepted that equipment should be qualified for SSE but with consideration of vibration aging from previous OBE events;
- It is important (and very challenging!) to account for aging mechanisms that may affect the seismic performance;
- Uncertainties of the response in the structural system supporting the equipment should be taken into account by broadening the RRS spectra resulting from structural analysis;

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