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Earthquake experience and seismic qualification by indirect methods in nuclear installations

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Engineering Safety Section
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FOREWORD

In recent years, many operational nuclear power plants around the world have conducted seismic re-evaluation programmes either as part of a review of seismic hazards or to comply with best international nuclear safety practices. In this connection, Member States have called on the IAEA to carry out several seismic review missions at their plants, primarily those of WWER and RBMK design. One of the critical safety issues that arose during these missions was that of seismic qualification (determination of fitness for service) of already installed plant distribution systems, equipment and components.

The qualification of new components, equipment and distribution systems cannot be replicated for equipment that is already installed and operational in plants, as this process is neither feasible nor appropriate. For this reason, seismic safety experts have developed new procedures for the qualification of installed equipment: these procedures seek to demonstrate that installed equipment, through a process of comparison with new equipment, is apt for service. However, these procedures require large sets of criteria and qualification databases and call for the use of engineering judgement and experience, all of which open the door to wide margins of interpretation.

In order to guarantee a sound technical basis for the qualification of in-plant equipment, currently applied to 70% to 80% of all plant equipment, the regulatory review of this type of qualification process calls for a detailed assessment of the technical procedures applied. Such an assessment is the first step towards eliminating the risk of large differences in qualification results between different plants, operators and countries, and guaranteeing the reliability of seismic re-evaluation programmes.

Bearing this in mind, in 1999, the IAEA convened a seminar and technical meeting on seismic qualification under the auspices of the IAEA Technical Co-operation programme. Altogether 66 senior experts attended the two meetings, contributing their knowledge and experience to the lectures and discussions. This report presents in detail the technical material presented at these meetings for further consideration by plant designers, owners, operators and safety regulators. The material is laid out in two parts for ease of consultation and reference.

The work of the contributors to the drafting and review of this publication is greatly appreciated. In particular, the contributions of R. Campbell (USA), P. Sollogub (France) and Hui Tsung Tang (USA) are acknowledged. The IAEA also wishes to thank A. Birbraer (Russian Federation), O. Coman (Romania), K.P. Kamm (Germany), R. Masopust (Czech Republic) and R. Murray (USA) for their contribution to this publication.

The IAEA officers responsible for this publication were P. Contri and P. Labbé of the Division of Nuclear Installation Safety.

CONTENTS

1. INTRODUCTION

1.1. Background

Seismic design of new nuclear facilities is a well established discipline. However, seismic re-evaluation programmes for existing facilities generally rely on equipment qualification procedures that vary from those applied in the design of new plants. Differences arise mainly because of the difficulty in accessing equipment items already installed and in operation as well as owing to economic constraints that make the design approach unsuitable for existing plants.

There is no international consensus on the approach to be applied for seismic qualification of distribution systems[1], equipment and components in plants currently in operation. As a result, many engineering companies and utilities have opted to develop their own methodologies, which they apply at a great cost to close to 80% of the items of equipment covered in seismic re-evaluation programmes.

A common feature of these individual methodologies is that they rely to a very large degree on engineering assumptions that often cannot be reviewed with ease by the regulatory body. Two aspects in particular are affected by the use of engineering assumptions:

— the procedures for the seismic qualification of some distribution systems, equipment and components using the 'indirect method', i.e. by comparison, as set forth in IAEA Safety Guide 50-SG-D15 [1]; and

— the procedures applied to the seismic re-evaluation of piping.

To support the Member States in the evaluation of the safety aspects of the seismic qualification procedures for existing plants, the IAEA organized in 2000 (a) a technical meeting to cover seismic qualification using the 'indirect method' and (b) a seminar to cover the seismic re-evaluation of piping. Both meetings were well attended, particularly by participants from countries that operate WWER plants.

- Twenty-one experts attended the plenary session of the technical meeting: representatives from Armenia, Bulgaria, Hungary, Lithuania, Russia, Ukraine, Slovakia, along with engineering consultants and experts designated by the IAEA who chaired the meeting, evaluated the technical content of the qualification procedures submitted and made recommendations for their improvement.
- Forty-five experts attended the seminar: representatives from the Bulgarian Regulatory Body, the Bulgarian National Electric Company, the Kozloduy plant, the Bulgarian Academy of Sciences, Atomenergoinvest, Energoproject and other engineering companies involved in seismic re-evaluation tasks in Bulgaria and elsewhere.

This TECDOC is the outcome of a large co-operation effort between the technical officers, the experts designated by the IAEA, some engineering consulting companies and national representatives.

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[1] As provided in IAEA Safety Guide 50-SG-D15, distribution systems encompass plant piping, cable trays, conduits, tubing and ducts and their supports [1].

This TECDOC is also a support initiative to the IAEA Safety Guide Review Program, which is in progress at IAEA/NS. Particularly, the Safety Guide dealing with the seismic qualification and design of NPP components [1] will receive some feedback from the discussion presented here.

Also the IAEA Safety Report for the seismic re-evaluation of nuclear power plants (NPPs) [2] was upgraded as a follow-up of this clarification initiative.

1.2. Objective

The objective of this TECDOC is to provide a technical basis to help regulators, plant owners and designers in the definition, implementation and review of seismic qualification procedures, mainly for existing plants, that are consistent with the IAEA nuclear safety standards [1, 3–6].

It is not intended to propose a 'best' approach among those available for seismic qualification: various factors may influence the choice of a specific procedure. The most suitable approach can be selected only on a case by case basis.

In the field of component qualification, the following objectives were identified:

- understanding of the basis for seismic qualification by similarity
- analysis and comparison of the proposed approaches, understanding their limitations and their optimal use
- identification of major safety issues and highlighting of areas of potential future improvement of their reliability
- development of recommendations for future IAEA actions.

As for the seismic re-evaluation of piping, the following specific objectives were identified:

- collection of experience feedback and experimental data on safety margins in seismic design practice for piping systems
- analysis of physical phenomena that enable the interpretation of the experimental data
- development of proposals for new design criteria and new engineering practices for the re-evaluation of piping in existing plants.

1.3. Scope

The seismic qualification techniques discussed in this report are applicable mainly to existing nuclear power plants. However, these techniques have also been used for new plants, particularly for piping design, where a specific evaluation of the design safety margin is explicitly required.

Concerning the qualification procedures by similarity, a very specific scope was identified for this TECDOC, with reference only to the walkdown approach. Particularly, the main phases of this approach are:

(1) acquisition of as-built and as-is configurations of the systems to be qualified
(2) selection of the items to be qualified

(3) evaluation of seismic demand, which implies the definition of the review level earthquake and the evaluation of the floor response spectra
(4) evaluation of seismic capacity, which implies the evaluation of the equipment functionality, of the anchorage capacity, the interaction problems and the selection of proper performance limits
(5) comparison of demand vs. capacity and therefore evaluation of the safety margin
(6) prioritization and design of upgrading,

Only steps 2, 3, 4, 5 are explicitly addressed in this report, as they have been recognized as the areas where a consensus among Member States is still lacking.

Moreover, the seismic qualification approach is usually influenced by the methodology used (e.g.: SMA, PSA, GIP, etc.) in the re-evaluation of the overall facility. Therefore this report has to address the item qualification in relation to the choice of the methodology chosen. However, such methodologies are mentioned here only to provide an understanding of the context of the qualification of the items and of the relevant requirements (e.g.: definition of the HCLPF, fragility, screening criteria, etc.).

1.4. Structure

The material presented has been compiled from the following sources:

- the analysis of technical presentations and lectures given at the meetings
- the experience of the IAEA based on the most recent review missions
- the analysis of available technical documents with the description of the proposed approaches [7–10]
- discussion at the meetings/seminars.

This report is divided into two parts: Part I covers the seismic qualification of distribution systems, equipment and components using indirect methods and Part II addresses seismic design and re-evaluation of piping.

PART I — SEISMIC QUALIFICATION OF EQUIPMENT AND COMPONENTS BY INDIRECT METHODS

2. GENERAL BACKGROUND

2.1. Introduction

Indirect methods are mostly applied in a context of re-evaluation of existing plants, where the application of direct methods (analysis or test) for component qualification often is either unfeasible or inconvenient. In fact in existing plants, analysis can cover the functionality aspects only partially, and testing of existing, already installed, components implies removal, decontamination, shipping, remounting which at the end prove unfeasible because of costs and out-of-service time. On site testing is usually limited to only a few qualification aspects, proves expensive and often conflicts with accessibility.

This report is therefore compelled to make continuous reference to such procedures where many tasks, not really dealing with the qualification itself, actually affect the qualification process through assumptions on the items to be qualified, the seismic demand and the margin evaluation.

Qualification by similarity is in principle allowed by IAEA Safety Guides on Design of new NPPs [1], but no reference is available of any application of such methodologies to new structures in any Member State.

Many approaches have been developed in recent years for the seismic re-valuation of existing plants, based on deterministic or probabilistic criteria, with different requirements in term of component qualification: for example, a safety margin approach requires the availability of a measure of the margin in the seismic capacity of the item (often expressed in terms of HCLPF [11]), while a PSA approach requires the availability of a fragility curve for the same item. All these quantities associated to the components represent their qualification: they might be evaluated by analysis, test or indirect methods. Only the latter are of interest for this report for the reasons explained in the general introduction.

In such a framework, some background information have to be provided concerning the context (i.e. the global approaches to facility re-evaluation) where a component qualification is required, to be able to understand the boundary conditions for the qualification of components, equipment and distribution systems.

This section is dedicated to such preliminary analysis.

2.2. Reference experience on re-evaluation methodologies: The US approach

Approaches for new design of NPPs are well documented in codes, standards and regulatory requirements of many countries that design, build and operate NPPs. Requirements for new design require rigorous analysis and testing of active and passive components to demonstrate their ability to function during and after a design basis earthquake or a review level earthquake. In countries that operate NPPs that do not have a complete seismic design basis established, it is important to establish criteria for re-evaluation that meet desired safety goals but that are efficient and practical to implement.

The US addressed this issue in the resolution of Generic Safety Issue A-46. Some 72 operating NPPs had incomplete qualification of equipment. Efficient methods for demonstrating seismic adequacy were developed by a Seismic Qualification Utility Group (SQUG) using the results of the performance of similar equipment in strong motion earthquakes. Earthquake experience data were collected and studied and criteria were formulated to screen existing equipment against a set of acceptance rules. If all of the acceptance rules were met, the equipment was considered to be seismically adequate to perform its function after a Safe Shutdown Earthquake (SSE). Special rules based on a collection of test data were formulated to demonstrate the function of relays during the earthquake shaking. These criteria are documented in a Generic Implementation Procedure (GIP) [12] that has been accepted by the US regulators for demonstrating seismic adequacy of active and passive equipment in these A-46 plants. The criteria are also used for new and replacement items in these plants but have not been accepted for use in qualification of new and replacement items in plants that had their design basis established by the more rigorous requirements currently specified for new design.

The US has also requested that all operating NPPs perform an Individual Plant Examination of External Events (IPEEE). In this case, the licensees were given an option of performing a Seismic Margin Assessment (SMA) or a seismic Probabilistic Safety Assessment (PSA). The intent was to assess the consequences of earthquakes beyond the design basis. Specific criteria were developed for performing a deterministic seismic margins study [11, 13]. These criteria were similar to the GIP criteria used for establishing a design basis but in general were more liberal. The rules were formulated to establish a High-Conficence-of-Low-Probability-of-Failure (HCLPF). The rules are deterministic but have a probabilistic basis wherein the HCLPF is established as 95% confidence that there is less than 5% probability of failure. It is assumed that the HCLPF of the plant is equal to the HCLPF of the weakest component in the highest capacity safe shutdown path. In order to determine a margin above the SSE, a review level earthquake (RLE) was set at a level above the SSE.

Optionally the licensee could conduct a seismic PSA. In the seismic PSA approach, the seismicity and the capacity of plant components are defined in a probabilistic manner and the response of the plant to component malfunctions during an earthquake are modelled using event tree/fault tree logic. The PSA is used to define the probability of core damage. Additionally, the plant level HCLPF can be established based on the more thorough modelling of response of the plant to component failures. NUREG/CR-1407 [14] outlines the requirements and acceptable procedures for performing and reporting the IPEEE.

The purpose and goal of the procedures adopted for resolution of A-46 and for performing IPEEE are different. The A-46 procedures, using seismic and testing experience to establishing a design basis, are considered to be equivalent to qualification. The IPEEE procedures for seismic margins and seismic PSA are to examine the consequences of exceeding the design basis and are not considered as equivalent to the criteria for establishing a design basis.

The US Department of Energy has established performance based criteria for new and existing facilities. Four performance categories are defined and rules for achieving each performance category are defined. Performance category 4 is the highest category and results in failure rates due to an earthquake occurring at the site being less than 1E-5 per year. A modification and extension of the SQUG GIP is a major part of these performance based criteria. The DOE document that contains these performance based criteria for equipment is contained in DOE/EH-0545 [15].

There is an ongoing effort in the US to use seismic and testing experience to establish a design basis for new design and new and replacement items in all operating NPPs. ASME and IEEE 344 committees have been working jointly for several years to establish criteria for using seismic and testing experience for seismic qualification. ASME QME-1-2000 (Draft) [16] and IEEE 344 draft revision [17] contain general guidelines which are under review. It is anticipated that these guidelines will be accepted by the US regulators in the near future. The guidelines are general and consist of guidance on the number and type of earthquake recordings required, the minimum number of components required in the earthquake experience database and provide weighting functions on how to determine capacity from the data. It is desirable that the GIP in its current state comply with these general guidelines.

Moreover, there are several geographical areas in the world where nuclear power plants are located which include northern Europe, eastern South America and the South-eastern United States which are defined as low seismicity sites (pga < 0.12g). For nuclear power plants located in these regions where mean probabilities of exceedence at the 10^{-4}/year level are less than 0.1g peak ground acceleration, many efforts are spent in US developing reduced scope Seismic Margin Assessment procedures. The existing procedures which were developed on a site specific basis for moderate (0.12 – 0.33g) pga sites may not be appropriate or cost-benefit effective for such low seismicity sites.

Even though the US has defined a definite distinction between the GIP procedures for demonstrating seismic adequacy and the seismic margins and PSA procedures for examining plant performance for earthquakes beyond the design basis, other countries have selectively used seismic margins procedures and seismic PSA to examine and upgrade their operating NPPs. These seismic margins and PSA studies have been used to establish an equivalent to a design basis or to demonstrate a safety goal. In order for other agencies to use the above documents in re-evaluation of NPPs without an established seismic design basis it is important to understand the fundamental differences between the approaches. Fig. 1 is a flow chart that shows the process currently established in the US for seismic design, seismic margins and seismic PSA. The steps are fundamentally the same but the details differ. Following is a brief description of the important steps.

2.2.1. Seismic hazard

For design the seismic hazard has classically been defined as a maximum event that can occur at the site. Conservative deterministic methods have been used to establish a peak ground acceleration at the NPP site. The amplification of this peak ground acceleration has been defined by US Regulatory Guide 1.60 [18] and is nominally a mean plus one standard deviation amplification of peak ground acceleration. Current guidance is to use probabilistic methods to define the peak ground acceleration and the spectral ordinates. Regulatory guide 1.165 [19] describes current USNRC requirements. The SSE is defined as a 100,000 year return period median ground motion spectrum.

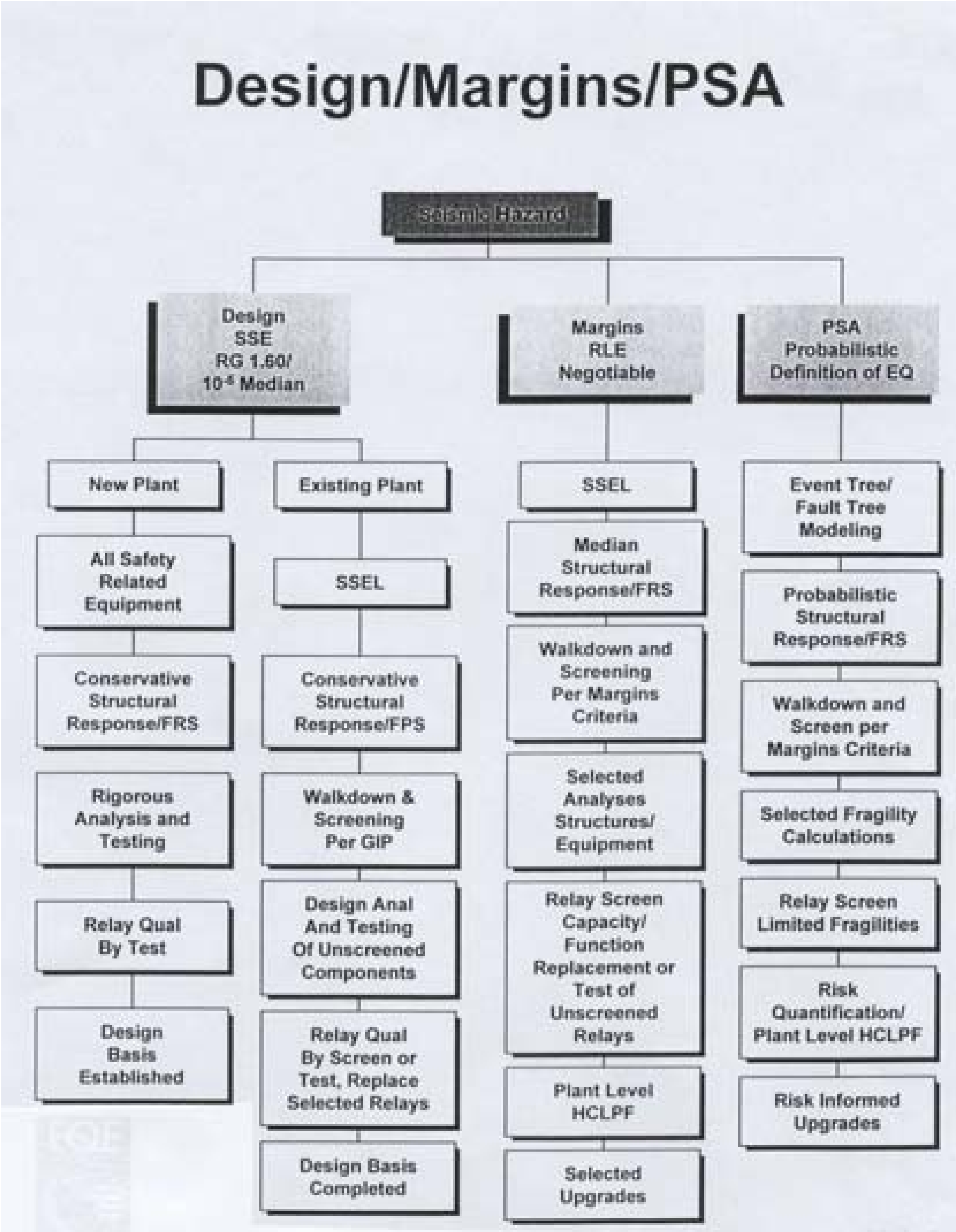


FIG. 1. Comparison among design, margin and PSA approaches.

If a seismic margins evaluation is performed the earthquake is a negotiable level. The deterministic rules for performing a seismic margins assessment and calculating HCLPFs are predicated on the Review Level Earthquake (RLE) being conservatively established as an 84th percentile non-exceedance probability earthquake. In practice, the US regulators specified for most plants that the review level earthquake be 0.3g pga and that the spectral ordinates be defined as a NUREG/CR-0098 [20] median amplification spectrum. The amplification of pga of the NUREG/CR-0098 [20] spectrum is much less than that of the Regulatory Guide 1.60 [18] spectrum (Fig. 2).

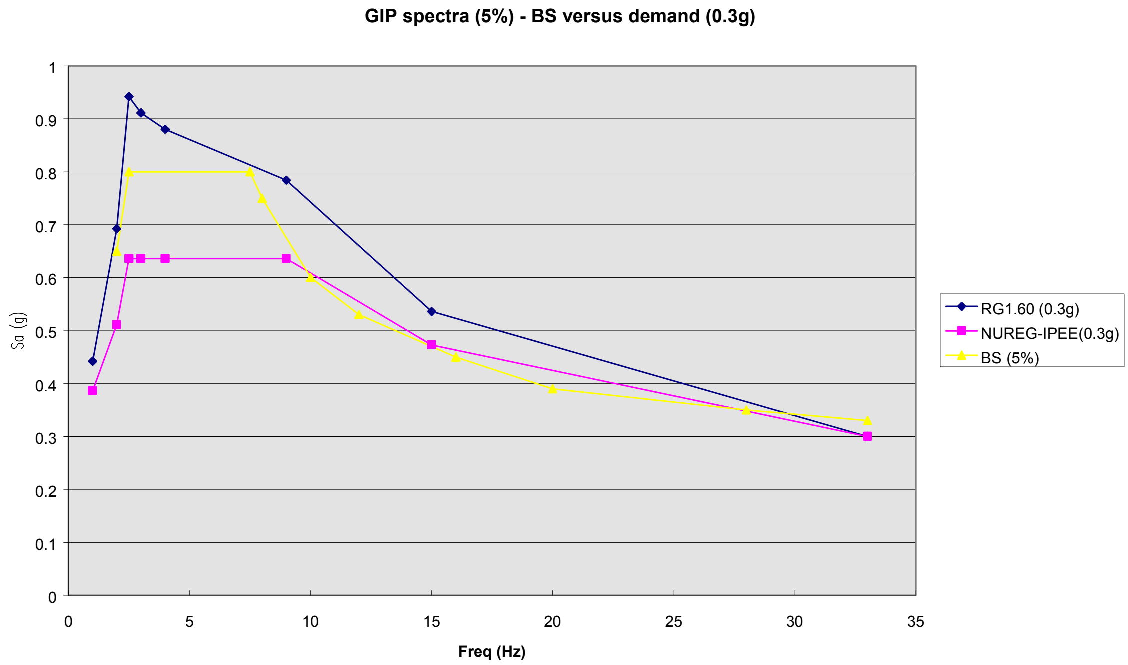


FIG. 2. GIP spectra(5%): BS versus demand (0.3g).

If a seismic PSA is conducted, the ground motion is defined probabilistically. For the US IPEEE programme the pga was defined for recurrence frequencies down to about 1E-8 per year or out to a 1.0g peak ground acceleration. The uncertainty in the seismic hazard was defined by providing the pga curves for 15, 50 and 85 percentile non-exceedance probabilities. The mean was also provided. The ground motion spectra were defined as Uniform Hazard Spectra (UHS). This means that every ordinate on the spectrum has an equal probability of occurrence. UHS were typically provided at the 15, 50 and 85th percentile non-exceedance probabilities for occurrence frequencies of 1E-3, 1E-4 and 1E-5 per year.

2.2.2. List of equipment to be qualified

In the USI A-46 programme all equipment necessary for safe shutdown and mitigation of a loss of coolant accident was included. Equipment for containment isolation, containment cooling, spent fuel cooling and radioactive waste storage and handling was not included. The objective was to establish a design basis for equipment required to safely shutdown the plant and to mitigate a loss of coolant accident. Only equipment not previously qualified was included. Piping and reactor internals, steam generators, etc. were not included.

In the IPEEE programme all equipment and piping required for safe shutdown and containment isolation and cooling was included. A small LOCA was to be assumed and equipment required to mitigate the small LOCA was included. Large LOCA was excluded from the studies. If a PSA was conducted, many non-safety equipment were modelled as well as safety equipment to take advantage of successes as well as failures. Operator actions were also modelled and seismic induced failures were combined with random failures to appropriately model response of the plant to a seismic event.

2.2.3. Development of floor response spectra

For design, the development of floor response spectra is governed by regulatory guides and the NUREG-0800, Standard Review Plans [21]. Current regulatory guidance results in structural response predictions that are nearly median centred. Earlier guidance resulted in very conservative response predictions. Conservatism is introduced by the requirement to broaden and smooth spectra in accordance with Regulatory Guide 1.122 [22]. In addition, for soil sites, variations in soil shear stiffness should be addressed. Response from three soil cases using best estimate G, ½ G and 2 times G should be broadened and enveloped.

For seismic margins, median spectra are developed, however, variations in soil parameters are required. Typically, the soil shear modulus is varied the same as for design and the results are enveloped but not broadened. Alternatively, probabilistic spectra can be developed and the median value used. Methodology for efficient development of probabilistic spectra was developed in the USNRC Seismic Safety Margins Research Programme (SSMRP) and are described in [23]. This procedure usually results in significantly lower and much narrower floor response spectral. For seismic PSA, probabilistic spectra are desirable. Alternatively, the deterministic floor response spectra are scaled to median values and uncertainty is estimated. Median probabilistic spectra may also be used in seismic margin assessment.

2.2.4. Qualification including relays

For new design, qualification of active and mechanical components is conducted by analysis, test or combinations of both. Analysis is governed by the appropriate design codes and standards such as ASME or AISC. Testing is governed by IEEE 344 [17]. For existing plants with insufficient qualification, the procedures in the SQUG GIP that define capacities relative to seismic and testing experience are used to demonstrate seismic adequacy. The GIP procedures are based on walkdown screening and detailed inspection and analysis of anchorage. Components that do not meet the GIP screening criteria are deemed outliers and should be demonstrated to be acceptable by other means or else upgraded.

If a seismic margins evaluation is conducted, the procedure is similar to that for using the GIP procedures except that the walkdown and screening rules are, in general, more liberal. Components that do not meet the screening rules should be addressed by analysis or other means. Since the IPEEE was a request for information there was no formal requirement to replace components that did not have a HCLPF equal to or greater than the RLE. Upgrading was negotiated on a case by case basis.

The seismic margins criteria are based on the assumption that the plant has a seismic design basis and that the construction meets all QC and QA requirements, hence it is not required to perform detailed inspection on anchorage bolts. Formal QA is also not a requirement but in the IPEEE programme, the US regulators required peer review regardless of whether the project was performed to a QA programme or not.

If a seismic PSA is conducted, there are less formal guidelines. Walkdown and screening is conducted and components are screened in accordance with the seismic margins screening criteria. Components that meet the screening rules for each of two screening levels are usually assigned generic fragilities whose HCLPFs are defined by the screening level. Detailed fragility descriptions are developed for unscreened components. Lower ruggedness relays are usually replaced if chatter can lead to adverse conditions. Otherwise the effects of chatter are assessed in the risk computations.

2.2.5. Quantification of margin and risk

If a design basis evaluation is being established, there is no requirement to determine and report margin above the design basis, although in most cases, this is implicit in the comparison of demand to capacity. For margins studies, component level and plant level HCLPFs are calculated. The margin can then easily be determined by finding the scale factor by which the earthquake should be scaled to reach a target capacity such as the RLE. Reporting of HCLPFs was required in the IPEEE programme but reporting of margins above the SSE was not a requirement.

If a PSA is conducted, the NRC guidance for IPEEE required that only the mean core damage frequency (CDF) be reported. In addition, the dominant contributors to CDF and their HCLPFs were required to be reported. Some plants chose to do full uncertainty analysis and reported these results. Since the IPEEE [14] programme required the evaluation of containment, the HCLPFs of items associated with containment isolation, bypass and cooling were required to be reported.

Two candidate methods for calculating the HCLPF capacities for components have been recommended [14]:

- the Conservative Deterministic Failure Margin (CDFM) method
- the Fragility Analysis (FA) method

The Fragility Analysis method was used for several NPP seismic margin studies This method requires evaluation of parameters such as the median capacity, the randomness variability factor $ß_R$ and uncertainty variability factor $ß_U$ using considerable judgment.

The CDFM method prescribes the parameter values and procedures to be used in calculating the HCLPF capacities and requires less subjective judgment than the FA method, although, some subjective decisions were made in formulating the procedures used in the CDFM method.

One aspect of the FA method is that it presents for each component a suite of curves (corresponding to different confidence levels) of probabilities of failure versus ground motion levels. This complexity is necessary for use in SPRAs, but it leads to significant difficulty in making decisions as to whether an adequate seismic margin exits. Such decisions are easier when only a single conservative but realistic capacity is reported for each SSC. In order to discuss the adequacy of seismic margins with the NRC staff and the Advisory Committee on Reactor Safeguards (ACRS), it was found useful to convert the information displayed in the seismic fragility curves into a single seismic margin descriptor. The descriptor chosen was the High-Confidence-Low-Probability-of-Failure (HCLPF) capacity, which corresponds to about 95% confidence of less than about a 5% probability of failure or alternatively more recently to a composite fragility curve with less than about 1% probability of failure. Such a descriptor is conservative because there is very little chance of failure below the HCLPF capacity; and yet it is realistic because it is an attempt to describe the failure level.

Although HCLPF capacities obtained from fragility curves using the FA method proved to be a useful descriptor of seismic margin, several potential deficiencies were identified in the method:

- The method requires large number of judgements and calculations because a median capacity, a randomness, and an uncertainty variability factor should each be estimated before the HCLPF capacity can be calculated. However, if one only needs the HCLPF capacity to verify seismic adequacy and does not need the entire fragility curve, the direct CDFM to compute the HCLPF capacity is recommended.
- There are a limited number of professionals capable of making seismic fragility estimates. On the other hand, a large number of seismic design engineers have substantial experience in making and reviewing deterministic margin evaluations by using criteria similar to that used in standard design and in the SEP.
- Because of the requirement for a significant use of judgement in the estimation of median capacities, randomness, and uncertainty factors, and because of the dependencies of the HCLPF capacity on all three, there was a lack of consistency in the estimated HCLPF capacities for different plants or different components in the same plant even when made by the same team of people.
- At present time there is no consensus methodology available to develop randomness and uncertainty factors required for the FA method in a consistent manner.

Because of the considerations described above, CDFM type methodology criteria was more frequently applied to a number of WWER type nuclear power plants in a number of Eastern European countries.

2.3. The IAEA approach to seismic re-evaluation

IAEA guidelines for seismic re-evaluation of WWERs at Paks, Mochovce, Bohunice and Armenia NPPs [24–27] were developed in recent years as a combination of the GIP, seismic margins and the DOE 1020 [28] standard for evaluation of structures for natural hazards. For equipment, the emphasis was on use of the GIP. In general, the IAEA guidelines result in more uniform, but in some cases lower, factors of safety than result from following rigorous procedures for new design.

Higher level IAEA documents developed for new installations are the only references available for a review of seismic re-evaluation programmes, as shown in the Table I, structured in the typical IAEA sequence.

To date only a few countries have established official standards for the seismic re-evaluation of **existing** nuclear power plants. More often general guideline documents have been issued but without legal force. The currently used guidelines of the IAEA and regulatory authorities of Member States are in fact established for the siting, design and construction of **new** facilities.

Keeping the standards for new plants as a reference, Re-evaluation Guidelines were developed at the IAEA mainly for WWER plants [24–27]. A panel of experts proposed some modifications to the traditional CDFM method, trying to develop an approach more suitable for the WWER type reactors. In fact, originally in the CDFM method the Ground Response Demand Spectrum was specified as the 84 percentile non-exceedance probability site specific spectra, but in recent applications, a median shape spectrum normalized to mean peak ground acceleration has been used in order to not bias the HCLPF results. The main parameters of the CDFM method, as modified in the IAEA guidelines, are shown in Table II.

TABLE I. IAEA DOCUMENTS TO BE APPLIED IN THE SEISMIC RE-EVALUATION OF EXISTING PLANTS

General safety requirement	Code on the Safety of NPPs: Siting [3] Code on the Safety of NPPs: Design [4]
INSAG document	A common basis for judging the Safety of Nuclear Power Plants Built to Earlier Standards - INSAG 8 [29]
Guidelines for seismic siting and design	Safety Guide on Earthquakes and siting SG-50-S1 [5] Safety Guide on Safety Aspects on Foundations SG-50-S8 [6] Safety Guide on Seismic Design SG-50-D15 [1]
Implementation and experience	Safety Series Report No. 3 and 12 [30, 31]

TABLE II. SUMMARY OF CDFM APPROACH MODIFIED FOR THE IAEA GUIDELINES

Load Combination	Normal + Seismic Margin Earthquake
Ground response Spectrum	Median shaped spectrum taken as a minimum 1.5 times the SL-2 spectrum but not more than a 10^{-6}/year probability of exceedence. Conservative specified 84% NEP, site specific spectrum
Damping	Conservative estimate of median damping
Structural Model	Best estimate (median) + uncertainty variation in frequency
Soil Structure Interaction	Best estimate + SSI parameter variation by spectral broadening
Material Strength	minimum strength or 95% exceedance actual strength if test data are available
Static Capacity Equations	ACI, AISC Code load factor and strength design in concrete and structural steel, Service Level D (ASME) or functional limits for mechanical structures and components. If test data are available fragility limits divided by 1.25 are recommended to define HCLPF values.
Inelastic Energy Absorption	For non-brittle failure modes and linear analysis, use IAEA specified ductility limits
In-structure (Floor) Spectra generation	Frequency shifted rather than peak broadening to account for uncertainty is permitted

2.4. The general re-evaluation process and the similarity criteria

Despite the differences in the national approaches, there is a general consensus on the reference methodology to be applied in the seismic qualification of equipment by similarity as part of the seismic re-evaluation process. It is mainly a three step process relying on:

- a screening "walkdown", where qualification is straightforward based upon simplified criteria,
- a detailed "walkdown", applied in the detailed assessment of equipment functionality, anchorage integrity and interactions for items meeting some general criteria;
- a solution of the "outliers" that might require some special techniques to solve the peculiarity of some components screened out by previous phases.

Such process is part of a general seismic re-evaluation process for the facility which encompasses some major phases. The management of such linked phases provides rigid boundary conditions for the process of interest and therefore they have to be defined for reference in the next sections.

(1) Selection of a review level earthquake based on site seismicity studies
(2) Elaboration of seismic demand (floor response spectra)
(3) Selection of equipment to be reviewed (SSEL)
(4) Gathering of available documentation of the seismic design
(5) Assessment of ruggedness of SSEL equipment by means of
(6) preliminary screening to separated inherently rugged equipment from those to be more precisely checked
(7) walkdown review to identify as built configuration, seismic interaction, anchorage features
(8) quick fixes for obvious weak points
(9) additional evaluations for equipment not screened out (”outliers”)
(10) final plant upgrading.
(11) final walkdown review.

The tasks of main interest for this report are those concerning the assessment of the safety margin (Nos. 5 and 7) that mainly rely upon two basic ingredients:

(1) a database of "earthquake experience data" and "generic seismic test data". GIP [12] database includes experience data collected in about 100 facilities (typically non-reactor) located in areas of strong ground motions from 20 earthquakes (with Pga=0.10-0.85 g and duration=3–50 sec.) an 300 shake table test covering 15 generic classes of equipment. Capacity data for expansion anchor bolts covering 1200 ultimate capacity tension and shear tests have been also included
(2) a list of inclusion/exclusion rules ("caveats") that represent specific characteristics and features particularly important for seismic adequacy of a particular class of equipment. If caveats are satisfied, then the capacity of the equipment class can be represented by the seismic experience reference spectrum or by the generic ruggedness spectrum from test data. The caveats have been usually validated on the databases, but recently other criteria have been developed independently from the databases, with a rising concern on their validation.

The GIP includes 20 equipment classes, the seismic ruggedness of which may be verified by applying specific caveats. Classes are identified as in the following:

(1) Motor Control Centres,
(2) Low Voltage Switchgears,
(3) Medium Voltage Switchgears,
(4) Transformers,
(5) Horizontal Pumps,
(6) Vertical Pumps,
(7) Fluid-Operated Valves,
(8) Motor-Operated and Solenoid-Operated Valves,
(9) Fans (ventilators),
(10) Air Handlers
(11) Chillers,
(12) Air Compressors,
(13) Motor Generators,
(14) Engine Generators,
(15) Distribution Panels,
(16) Batteries on Racks,
(17) Battery Chargers and Inverters,
(18) Instruments on Racks,
(19) Temperature Sensors,
(20) I&C Panels and Cabinets.

Furthermore, special guidance is provided also for the following items:

- Relays
- Tanks and heat exchangers
- Cable and conduit raceways

as well as for the evaluation of the following generic aspects:

- Anchorage
- Seismic interaction

The criteria to be met for the qualification of an item are the following:

(1) the experience based capacity spectrum should bound the plant seismic demand spectrum
(2) the equipment item should be reviewed against certain inclusion rules and caveats
(3) the component anchorage should be evaluated
(4) any potential significant seismic systems interaction concerns that may adversely affect component safe shutdown function should be addressed.

The main concern in the application of similarity criteria is the application of criteria developed for US plants to other plants (namely WWER and RBMK). The generic solution to this problem is the use of the same databases used for GIP (eventually upgraded with new experience data) and the development of modified similarity criteria dealing with the following quantities:

- most probable failure modes
- predominant critical frequencies and mode shapes
- critical damping
- main physical equipment characteristics (size, making, centre of gravity, load path, cantilever parts, attached devices…)

As a consequence, GIP equipment classes and caveats have been reviewed by some suppliers of re-evaluation methodologies and minor modifications have been introduced in the similarity criteria ("caveats"):

- to account for specific features of WWER equipment
- to introduce the 12 Hz frequency boundary for use of bounding spectrum.

A comparison of the seismic spectra at 0.3 g with the bounding spectra (GERS) defined at GIP for mast classes is shown in Fig. 3.

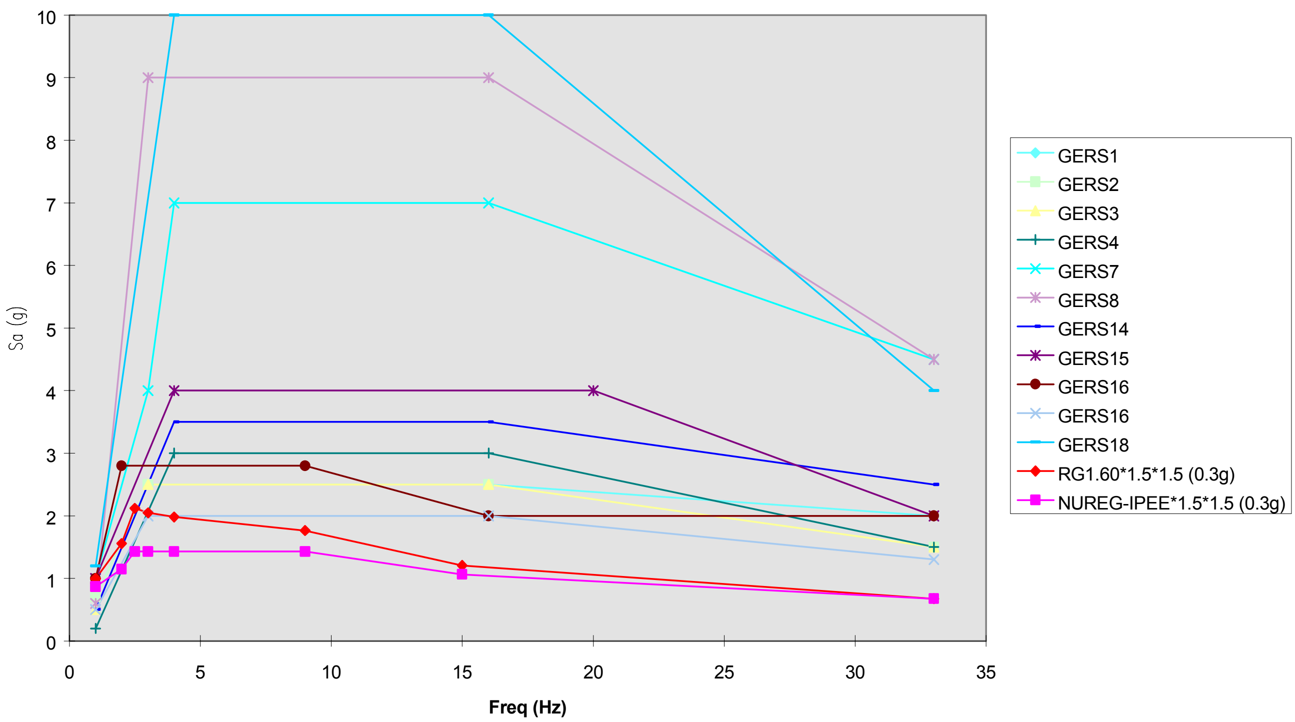


FIG. 3. GIP spectra (5%) – GERS versus demand (0.3g).

2.5. Reference methodologies for indirect qualification of components

Recently, new approaches have been developed for seismic qualification of component, equipment and distribution systems particularly for application to seismic re-evaluation projects in WWER plants and other facilities in US. They are mainly derived from the US practice described in the previous section (even if it was originally developed for totally different purposes) and in some cases they updated the reference databases both for earthquake records and experience data.

For the scope of this report, three of them have been selected for a detailed analysis and comparison, mainly according to the number of applications to the seismic re-evaluation of WWER plants. They also need to represent a sample of the broader choice of available methodologies and therefore their comparison might be extended to other similar approaches. The methods selected for a comparison in this report are:

- **Method 1**: developed by Siemens A.G. [7], mainly applied in Paks NPP, Bohunice-V1 NPP, Kozloduy NPP

- **Method 2**: developed by Stevenson & Associates [8, 9], mainly applied in Paks and Bohunice-V2 NPPs

- **Method 3**: developed by US/Department of Energy (DOE) [10], applied only to DOE facilities and considered as an emerging standard in US

In the rest of the report, reference is made also to the IAEA Technical Guidelines [24–27] and to the original GIP [12] publication for comparison purposes.

In the next sections, the three reference methods identified above are analysed and compared with reference to this general framework.

3. AVAILABLE METHODOLOGIES AND EXPERIENCE FROM THEIR APPLICATION

3.1. Method 1

3.1.1. SSEL list

For the *design of new nuclear plants* the equipment and components should be divided into two classes:

Seismic Class 1 (SC1):
Plant components

- which are required for shutting down the plant safely,
- which are required for maintaining the plant in a shutdown condition,
- which are required for removing the residual heat, the damage or failure of which can cause or result in an accident involving an impermissible release of radioactive materials to the environment,
- which are necessary to prevent an impermissible release of radioactive materials to the environment.

Seismic Class 2 (SC2):
Plant components that are not required to satisfy SC1 safety items.
Interaction between SC2 and SC1 should be considered.

With regard to *seismic re-evaluation* of operating nuclear plants (i.e. older plants the original design of which did not sufficiently account for seismic hazard), it is common practice to define a more liberal set of safety requirements. Based on a minimum set of safety requirements (safety shutdown path) the seismic classification for operating nuclear plants should at least include the following items:

Seismic Class 1 (SC1):
Plant components

- which are required for shutting down the plant safely,
- which are required for maintaining the plant in a shutdown condition for at least 72 hours following an SSE,
- which are required for removing the residual heat for at least 72 hours following an SSE.

SC2 is kept as for the design of new facilities.

3.1.2. Capacity requirements

The objective of the verification of seismic resistance can be one of the following:

- Functional capability,
- Integrity,
- Support stability.

By definition the objective functional capability includes integrity and support stability, whereas integrity covers the item support stability.

Functional capability:

- For the verification of functional capability the capability of fulfilling the required tasks, beyond support stability and integrity, in the case of an earthquake should be demonstrated. For this purpose, deformation restrictions may become necessary.
- With regard to functional capability, a distinction is made as to whether this should be available during or after the earthquake, or during and after the earthquake. In this case, a distinction is made between active and passive functional capability.
  (a) Active functional capability:
  (b) Active functional capability ensures that the specified mechanical movements (relative movement between parts) can be executed (e.g. considering the possibility of a clearance).
  (c) Passive functional capability:
  (d) Passive functional capability means that admissible levels of deformation and displacement are not exceeded and that the function of the component is preserved.
  (e) Active components are those for which mechanical movements are specified for the fulfilment of safety related purposes, e.g. pumps, valves. All other components are passive components, e.g. vessels, tanks, pipes.

Integrity:

- For the verification of integrity it should be shown that the pressure retaining walls resist to an admissible degree all specified pressure and other mechanical loads within the scope of the specified occurrence frequencies and life-time.

Support stability:

- With regard to support stability the position retention (e.g. overturning, falling, excessive displacement, inadmissible slippage) should be verified.

3.1.3. Verification procedures

The following indirect verification methods are applied to prove sufficient ruggedness of equipment and components against seismic loads:

- Analogy-based methods,
- Methods using seismic experience and generic tests (walkdown)

Verification by **analogy** is an indirect method of qualification:

The seismic adequacy of the candidate item is verified by establishing its similarity to a reference item previously qualified by calculation, by test, or by plausibility.

Analogy requires that the seismic input to the reference item equals or exceeds that required for the candidate item. Analogy also requires that the physical and support conditions, the functional characteristics for active items, and the requirements of the candidate item closely resemble those of the reference item.

As an example, analytical verification of a series of similar components is often simplified by selecting the worst case candidate. When verifying seismic adequacy of that candidate, the other components of the series are qualified by analogy.

A special kind of analogy is the investigation of scaled models. With scaled model testing, proper similitude relationship for the component and for the seismic input should be considered.

Verification of seismic adequacy of equipment and components by **walkdown** are mainly based on seismic experience and generic test data. In many cases, walkdown based verification methods are an effective means not only to detect seismic insufficiencies but also to verify seismic adequacy in a quick and economic way. Generally, it should be applied to operating nuclear plants.

Walkdown based verification methods are based either on experience with real earthquakes and generic test series performed with similar items, or on analytic investigations of representative structures, the results of which are adequately condensed and allow an immediate on-site verification of seismic resistance.

Also, walkdowns are necessary to check the as-built situation, the design quality, and the hazard for SC1 components posed by SC2 items (seismic interaction).

Applying seismic experience and generic test data requires that - with regard to seismic excitation - the component in question is effectively enveloped by the database item. It also requires that the component has similar physical characteristics, and that support or anchorage characteristics are comparable. In the case of components which require active functional capability, in general, it is also necessary to show that the items subjected to the earthquake or the test were able to fulfil the required functional capability during or following the seismic excitation.

With regard to the personal qualification requirements, the walkdown team should consist of seismic capability engineers, being specifically trained for application of seismic experience and generic test data.

The Generic Implementation Procedure (GIP) (see Ref. [12] provides a special framework and guidance based on the methodology developed by the SQUG (Seismic Qualification Utility Group) in order to verify the seismic adequacy of existing and already installed equipment required to bring the plant into a safe shutdown condition.

In order to provide a comprehensive tool for qualification of nuclear power plants - especially of WWER NPPs - the GIP equipment classes and items have been extended to appropriate modifications (ModGIP category) and supplements (NonGIP category).

ModGIP may refer to plant-specific topics or to NPP type-specific topics. With reference to the US nuclear power plants, it accounts for deviations in material, design and quality. ModGIP criteria catalogues have been elaborated for

- Anchorage verification,
- Cable tray verification,
- Seismic interaction evaluation.

The criteria are based on simple calculations or on tests, respectively.

NonGIP covers those topics not treated in the GIP. The NonGIP criteria catalogues are elaborated applying simple calculations as well as small computer programmes, taking plant-specific items like seismic excitation for input. NonGIP criteria are presented in

- Piping evaluation guidelines (providing admissible spans, support loads, component nozzle loads[2], displacements[3], and flexibility criteria),
- Piping support criteria catalogues (providing admissible support types and dimension),
- HVAC ducts criteria catalogues (providing admissible spans).

A flow chart showing an example for a walkdown-based evaluation procedure within a seismic re-evaluation programme is given in Figure 4.

3.1.4. Seismic margin assessment

Generally, seismic margin assessment (SMA) answers the question up to which site excitation (zero period excitation, ZPA) a component is verified to fulfil the respective verification objectives. With regard to SMA, a seismic margin earthquake (SME) is specified, which states that for all safety relevant components the seismic adequacy is verified at least up to that SME.

When an SSE has been established for a nuclear plant, and an SMA has been performed for the safety relevant components of that plant, the consequences of an increased seismic hazard can easily be estimated. SMA is useful for new designed nuclear plants as well as for operating nuclear plants, but because of some reasonable probability assumptions the main advantage will be given when applying to operating nuclear plants.

For a new designed nuclear plant, an SMA can be performed as a supplement to the code based design calculations. In addition to the standard verification of seismic resistance of the SC1 components, the seismic capacity usage factor is to be expressed in terms of seismic excitation of the site. The procedure may be described as code based deterministic seismic margin assessment.

For an operating nuclear plant, an SMA may be performed by applying one of the following approaches :

- Seismic probabilistic risk analysis (SPRA)
- Deterministic seismic margin assessment (DSMA)
- High confidence low probability of failure (HCLPF)

[2] Nozzle loads - if significant - are used for evaluating the component anchorage loads.
[3] Displacements are used for checking the piping with regard to flexibility criteria.
Lateral displacements are used for checking sliding guide pipe sup ports with regard to prevent drop down of the pipe, as well as for checking seismic interaction items.

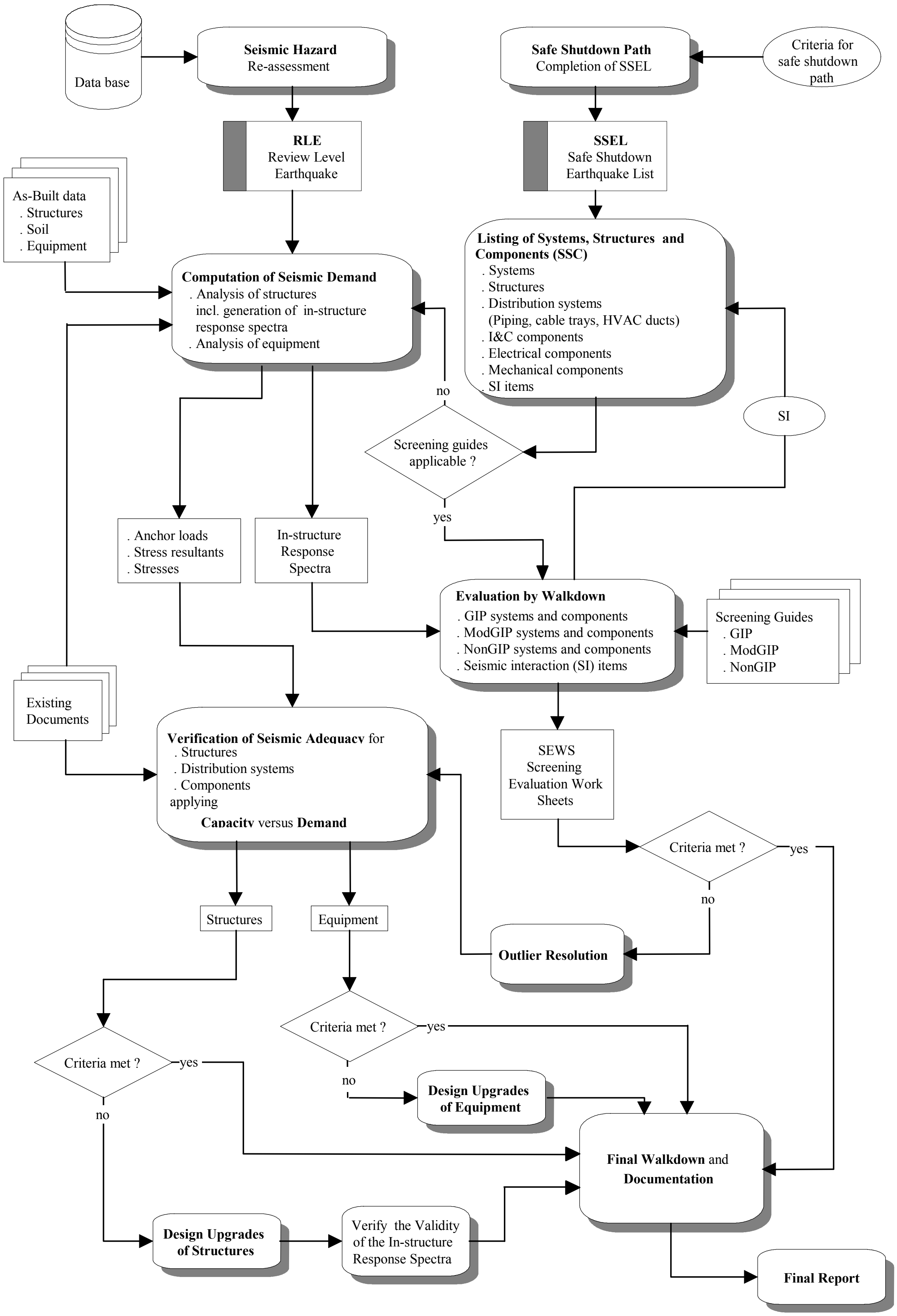


FIG. 4. Walkdown-based screening procedure within a seismic re-evaluation programme.

With reference to [11], application of HCLPF approach is recommended, which is a reasonable compromise between SPRA and DSMA approach.

For evaluating HCLPF values, two approaches may be selected, i. e.

- the fragility analysis (FA) approach, and
- the conservative deterministic failure margin (CDFM) approach.

Application of the latter one is recommended in [11].

In the following, the main aspects of the HCLPF/CDFM approach are presented:

- The seismic classification will meet the minimum set of requirements (safety shut down, shut down condition and heat removal for at least 72 hours).
- The referring set of components is called a ‘success path’. At least two different success paths are to be accounted for.
- A seismic margin earthquake (SME) will be conservatively specified which will be referred to in the seismic margin review. Normally, the SME will exceed the SSE.
- Screening guidelines are to be established. These guidelines will be used to screen out those components from the seismic margin review, which are rugged to withstand the SME.
- The SME loads will be combined with normal operating loads (NOL).
- For the predicted structural and equipment response to the SME approximately 84% non-exceedance probability (NEP) (median values for damping, ductility, parameters for evaluation of in structure response spectra).
- The capacity assessment for a given response will have an exceedance probability of about 95% (conservative material strength parameters).
- The seismic margin capability of the success paths (expressed in terms of HCLPF) is then equal to the seismic margin capability of the weakest of the highest capacity success path.

3.1.5. Similarity criteria

When performing a seismic verification based on analogy, seismic experience or generic test data, there is a generic problem: how to assess deviations between the component to be qualified and the reference item. A case by case approach is performed taking into account the fundamental design data and their effect on seismic responses. In the Generic Implementation Procedure (GIP, see Ref. [12]), the problem has been solved by covering a series of items for each of the generic components (e.g. pumps), by accounting for a large range of geometric measure, flow rate, power rate. In the following, basics of similitude theory are presented, and an application to seismic verification of mechanical components is given. Theoretical basics are taken from [32].

In general, similitude means that with reference to at least one physical quantity the ratio of a reference component (index 0) and a component in question (index 1) will remain constant (i.e. invariant). For example, geometric similitude is given if

$$\varphi_L = L_{(1)}/L_{(0))}$$

remains invariant for all the geometric measures. In an analogous way, it is possible to define invariant ratios with regard to the quantities of time, forces, electricity, temperature, and others. If there is more than one ratio coincidentally invariant, this leads to special cases of similitude. So, for example, static similitude means invariance of geometric and force ratios (φ_L, φ_F), and kinematic similitude represents invariance of geometric and time ratios (φ_L, φ_t). The very important dynamic similitude (invariance of geometric, time and force ratios (φ_L, φ_t, φ_F)) concerns forces related to their origin.

For easy handling of those combined similitude ratios, sets of characteristic numbers have been developed, the most known of them is the Reynolds number, which states the invariance of inertia forces and friction forces in a moving fluid. For application to mechanical components, suitable characteristic numbers are defined. Marking by NN those states where no specific designation exists in the literature relevant to the subject.

Using the following abbreviations:

L = quantity of length
t = quantity of time
v = quantity of velocity
a = quantity of acceleration
F = quantity of force
ρ = quantity of density
E = quantity of modulus of elasticity

the basic ratios of similitude may be given as follows:

Static similitude (φ_L, φ_F):

Hooke: $Ho = F / (E * L^2)$
(related elastic force)

Dynamic similitude (φ_L, φ_t, φ_F):

Newton : $Ne = F / (\rho * v^2 * L^2)$
(related inertia force due to component related *internal* acceleration, i. e. $a = L / t^2$)

NN : $Nn = F / (\rho * a * L^3)$
(related inertia force due to component non-related *external* acceleration, e.g. acceleration due to gravity, or floor acceleration)

Using these basic ratios other similitude ratios can be derived:

Cauchy: $Ca = Ho / Ne$
$= \rho * v^2 / E$
(*internal* inertia force related to elastic force)

NN: $Cn = Ho / Nn$
$= \rho * a * L / E$
(*external* inertia force related to elastic force)

All of them are non-dimensional numbers.

In order to simplify the relationships, the components (0) and (1) can be assumed to be made of comparable material (e.g. ductile ferritic steel), i. e.

$$\varphi_E = \varphi_\rho = 1 ,$$

so with reference to Ca this gives

$$\begin{aligned} \varphi_{Ca} &= \varphi_\rho * \varphi_v^2 / \varphi_E \\ &= \varphi_v^2 \\ &= 1 \end{aligned}$$

i. e. $\varphi_t = \varphi_L$,

and with reference to Cn

$$\begin{aligned} \varphi_{Cn} &= \varphi_\rho * \varphi_a * \varphi_L / \varphi_E \\ &= \varphi_a * \varphi_L \\ &= 1 \end{aligned}$$

i. e. $\varphi_a = \varphi_L^{-1}$.

If *geometric similitude* is given, for quantities caused by *internal* inertia forces the following relationship can be stated:

Natural frequency	φ_L^{-1}
Stresses, strains	φ_L^{0}
Forces	φ_L^{+2}
Masses, weights	φ_L^{+3}

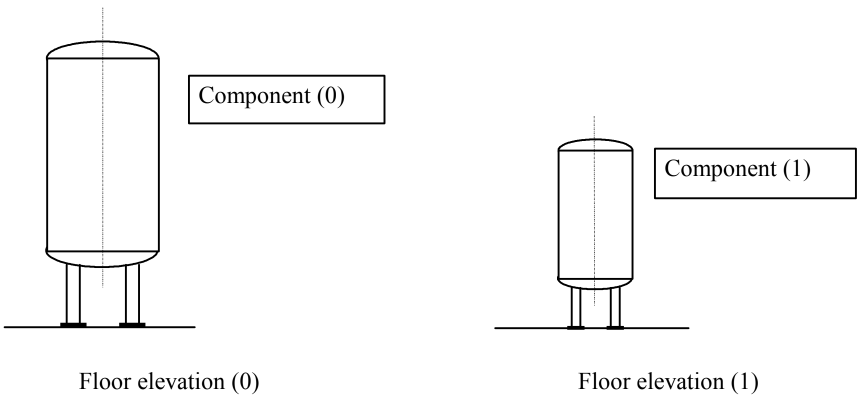
For quantities caused by *external* inertia forces (e.g. caused by acceleration of gravity, seismic acceleration) the following relationship can be stated:

Stresses, strains	$\varphi_L^{+1} * \varphi_a^{+1}$
Forces	$\varphi_L^{+3} * \varphi_a^{+1}$

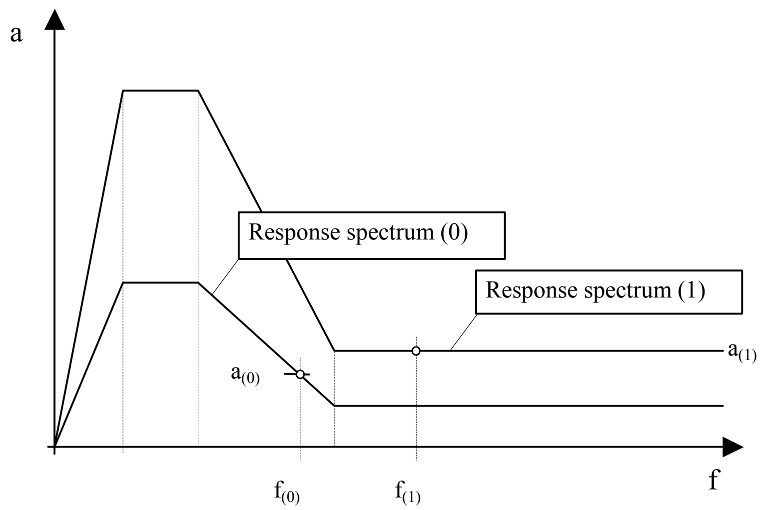
The application of the relationships derived above are demonstrated by the example of Fig. 5.

A component to be qualified (index 1) should have 2/3 the geometric dimensions than the reference component (index 0), i. e. $\varphi_L = 2/3$. The components are anchored on different building floor elevations (0) and (1), the floor response spectra (0) and (1) have been generated for. Then the fundamental natural frequency of the candidate item can be evaluated by

$$\begin{aligned} f_{(1)} &= \varphi_L^{-1} * f_{(0)} \\ &= 3/2 * f_{(0)} . \end{aligned}$$



a) Similar components (0) and (1), geometric similitude $\varphi_L = 2/3$.



b) Response spectra at floor (0) and (1), seismic acceleration similitude $\varphi_a = 4/3$.

FIG. 5. Example for the application of similitude laws

With $f_{(1)}$ the appropriate seismic acceleration $a_{(1)}$ can be determined using the appropri-ate floor response spectrum. Corresponding to the higher floor elevation (1), let us as-sume $a_{(1)}$ to be 4/3 times $a_{(0)}$ (e.g. $a_{(0)} = 6.0$ m/s^2 and $a_{(1)} = 8.0$ m/s^2), i. e. $\varphi_a = 4/3$. Then the seismically induced stress of the component may be evaluated as

$$\begin{aligned}
\sigma_{(1)} &= \varphi_\sigma * \sigma_{(0)} \\
&= \varphi_L * \varphi_a * \sigma_{(0)} \\
&= 2/3 * 4/3 * \sigma_{(0)} \\
\sigma_{(1)} &= 0.89 * \sigma_{(0)} \ .
\end{aligned}$$

Provided that the seismic resistance of the reference component (0) has been verified by means of analysis, test, analogy, or by using seismic experience and generic test data (frequency estimation included), then the seismic adequacy of the component (1) is demonstrated by applying the similitude laws.

3.2. Method 2

3.2.1. Introduction

The modified GIP [8, 9] titled as GIP-WWER can be used to verify seismic adequacy of the safe shutdown mechanical, electrical equipment and distribution systems of operating or constructed WWER-type NPPs, namely WWER-440/213 and 1000 type NPPs.

The procedure GIP-WWER was developed using the following background:

- public available information contained in SSRAP, GIP, U.S. DOE, LLNL and MCEER documents [12, 15, 33, 34, 35],
- information extracted from the documents prepared in a frame of the IAEA Benchmark Study for the Seismic Analysis and Testing of WWER-Type Nuclear Power Plants [36],
- information extracted form the results of available seismic tests performed mostly in Czech Republic during the last about 15 years and collected systematically and studied by S&A-CZ,
- experience taken from various many seismic walkdowns, evaluations and analyses of WWER-type NPPs equipment performed by S&A-CZ during the last eight years for these NPPs located in Czech, Slovakia and Hungary,
- information extracted from scientific papers and documents [37–43].

The scope of equipment covered by the current version of the GIP-WWER procedure includes the original GIP twenty classes of mechanical and electrical equipment [8, 9].

Western European and particularly WWER-type relays, switches, transmitters and electric penetrations (class 21 and 22) are significantly different from those included into the original GIP databases. These classes of equipment are not included into the GIP-WWER procedure and their seismic verification should be based on testing. In addition to the twenty classes of GIP, the GIP-WWER procedure also includes guidelines for simplified analytical seismic evaluation of the following classes of equipment:

(23) Cable supporting structures (based mainly on the EPRI methodology [44]) ,
(24) Tanks, heat exchanger, filters (based mainly on the documents [45, 46]).
(25) Pipelines and HVAC ducts (based on the public available documents [47-50].

GIP-WWER also includes two special guidelines to verify adequacy of anchorage and seismic adequacy of non-bearing masonry walls. A summary of GIP-WWER equipment classes and guidelines is given in Table III.

3.2.2. General description of GIP-WWER in relation to twenty main equipment classes

As shown in Figure 6, GIP-WWER is primarily a screening and walkdown procedure. However, if a safe shutdown equipment item is classified as an outlier, rigorous approaches as testing on shaking table, deep study of input data, sophisticated analysis, etc, may be used to verify its seismic adequacy. Generally, the four major steps of this GIP-WWER procedure are as follows:

- selection of Seismic Review Team (SRT),
- identification of safe shutdown equipment,
- screening verification and walkdowns,
- outlier identification and resolution.

TABLE III. SUMMARY OF GIP-WWER EQUIPMENT CLASSES

Equipment Class	Data and Documents Available for Seismic Verification [1, 2, 3, 4)]
20 Main Classes	
1. Motor Control Centres	BS (0.33 g), User Manual and SEWS / SVDS
2. Low Voltage Switchgears	BS (0.33 g), User Manual and SEWS / SVDS
3. Medium Voltage Switchgears	BS (0.33 g), User Manual and SEWS / SVDS
4. Transformers	BS (0.33 g), User Manual and SEWS / SVDS
5. Horizontal Pumps	BS (0.50 g), User Manual and SEWS / SVDS
6. Vertical Pumps	BS (0.33 g), User Manual and SEWS / SVDS
7. Fluid-Operated Valves	BS (0.50 g), User Manual and SEWS / SVDS
8. Motor-Operated and Solenoid-Operated Valves	BS (0.50 g), User Manual and SEWS / SVDS
9. Fans	BS (0.33 g), User Manual and SEWS / SVDS
10. Air Handlers	BS (0.33 g), User Manual and SEWS / SVDS
11. Chillers	BS (0.50 g), User Manual and SEWS / SVDS
12. Air Compressors	BS (0.50 g), User Manual and SEWS / SVDS
13. Motor Generators	BS (0.50 g), User Manual and SEWS / SVDS
14. Distribution Panels	BS (0.50 g), User Manual and SEWS / SVDS
15. Batteries on Racks	BS (0.33 g), User Manual and SEWS / SVDS
16. Battery Chargers and Inverters	BS (0.33 g), User Manual and SEWS / SVDS
17. Engine Generators	BS (0.50 g), User Manual and SEWS / SVDS
18. Instrument Racks	BS (0.33 g), User Manual and SEWS / SVDS
19. Temperature Sensors	BS (0.33 g), User Manual and SEWS / SVDS
20. I&C Panels and Cabinets	BS (0.33 g), User Manual and SEWS / SVDS
B. *Additional Classes*	
21. Relays, Switches, Transmitters, Solenoids, Sensors	not applicable for WWER-type equipment
22. Electrical Penetration Assemblies	not applicable for WWER-type equipment
C. *Special Approaches*	
23. Cable Supporting Structures	User Manual and SWS / SVDS
23. Tanks, Heat Exchangers and Filters	User Manual and SWS / SVDS
25. Pipes and HVAC Ducts	User Manual and SWS / SVDS
D. *Special Guidelines*	
Adequacy of Equipment Anchorage	User Manual
Seismic Adequacy of Non-Bearing Masonry Walls	User Manual

Note: (1) BS = Bounding Spectrum,
BS (0.33 g) is the same as introduced by SSRAP and used by GIP [7, 8],
BS (0.50 g) = 1.5 times BS (0.33 g).
(2) SEWS = Seismic Evaluation Work Sheet,
(3) SVDS = Seismic Verification Data Sheet,
(4) SWS = Seismic Walkdown Sheet

The engineering judgment is the major tool used by SRT during the screening verification and walkdowns to evaluate seismic adequacy of the equipment. The SRT normally includes system engineers, plant operation personnel, experienced and professionally trained seismic capacity engineers, as well as other personnel to identify and evaluate essential relays (if necessary).

The basic criteria to verify seismic adequacy of an equipment item during the screening walkdown are (see also Figure 6):

- **seismic capacity greater than seismic demand** (by comparison of the corresponding $ISRS_{SSE}$ or GRS_{SSE} to the Bounding Spectrum (Fig. 7, Table IV),
- **similarity** to the equipment in the seismic experience databases (checking of caveats, based on walkdowns and information available from documentation),
- adequate **anchorage** of equipment (calculations or engineering judgment, based on walkdowns and information available from documentation),
- potential seismic **interactions** evaluated (based on walkdowns).

The GIP-WWER procedure uses two bounding spectra (BS):

(a) BS attached to PGA = 0.33 g (the same as introduced by SSRAP and used by GIP),
(b) BS attached to PGA = 0.50 g (1.5 times SSRAP BS) for selected WWER equipment classes, which are evidently robust and rugged (Fig. 7).

The following sheets are used for seismic verification and walkdowns:

- *Screening Verification Data Sheet* (SVDS) in which an each equipment component or distribution line to be evaluated is identified simply by a single live item (used by the most experienced experts when all important factors relating to seismic adequacy are evidently obvious),

- *Seismic Evaluation Work Sheet* (SEWS) for more detail seismic verification of individual equipment component items or distribution lines,

- *Seismic Walkdown Sheet* (SWS) for equipment component items and distribution lines verified by analysis to check their proper performance in accordance with documentation, their anchorage adequacy, absence of potential seismic interactions and other aspects of their seismic resistance.

There is also another sheet titled as *Outlier Seismic Verification Sheet* (OSVS) in which the discovered outlier issues and proposed methods for their resolution are described. The form of this sheet is more or less free.

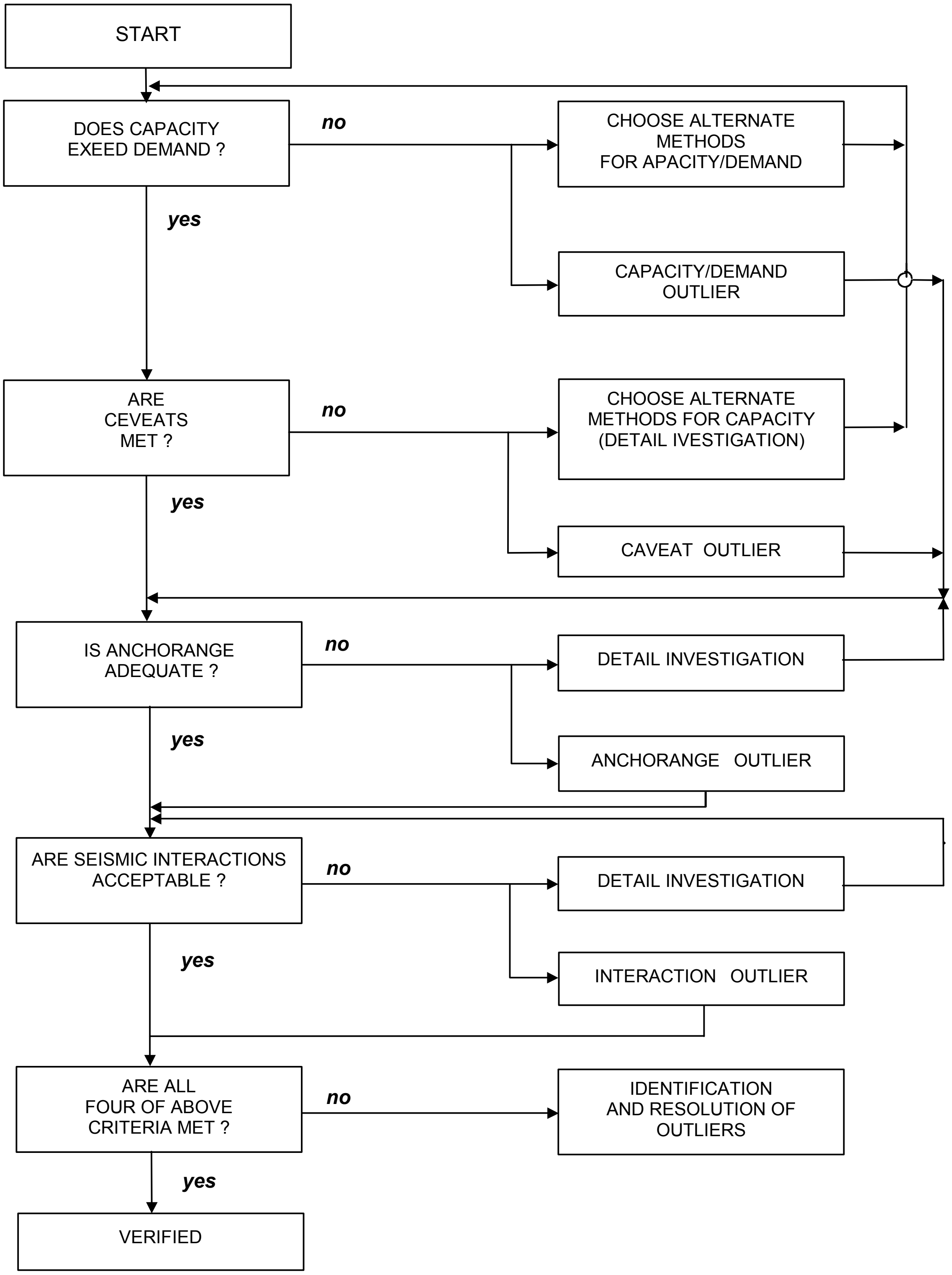


FIG. 6. Screening Verification and Walkdown Procedure GIP-WWER.

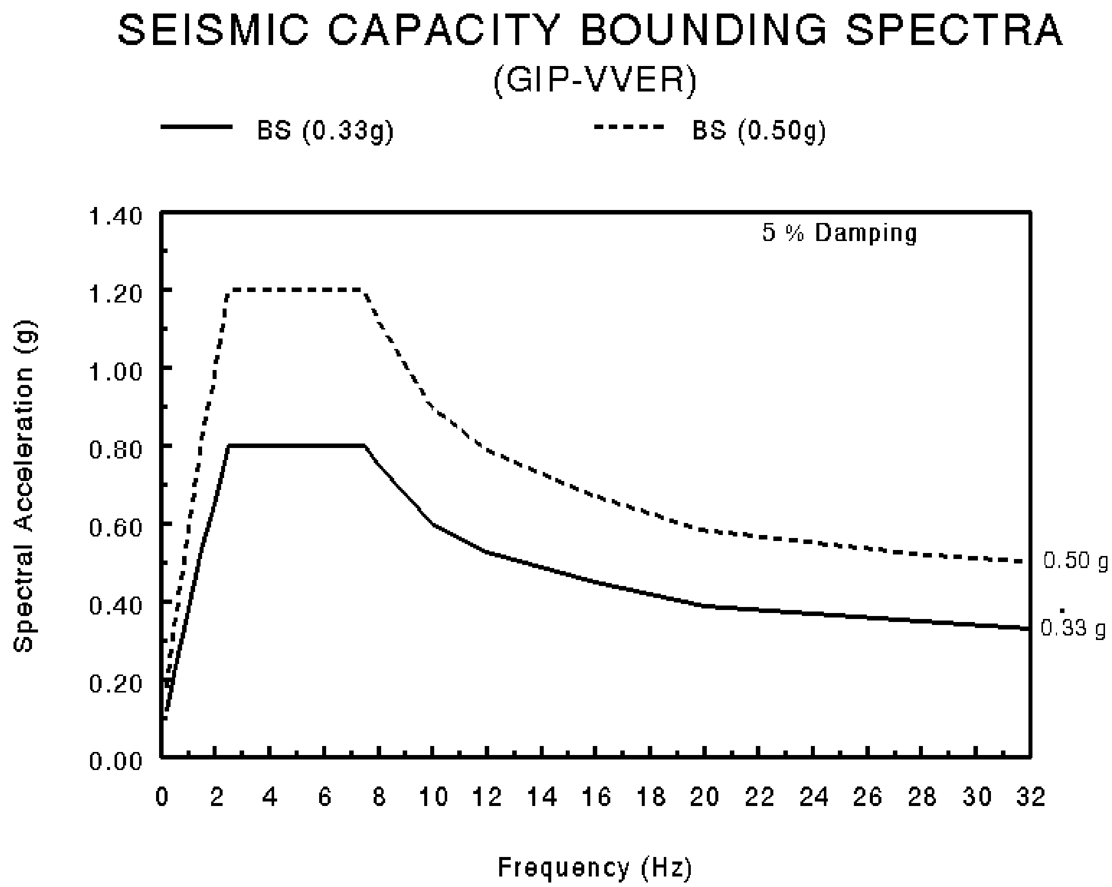


FIG. 7. GIP-WWER seismic capacity bounding spectra.

In general, the seismic capacity spectrum as defined in Fig. 7 (BS or 1.5 times BS attached to PGA = 0.33 g or 0.50 g) envelops the seismic demand spectrum (GRS or ISRS as done or calculated for the prescribed RLE (SL2, SSE)). Nevertheless, the seismic capacity needs only to envelop the seismic demand spectrum for frequencies at and above the conservatively estimated lowest natural frequency of the equipment item to be evaluated. Also narrow peaks in the seismic demand spectrum may exceed the seismic capacity spectrum under the conditions specified in the corresponding user manual.

It should also be noted that it is allowed to use seismic demand spectra without broadening for this comparison, however when doing so, uncertainty in the natural frequency of the building structure should be taken into account by corresponding shifting of the seismic demand spectrum at these peaks.

TABLE IV. CRITERIA OF COMPARISON SEISMIC CAPACITY TO SEISMIC DEMAND[(1)]

A. Comparison with RLE (SL2, SSE) Ground Response Spectra (GRS) [2)]

This can be used when the equipment item is mounted below about 12 m above the effective grade and when the natural frequency of equipment is greater than 12 Hz [3)]

$BS \geq GRS_{RLE\ (SL2,SSE)}$ (5% damping) [4)]

B. Comparison with RLE (SL2, SSE) In-Structure Response Spectra (ISRS)

1.5 x BS ≥ realistic (median, mean, best estimated) $ISRS_{RLE\ (SL2,SSE)}$ (5% damping) [4)]

Notes: (1) Apply at least one of these two rules, which applicable.
(2) The criterion A can be used only with the well rigid building structures as the lower concrete parts of the WWER-440 reactor building, the WWER-1000 reactor building, the WWER–1000 diesel-generator buildings etc. Do not use this criterion with such flexible building structures as the longitudinal and transversal galleries of the WWER–440 reactor buildings, the WWER-440 and also WWER-1000 auxiliary buildings, the WWER-440 diesel-generator buildings etc.
(3) Do not apply the 12 Hz limit for equipment mounted on piping systems (valves, valve operators etc.).
(4) These criteria should be met for all three orthogonal spatial directions.

3.2.3. Similarity of WWER-type equipment with equipment included in the SQUG databases — Principles

Similarity of WWER-type equipment to equipment included in the SQUG databases [37] is the most important keystone of practical application of the GIP-WWER procedure. Generally, the principle of similarity is based upon comparison of equipment dynamic and its most important physical characteristics [38]. The comparison uses the following definitions to categorize different items or aspects.

There are several possible results from such a comparison:

Critical device	A safety related device whose malfunction produces the lowest possible fragility level of excitation for an equipment item.
Device	A secondary component attached to a primary equipment structure.
Physically similar equipment	Different equipment items whose dynamic response and functional (operational) characteristics are approximately equal within a specific frequency range, or equipment whose fragility functions are nearly equal in the most sensitive frequency domain.

Critical frequency	Frequency at which the peak value of the primary equipment structural response related directly to the malfunction of the equipment occurs.
Critical mode	Mode for which the peak value of the primary equipment structural_response related directly to the malfunction of the equipment occurs.
Critical equipment damping	Damping ratio for critical mode of equipment item.

The procedure for establishing similarity within each equipment class includes comparison of the following:

- most probable modes of malfunction
- (based on recognized behaviour of all equipment critical devices) ,
- predominant resonant and critical frequencies and mode shapes,
- critical damping,
- most important physical equipment characteristics
  - equipment size, mass and position (vertical, horizontal, inclined etc.),
  - general making, quality of making, age of equipment,
  - location of the centre of gravity, presence and location of cantilevered parts,
  - implementation of heavy and / or moving internal parts,
  - implementation of supports and anchorage,
  - implementation of attached lines, substructures, devices etc.
  - presence of devices (mechanical or electrical) sensitive to vibrations and shocks.

3.2.4. Similarity of WWER-440/213 type equipment with equipment included in the SQUG databases — Results of investigation

Class 1 Motor Control Centres (MCC)

The WWER-type MCCs are generally similar to those included in the corresponding SQUG database. The GIP-WWER caveats for this equipment class are almost the same or only formally modified in comparison to the original SQUG-GIP caveats. One important caveat was stiffened up, which means that that the first conservatively estimated natural frequency of a fully equipped MCC cabinet should be higher than 12 Hz (not 8 Hz as requested by SQUG-GIP).

Class 2 Low Voltage Switchgears (LVS)

The WWER-type LVSs are generally similar to those included in the corresponding SQUG database. The GIP-WWER caveats for this equipment class are almost the same or only formally modified in comparison to the original SQUG-GIP caveats. There is only one additional requirement that the first conservatively estimated natural frequency of such a fully equipped LVS cabinet should be higher than 12 Hz (similarly as required for MCCs).

Class 3 Medium Voltage Switchgears (MVS)

The WWER-type MVSs are generally similar to those included in the corresponding SQUG database. The GIP-WWER caveats for this equipment class are almost the same or only formally modified in comparison to the original SQUG-GIP caveats.

Class 4 Transformers (TRN)

The WWER-type TRNs are generally similar to those included in the corresponding SQUG database. The GIP-WWER caveats for this equipment class are almost the same or only formally modified in comparison to the original SQUG-GIP caveats. There is only one additional requirement that the base isolators under the TRN internals should be checked against seismic effects, particularly in both horizontal directions and improved by restraints if necessary.

Class 5 Horizontal Pumps (HP)

The WWER-type HPs are generally similar to those included in the corresponding SQUG database. The GIP-WWER caveats for this equipment class are almost the same or only formally modified in comparison to the original SQUG-GIP caveats. It is usually necessary with WWER-type HPs to provide a separate verification of seismic adequacy of nozzles, namely when they are flange-type and when the size of the attached line is reduced just near the nozzle which is typical for many of WWER-type HPs.

Class 6 Vertical Pumps (VP)

The WWER-type VPs are generally similar to those included in the corresponding SQUG database. The GIP-WWER caveats for this equipment class are almost the same or only formally modified in comparison to the original SQUG-GIP caveats.

Class 7 Fluid-Operated Valves (FOV)

The WWER-type FOVs are generally similar to those included in the corresponding SQUG database. The GIP-WWER caveats for this equipment class are almost the same or only formally modified in comparison to the original SQUG-GIP caveats. One caveat related to nearby local air tanks (if any) has been added.

Class 8 Motor-Operated Valves (MOV) and Solenoid-Operated Valves (SOV)

The WWER-type MOVs and SOVs are generally similar to those included in the corresponding SQUG database. The GIP-WWER caveats for this equipment class are almost the same or only formally modified in comparison to the original SQUG-GIP caveats. Two caveats related to MOVs with remotely located operators and presence of sensitive actuating relays have been added.

Class 9 Fans (FAN)

The WWER-type FANs are generally similar to those included in the corresponding SQUG database. The GIP-WWER caveats for this equipment class are almost the same or only formally modified in comparison to the original SQUG-GIP caveats.

Class 10 Air Handlers (AH)

The WWER-type AHs are generally similar to those included in the corresponding SQUG database. The GIP-WWER caveats for this equipment class are almost the same or only formally modified in comparison to the original SQUG-GIP caveats.

Class 11 Chillers (CHL)

Investigation of similarity for this class of equipment is not finished yet. CHLs do not occur on WWER-440 NPPs.

Class 12 Air Compressors (AC)

Investigation of similarity for this class of equipment is not finished yet. It is typical for almost all WWER-type NPPs that diaphragm fluid operated valves are manipulated by air from local nearby pressure air tanks the capacity of which is enough at least for 5-10 open-close operations. Also all emergency engine-generators are equipped by pressure air tanks to provide their start. It means that in such cases air compressors need not to be operational during and after an earthquake.

Class 13 Motor Generators (MG)

The WWER-type EGs are generally similar to those included in the corresponding SQUG database. The GIP-WWER caveats for this equipment class are almost the same or only formally modified in comparison to the original SQUG-GIP caveats.

Class 14 Distribution Panels (DP)

The WWER-type DPs are generally similar to those included in the corresponding SQUG database. The GIP-WWER caveats for this equipment class are almost the same or only formally modified in comparison to the original SQUG-GIP caveats. There is only one additional requirement that the first conservatively estimated natural frequency of a fully equipped switchboard cabinet should be higher than 12 Hz (similarly as required for LVSs).

Class 15 Batteries on Racks (BAT)

The WWER-type BATs are generally similar to those included in the corresponding SQUG database. The GIP-WWER caveats for this equipment class are almost the same or only formally modified in comparison to the original SQUG-GIP caveats.

Class 16 Battery Chargers and Inverters (BCI)

The WWER-type BCIs are generally similar to those included in the corresponding SQUG database. The GIP-WWER caveats for this equipment class are almost the same or only formally modified in comparison to the original SQUG-GIP caveats. There is only one additional requirement that the first conservatively estimated natural frequency of such a fully equipped BCI cabinet should be higher than 12 Hz (similarly as required for MCCs and LVSs).

Class 17 Engine Generators (EG)

The WWER-type EGs are generally similar to those included in the corresponding SQUG database. The GIP-WWER caveats for this equipment class are almost the same or only formally modified in comparison to the original SQUG-GIP caveats.

Class 18 Instruments on Racks (IR)

The WWER-type IRs are generally similar to those included in the corresponding SQUG database. The GIP-WWER caveats for this equipment class are almost the same or only formally modified in comparison to the original SQUG-GIP caveats. One important caveat was stiffened up, which means that that the first conservatively estimated natural frequency of a fully equipped IR should be higher than 12 Hz (not 8 Hz as requested by SQUG-GIP).

Class 19 Temperature Sensors (TS)

The WWER-type TSs are generally similar to those included in the corresponding SQUG database. The GIP-WWER caveats for this equipment class are practically the same in comparison to those as given in the original SQUG-GIP.

Class 20 I&C Panels and Cabinets (I&C)

The WWER-type I&Cs are generally similar to those included in the corresponding SQUG database. The GIP-WWER caveats for this equipment class are almost the same or only formally modified in comparison to the original SQUG-GIP caveats. There is only one additional requirement that the first conservatively estimated natural frequency of such a fully equipped I&C cabinet or panel should be higher than 12 Hz (similarly as required for MCCs and LVSs).

3.2.5. Seismic interactions

Seismic interactions are physical interactions of any structures, distribution systems or mechanical or electrical components with nearby items of safety related structural systems or equipment components caused by an earthquake. An inspection has to be performed in the area adjacent to and surrounding safety related structures, distribution systems and equipment components to identify any seismic interactions that could adversely affect their capability to withstand earthquake effects.

The four seismic interaction effects that are considered are:

- *proximity* (impacts of adjacent equipment or structures on safety related equipment due to their relative motion during an earthquake),
- *structural failure and falling* of overhead or adjacent structures, systems, or equipment components,
- *flexibility of attached lines and cables*,
- *flooding* due to earthquake induced failures of tanks or vessels.

Interaction examples typical for WWER-type NPPs are as follows:

- unreinforced masonry walls adjacent to safety related equipment may fall and impact safety related equipment or cause loss of support of such equipment,

- fire extinguishers may fall and impact or roll into safety related equipment,
- inadequately anchored or braced equipment as vessels, tanks, heat exchangers, cabinets etc. may overturn, slide and impact adjacent safety related equipment,
- equipment carts, chains, air bottles, welding equipment etc. may roll into, slide, overturn, or otherwise impact safety related equipment,
- storage cabinets, office cabinets, files, bookcases etc. located, for instance in control rooms, may fall and impact adjacent safety related equipment,
- too flexible piping, cable trays, conduits, and HVAC ducts may deflect and impact adjacent safety related equipment,
- anchor movement may cause breaks in nearby piping, cable trays, conduits, HVAC ducts etc. that may fall or deflect and impact adjacent safety related equipment,
- emergency lights and lower ceiling panels can fall down and damage safety related equipment,
- free crane hooks by bang safety related equipment in their vicinity.

3.2.6. Feedback from the experience

Based on experience from several seismic walkdowns performed during the last five years on the WWER-type NPPs, it may be concluded that the main problems related to seismic adequacy of their mechanical equipment components that may occur are:

- missing or non-proper anchorage of components, missing anchor bolts, non-proper tightening of anchor bolts,
- large seismic nozzle loads due to long unsupported attached pipes,
- large valve operator cantilever length (special investigation requested),
- motor operated valves with drivers in remote locations (Cardan-type connection should be evaluated),
- missing or non-properly performed pipe and duct supports,
- additional pipe restraints (f.e. application of viscous dampers for large hot pipe systems)
- replacement of brittle elements (e.g., glass level indicators, etc.),
- inadequate base isolation,
- large and high vertical flat-bottom tanks without any positive anchorage
- large flat-bottom tanks free standing on the special supporting grid and liner (no anchorage, only friction, additional anchorage almost impossible)
- concrete pedestals under large horizontal tanks and heat exchanger (no information available about their reinforcement and anchorage to the structure under them),
- potential seismic interactions.

For electrical and I&C equipment components the main problems related to their seismic adequacy are:

- missing or non-proper anchorage of components, missing bolts, nuts and screws, non-proper tightening of anchor bolts,
- seismic functionality of relays, switches and similar items should be verified by seismic tests performed as usually separately from the supporting cabinets or panel,
- determination of in-cabinet seismic response spectra necessary for separate verification of internal items,

- fixation of internal drawers, relays, switches, sensors and similar items to the cabinet or panel structure is often weak,
- original accumulator batteries should be replaced,
- overloaded or not-properly anchored cable structures
- potential seismic interaction.

The GIP-WWER screening criteria have to be used with caution. The seismic capability engineers exercise sound engineering judgment during the screening walkdown and verification. Also a summary of all available seismic design and qualification data is prepared and provided to the experts before the walkdown.

3.2.7. Development of test and seismic experience databases

3.2.7.1. Background

The application of GIP database and relevant caveats to the seismic qualification of WWER components requested some dedicated studies, mainly carried out under the IAEA co-ordinated programmes. The most representative is [36].

The following similarity between WWER-440/213 type equipment and SQUG database was found [51]:

pumps, valves (with some exceptions)	up to 100%
motor control centres, switchgears	about 50%
HVAC equipment	about 90%
transformers	about 80%
diesel generators	up to 100%
distribution panels, cabinets	about 80%
batteries	about 80%
relays, switches, transmitters	low
cable trays	about 80%
tanks, heat exchangers, ducts, pipes	up to 100%

anchorage details are similar with several specific exclusions.

Therefore, in order to develop new caveats for the WWER type equipment, new test and experience database were developed to be applied to the items not qualified by GIP. Seismic experience database complemented with a FRS database can now provide background for fragility parameters evaluation to be used also in both SMA and SPRA applications for the same classes of equipment where GIP is not applicable.

3.2.7.2. Test database

Test data has been collected from EUROTEST - an authorized laboratory for seismic and environmental qualification of safety related nuclear equipment and components. Test data includes 123 items (mechanical and electrical equipment) and for 30 items full test reports are available. Detailed information concerning test data is presented in Ref. [9]. Other test data were collected from the available experience in WWER operating countries, mainly through the IAEA Co-ordinated research programme [36]

3.2.7.3. Seismic experience database

Experience data has been collected mainly from two power plants: Bucharest West and Bucharest South. Damage reports during the last three Vrancea earthquakes and seismic behavior include 332 items of mechanical equipment and 129 electrical equipment. Detailed information concerning seismic experience data is presented in Ref. [9]. The items of interest are the following:

Mechanical equipment:

10 heat exchangers (high pressure)
10 condenser cooler
44 Fans
18 feed water horizontal pumps
20 cooling water vertical pumps
40 air compressors
42 diesel generators
49 hot piping systems
49 heat water piping systems
24 isolation valves (manual operating)
26 valves (electric drive mechanism)

Electric equipment:

13 electrical panels
4 oil transformers 13.8 Kv
4 transformers 110/6 Kv, 26 MVA
4 transformers 1000 KVa
22 batery raks
17 electric cabinets
18 control panels
23 cable trays
24 Switchgear

The ground acceleration ranges between 0.1 to 0.22g for the Bucharest sites. The seismic motion parameters for the sites for 1977, 1986 and 1990 seismic events are given in Ref [9]. Other sites with ZPGA ranging from 0.17 to 0.4 g (close to the epicentre area are under investigation).

In order to provide homogeneous data to the database, these experience data from these two plants in Romania have been processed. In particular, the free field ground motion of the two sites for the recent Vrancea earthquakes is not available and therefore some complicated processing had to be carried out with a complete simulation of the propagation, attenuation and local amplification at the sites from the epicentre.

182 seismic events with M > 5, starting with year 984 to 1900 have been processed. The instrumental data catalogue covers this century (1901 to 1994) and includes 103 seismic events with magnitude M > 5. Also 137 seismic records from the last three Vrancea Earthquakes (1977, 1986 and 1990) have been processed. Detailed information concerning seismic hazard of the Vrancea earthquakes is presented in Ref. [9].

3.2.7.4. Equipment fragilities to be used in SMA and PSA

The probabilistic based FRS are useful also to derive the more detailed fragility information needed for SMA and PSA. The proposed approach is based on Reed and Kennedy method [52].

The seismic fragility of a structure or equipment item is the conditional probability of failure under a given level of seismic loading. Failure occurs when the component item fails to perform its intended function. The seismic loading is defined in terms of acceleration, such as zero peak ground acceleration (ZPGA) for sites, floor acceleration (ZPA) or spectral acceleration Sa.

The objective of the fragility evaluation is to estimate the capacity of a given component relative to the ground motion acceleration parameter such as ZPGA acceleration. A family of fragility curves can represent the capacity. Each curve represents a confidence level. The mean fragility is the average of the all-possible curves.

The acceleration capacity is given by:

$$A = A_m \varepsilon_R \varepsilon_U$$

In which A_m is the median capacity and ε_R and ε_U are random variables with unit medians, representing respectively the inherent randomness about the median and the uncertainty in the median value. We assumed that both ε_R and ε_U are log-normal distributed with logarithmic standard deviations β_R and β_U respectively.

The variables A_m, β_R and β_U determine a family of fragility curves representing various levels of confidence.

Of particular interest is the point on the 95% confidence curve that corresponds to a 5% probability of failure. This point commonly referred to as the High Confidence of a Low Probability of Failure (HCLPF) value:

$$HCLPF = A_m e^{-1.65(\beta_R + \beta_U)}$$

The evaluation of the seismic fragility of a component can be carried out *based on seismic experience data*. The database of experience data was also used for such application.

Given the random sample of PGAs the reliability function could be estimated by noting the percentage of sample, which survives a given PGA. The independent variable, PGA, is defined in intervals. The sample population within interval *i*, n_i, is the number of equipment items experiencing a PGA falling between the upper and lower bounds of the interval. N_i is the number of items surviving a PGA at least as greater as the of the interval (within the interval or higher PGAs). The probability of survival within PGA interval *i* is estimated as:

$$r_i = (N_i + 1 - f_i)/(N_i + 1)$$

Where f_i is the number of failures occurring within the interval and r_i is the probability of surviving interval i. In order for an item to survive a particular PGA interval, it should also survive the intervals of lower PGA. Therefore the "reliability" or surviving through a PGA equivalent to the upper bound of interval *i* is the product of survival probabilities of the preceding intervals:

$$R_i = (N_1+1-f_1)(N_1+1) \text{ x } (N_2+1-f_2)/(N_2+1) \text{ x } .... (N_i+1-f_i)/(N_i+1)$$

The probability of failure F_i or the fragility for he upper bound of interval *i* is:

$$F_i = 1 - R_i$$

The final objective of seismic experience data is to make possible calculation of fragility parameters for mechanical end electrical equipment components.

3.2.8. Floor response spectra evaluation preliminary to the walkdown

The evaluation of the floor response spectra to be used for the seismic qualification of the equipment should be carried out according with some statistic methodologies aimed at avoiding the use of FRS coming from the numerical analyses of the structural building, and based on statistical analyses of the structural behaviour of the buildings.

In fact, high values of FRS developed for buildings located in high seismic areas (ZPGA > 0.3g) may lead in some cases to results that make the qualification based on generic approach almost impossible. In fact the screening criteria is based on the comparison between the bounding spectrum, which define the *generic* seismic capacity of a group of similar equipment, to the applicable FRS which define the seismic demand. Therefore the availability of realistic FRS (as explained below) and realistic capacity spectra (the modified experience database is described above) can provide a better result to the whole qualification, avoiding excessive conservatism.

In order to validate this process of FRS modification, some statistical analyses were carried out on 106 FRS available from 10 US plants. The FRS have been processed to correspond to consistent building damping, equipment damping and ground response motion. Then further processing have been done to calculate the mean and standard deviation of the frequency dependent amplification factors for the bottom zone, middle height and top zone of the building.

This activity provided such an understanding of the distribution, characteristics, range of the FRS in a NPP building that a statistical methodology was developed to be an alternative to dynamic analysis of the structures and to provide FRS for the walkdown as an alternative to more simplified approaches like the "40 feet rule" of the GIP.

It was also considered that such a technique can provide information like amplification factors corresponding to different building elevations for different type of nuclear buildings. Such information is of much help to estimate the acceleration level of components located at a specific elevation when FRS are not available or to identify conservatism in existing FRS which shows high amplifications.

Due to the peculiarity of WWER structures compared to the reference US plants used for the development of the statistics, such simplified, statistically based rules, cannot be fully applied to the WWERs. Particularly, there are some locations were the structural behaviour, according to the numerical analyses, are much different than a traditional NPP and therefore deserve a special analysis in order to qualify the equipment hosted at their elevation, namely valves, tanks and pipelines.

The identified critical locations are those zones of the main building complex for which the calculated seismic floor response spectra significantly exceed the 1.5 times GIP-WWER bounding spectrum. These zones are as follows:

- Longitudinal gallery Elevation greater then +6m
- Transversal Gallery Elevation greater then +6m
- Roof of the Turbine Building and Reactor Building
- Condensed Towers

For equipment in these locations, dedicated FRS were calculated from the structural models.

In order to eliminate the high conservatism typical of the numerical analyses of the structural buildings, some calculation techniques were developed.

These transformation methods have the capability to transform the original existing in structure response spectra calculated by analysis, into more realistic FRS to be used for equipment qualification.

The evaluation of FRS followed the procedure described below:

ASCE 4-86/4-98, Section 3.4.2.3 [53] states that:

(a) In-structure response spectra should be broadened to account for uncertainties in the structural response due to the uncertainties in supporting structure frequencies and soil structure interaction analysis.
(b) The minimum broadening should be +/- 15% at each frequency in the amplified region.
(c) In conjunction with response-spectra peak broadening, a 15% reduction in peak amplitude is permissible. Further reductions are permissible if it can be shown that the probability of non-exceedance for the resulting response spectrum is not less than 90%.

Therefore, the following reduction factors were applied to the IRS evaluated by numerical analyses in the "critical areas" where simplified methodologies cannot be applied because of the non-unified local structural response.

- 0.85 peak clipping based on the References [53] to account for numerical effects,
- local interaction effect (mass ratio effect) as described in [54]. It has to be evaluated explicitly. In fact, it is noted that even a mass ratio for equipment to structure of 0.0001 corresponds to an equivalent added damping factor of 1% and a mass ratio of 0.001 to an added factor of about 3.2%.
- limited structural ductility can be used corresponding to 1.5 ductility factor, applied to high elevations only (+33 and roof).

based on the probabilistic approach as described in [55], a reduction factor range between 0.46 to 0.60 can be applied to FRS peaks to represent a median clipped peak as requested in the qualification procedures. In the proposed procedure such scaling factor was limited to 0.60.

3.3. Method 3

3.3.1. Introduction

At U.S. Department of Energy (DOE) facilities, safety analyses and facility-specific action require the evaluation of systems and components subjected to seismic hazards. A programme has been implemented in the DOE that emphasizes the use of facility walkdowns as a means of efficiently identifying and fixing deficiencies of the most critical systems and components through the use of screening criteria in which items that pass the criteria are accepted without detailed analysis or testing. The implementation of the programme is described in the Seismic Evaluation Procedure for Equipment in U.S. Department of Energy Facilities [15].

A primary objective of DOE/EH-0545 [15] is to provide comprehensive guidance for consistent seismic evaluations of equipment and distribution systems in DOE facilities. The approach that is often used to review the seismic capacity of equipment and distribution systems is to conduct sophisticated evaluations that can be very time consuming, complex, and costly. In contrast, an extremely cost-effective method for enhancing the seismic safety of facilities emphasizes the use of facility walkdowns and engineering judgement based on seismic experience data. This method is based on Part II of Revision 2 of the Seismic Qualification Utility Group (SQUG) Generic Implementation Procedure (GIP) [12] used by the nuclear power industry. DOE/EH-0545 [15] builds on the procedures and criteria in the SQUG GIP by incorporating DOE-specific requirements and guidance and by broadening the application of the experience-based methodology to equipment classes not contained in the SQUG GIP. The scope of equipment covered in DOE/EH-0545 [15] includes active mechanical and electrical equipment such as batteries on racks, motor control centres, distribution panels, valves, pumps, and motor generators. In addition, DOE/EH-0545 [15] includes guidelines for evaluating the seismic adequacy of tanks, cable raceway systems, piping systems, HVAC ducts, glove boxes, Unreinforced Masonry (URM) walls, and relays.

3.3.2. Differences between SQUG GIP and DOE procedures

Before highlighting key aspects of DOE/EH-0545 [15], a brief overview of the differences between the SQUG GIP and the DOE Seismic Evaluation Procedure is in order. DOE/EH-0545 [15] expands the SQUG GIP by incorporating DOE-specific requirements and guidance and by broadening the application of the experience-based methodology to equipment classes not contained in the SQUG GIP. DOE/EH-0545 [15] does not modify the technical content or numerical values of the equipment classes and anchorage procedure provided in the SQUG GIP, except where appropriately marked and referenced.

DOE facilities, objectives, and criteria are different from those for commercial nuclear power plants. The systems and components in DOE facilities are so diverse that they require other experience-based tools beyond those currently included in the EPRI / SQUG database. In addition, DOE facilities are not structurally equivalent to nuclear power plants which are typically stiff, shear wall structures. As a result, the EPRI / SQUG methodology has been modified for DOE use. Seven key differences are described here.

(1) The addition of DOE equipment classes, such as piping systems and unreinforced masonry walls, which are beyond the scope of the classes of equipment contained in the SQUG GIP. Since the additional classes are not in the SQUG GIP, they have not been technically reviewed by SSRAP as part of the SQUG programme. The general guidelines in Chapter 10 are not rigorous, but are intended to provide cost-effective and achievable techniques for increasing the seismic capacity of the equipment classes.
(2) Data from recent earthquakes, including the 1994 Northridge and 1995 Kobe Earthquakes, are supplementing information in the current earthquake-experience database.
(3) In contrast to the deterministic criteria in the SQUG GIP, DOE facilities are required to demonstrate the ability to achieve probabilistic performance goals. Experience data factors are used to scale in-structure response spectra which are derived from the Design Basis Earthquake (DBE) of a facility. The scaled in-structure spectra, or the Seismic Demand Spectrum (SDS), are compared with experience-based capacity spectra defined in DOE/EH-0545 [15].
(4) An attempt was made in the development of the DOE Seismic Evaluation Procedure to reduce some of the repetition in the SQUG GIP and make the procedure less cumbersome.
(5) Throughout DOE/EH-0545 [15], nuclear power plant and NRC-specific requirements and commitments from the SQUG GIP have been removed and replaced with DOE facility information. Several of the sections in DOE/EH-0545 [15] reflect DOE guidance and standards and are considerably different than equivalent sections in the SQUG GIP. These sections have generic changes in order to integrate the experience-based methodology with DOE Orders and Standards, such as DOE Order 420.1 [56] and DOE-STD-1020 [28]. DOE/EH-0545 [15] has been enhanced with information from the WSRC SEP-6 [57], UCRL-15815 [58], and other DOE guidance documents.
(6) The “40-foot rule” permits the use of the Bounding Spectrum to define the capacity for equipment with fundamental frequencies greater than about 8 Hertz and mounted within 40 feet above effective grade. The Bounding Spectrum has a generic deamplification of 1.5 as compared to the capacity definition used in DOE/EH-0545 [15] for earthquake-experience data, the Reference Spectrum, and is a simplified way for reducing the experience-based capacity to account for in-structure amplification. Since the “40-foot rule” was developed for nuclear power plants with massive and stiff shear wall structures which are not the typical structural types at DOE facilities, DOE/EH-0545 [15] does not have the “40-foot rule” or the Bounding Spectrum. Instead, the DOE approach uses the Reference Spectrum to define equipment capacity and to compare with in-structure response spectra at equipment locations.
(7) The relay review for DOE facilities focuses primarily on identifying low ruggedness relays and comparing seismic capacity to demand. The detailed procedure which is required for relay functionality reviews in nuclear power plants is not included in DOE/EH-0545 [15].

3.3.3. Key aspects of the DOE seismic evaluation procedure

The four major steps used in the DOE Seismic Evaluation Procedure for evaluating equipment and distribution systems are: selection of the seismic evaluation personnel, determination of the Seismic Equipment List (SEL), screening evaluation and walkdown, and outlier identification and resolution. For the screening evaluation and walkdown, guidelines are provided for evaluating capacity versus demand, anchorage, seismic interaction, and equipment classes. Some detailed information about these steps in DOE/EH-0545 [15] is provided in this paper with the discussions emphasizing or highlighting DOE-specific aspects of the procedure which differ from provisions in the SQUG GIP.

3.3.3.1. Seismic evaluation personnel

The purpose of Chapter 3 of DOE/EH-0545 [15] is to define the responsibilities and recommended minimum requirements of the individuals who will implement DOE/EH-0545 [15].

The seismic evaluation personnel include individuals who develop the Seismic Equipment List (SEL), perform the facility walkdown, evaluate the seismic adequacy of equipment listed in the SEL, and perform the relay screening and evaluation. The seismic evaluation personnel encompass a number of safety, facility, and engineering disciplines including structural, mechanical, civil, electrical, systems, and seismic. They include safety professionals and systems engineers, operations personnel, Seismic Capability Engineers (SCEs) who perform the seismic evaluation of the equipment and distribution systems listed in the SEL, relay evaluation personnel, and Piping Evaluation Engineers.

3.3.3.2. Seismic equipment list

The methodology and procedures for evaluating the seismic adequacy of equipment described in the DOE Seismic Evaluation Procedure are based on the observed performance, failure, and response of various types of components and systems during and after they were subjected to either actual earthquake motion or simulated earthquake motion on a shake table. Chapter 4 of DOE/EH-0545 [15] provides guidelines and some discussion to aid in preparing a Seismic Equipment List (SEL), which is a list of equipment and distribution systems that are seismically evaluated to meet the intent of DOE seismic requirements. A prescriptive method for developing the SEL is not provided because each DOE facility may utilize methods which address facility-specific issues.

After a SEL Team is selected, the first step of the process is the development of the preliminary SEL from a list of the facility structures, systems, and components (SSCs). The SEL Team will consist primarily of safety professionals and systems engineers with assistance from seismic engineers and facility operators. Only a portion of the facility SSCs will be contained in the SEL and, in many cases, the SEL will contain only safety related SSCs which should function during or after a seismic event. To determine which SSCs belong in the SEL, the selection is normally based on the results of accident analyses. These accident analyses consider all the appropriate facility hazards as required by DOE Orders and Standards.

For the DOE facility being seismically evaluated, accident analyses and their results are typically provided in a SAR and the SEL are based on information provided in this facility SAR. Using the guidance in DOE Orders and Standards as well as the appropriate accident analyses in the SAR, SSCs can be differentiated into Safety Class or Safety Significant and the SEL can focus on those facility SSCs. These SSCs are typically those which should function during or after a seismic event. For facilities without an SAR, accident analyses comparable to those required for an SAR are performed. Additional guidance for the development of the SEL is provided in DOE-STD-1021 [59] which considers the results of facility hazard classification, SSC safety classification, and performance categorization.

To develop the SEL, postulated facility conditions, system interaction considerations, and seismic vulnerability considerations are evaluated. Postulated facility conditions include offsite utilities, seismic induced accidents, single active failure, operator actions, and other accidents. For system interaction considerations, seismic interaction effects, common-cause failure effects, and performance during a seismic event are considered, while seismic vulnerability considerations include structural configuration, potential failure modes, generic seismic performance, and actual attachment and support conditions. Finally, an operational review needs to be performed to address operational and functionality considerations. With these evaluations, equipment and distribution systems may be excluded from the SEL if they have low safety significance, or for other facility-specific considerations.

3.3.3.3. Capacity versus demand

A screening guideline which has to be satisfied to evaluate the seismic adequacy of an item of equipment identified in the SEL is to confirm that the seismic capacity of the equipment is greater than or equal to the seismic demand imposed on it. Chapter 5 of DOE/EH-0545 [15] addresses the determination of the seismic demand and capacity for the equipment as well as the comparison of the demand to the capacity. A comparison of seismic capacity to seismic demand is also made for the equipment anchorage, for the equipment class evaluations using screening procedures, and for relays mounted in the equipment.

The seismic demand is defined by the Seismic Demand Spectrum (SDS) which is based on the DBE as defined for DOE facilities. The input motion for the equipment is determined by computing an in-structure response spectrum based on the DBE and the frequency response of the structure in which the equipment is mounted. Scaling factors from UCRL-CR-120813 [60] are applied to the in-structure response spectrum to compute the SDS. For DOE facilities, the DBE is a specification of the mean seismic ground motion at the facility site for the earthquake-resistant design or evaluation of SSCs at that site. The DBE is defined by ground motion parameters determined from mean seismic hazard curves and a median design response spectrum shape. These hazard curves relate hazard exceedance probabilities to response quantities, such as peak seismic acceleration. The methodology for determining the DBE is described in DOE Standards, such as DOE-STD-1020 which also permits the use of the median standardized spectral shape defined in NUREG/CR-0098 [20] as long as the shape is conservative for the site conditions. The sources of information for the DBE of a specific DOE facility include SARs and documentation in the hazards control or plant engineering departments of that DOE site.

Based on the dynamic characteristics of the DOE facility in which the equipment and distribution systems being evaluated are located, an in-structure response spectrum (IRS) is computed from the DBE. The SDS is derived from the IRS by scaling the spectra by a scale factor according to the following equation:

$$SDS = F_{ED} \times IRS$$

where:

SDS — Seismic Demand Spectrum or Scaled In-Structure Response Spectrum.

For relays, the SDS is modified to account for in-cabinet amplification.

F_{ED} — Experience Data Factor which depends on the performance category and capacity representation of the equipment.

IRS — In-Structure Response Spectrum which is determined for the appropriate attachment point(s) of the equipment and is a function of the DBE for the facility and the frequency content of the structure supporting the equipment.

The total demand (D_{TI}) for the SSC being evaluated is a combination of seismic loads (D_{SI}) and concurrent non-seismic loads (D_{NS}).

$$D_{TI} = D_{SI} + D_{NS}$$

where:

D_{TI} — Total Demand

D_{SI} — Seismic Loads reduced for Inelastic Behavior. According to DOE-STD-1020, the dynamic analyses used to compute the seismic loads should consider all three orthogonal components of earthquake ground motion (two horizontal and one vertical). For near-field sites, the vertical component of the DBE may exceed the horizontal components. Responses from the various directional components are combined with acceptable combination techniques, such as the Square-Root-Sum-of-the Squares (SRSS).

D_{NS} — Non-Seismic Operational Loads

When comparing D_{TI} to seismic capacity based on earthquake experience data or generic seismic testing data, the effects of all three orthogonal components of the earthquake ground motion and the effects of non-seismic operational loads are typically not explicitly considered for equipment adequacy assessment. According to the SQUG GIP, evaluation of the effects of the vertical component is implicit in the horizontal motion assessment since the earthquake-experience facilities typically experienced higher vertical motion than that explicitly considered. Equipment in the earthquake-experience database was also subjected to non-seismic operating loads concurrent with the seismic loads. For equipment subjected to both operating and seismic loads, the database may need to be reviewed to determine if the operating loads were implicitly considered.

As described in the SQUG GIP and its reference documents, the seismic capacity of equipment can be represented by a Reference Spectrum based on earthquake experience data, a Generic Ruggedness Spectrum (GERS) based on generic seismic test data, or a test spectrum from equipment-specific seismic qualification. The first two methods of representing seismic capacity of equipment can only be used if the equipment meets the intent of the caveats for its equipment class. The Reference Spectrum was developed from earthquake experience data that was obtained by surveying and cataloguing the effects of strong ground motion earthquakes on various classes of equipment mounted in conventional power plants and other industrial facilities. GERS were established based on a large amount of data collected from seismic qualification testing of nuclear power plant equipment.

With either the Reference Spectrum or a GERS, the seismic capacity of an item of equipment is compared to its seismic demand which is defined in terms of an IRS that is scaled with the applicable scale factors from the SDS. This comparison of an IRS with the Reference Spectrum, a GERS, or a test spectrum for equipment which is mounted at any elevation in the facility is illustrated in Figure 3. For these comparisons, the largest horizontal component of the 5% damped in-structure response spectra is used for the location in the facility where the item of equipment is mounted. The in-structure response spectrum used for the seismic demand normally is representative of the elevation in the structure where the equipment is anchored and receives its seismic input and this elevation needs to be determined by the SCEs during the facility walkdown.

3.3.3.4. Anchorage data and evaluation procedure

A screening guideline which is normally satisfied to evaluate the seismic adequacy of an item of equipment is to confirm that the anchorage of the equipment is adequate. Lack of anchorage or inadequate anchorage has been a significant cause of equipment failing to function properly during and following past earthquakes. The screening approach in Chapter 6 of DOE/EH-0545 [15] for evaluating the seismic adequacy of equipment anchorage is based upon a combination of inspections, analyses, and engineering judgment. Inspections consist of measurements and visual evaluations of the equipment and its anchorage, and supplemented by use of facility documentation and drawings. Analyses are performed to compare the anchorage capacity to the seismic demand imposed upon the anchorage. The four main steps for evaluating the seismic adequacy of equipment anchorage include:

- Anchorage installation inspection
- Anchorage capacity determination
- Seismic demand determination
- Comparison of capacity to demand

The steps for the anchorage evaluation are directly based on the anchorage evaluation methodology of the SQUG GIP. For the anchorage capacity determination, the information is grouped by the following anchor types: expansion anchors, cast-in-place bolts and headed studs, cast-in-place J-bolts, and grouted-in-place bolts. Two other anchor types, welds to embedded steel or exposed steel and lead cinch anchors, are evaluated using separate procedures. Information for the lead cinch anchors is from tests conducted at the Savannah River Site. To evaluate the seismic capacity of equipment anchorage, DOE/EH-0545 [15] contains tables of nominal allowable load capacities along with anchor-specific inspections which need to be performed. In some cases a capacity reduction factor is given which may be used to lower the nominal allowable load capacities if the inspection check reveals that the installation does not meet the minimum guidelines.

For anchorage demand evaluations, DOE/EH-0545 [15] contains generic equipment characteristics for use when equipment-specific data is not available for equipment mass, natural frequency, or damping. Finally, the anchorage demand and capacity are compared using shear-tension interaction equations.

3.3.3.5. Seismic interaction

The purpose of Chapter 7 of DOE/EH-0545 [15] is to describe seismic interaction and techniques for evaluating its effects on equipment in DOE facilities. Seismic interaction is the physical interaction of any structures, piping, or equipment with a nearby item of equipment caused by relative motions from an earthquake. Components with fragile appendages (such as instrumentation tubing, air lines, and glass site tubes) are most prone to damage by seismic interaction.

A screening guideline to be satisfied to evaluate the seismic adequacy of an item of equipment is to confirm that there are no adverse seismic spatial interactions with nearby equipment, systems, and structures and interaction from water spray, flooding, and fire hazards which could cause the equipment to fail to perform its intended function. A list of interaction examples is provided to assist the SCEs in identifying potential interaction concerns. In addition, guidance from DOE-STD-1021 on the treatment of seismic interaction effects is included.

It is the intent of the seismic interaction evaluation that real (credible and significant) interaction hazards be identified and evaluated. Interaction evaluations focus on areas of concern based on past earthquake experience. Systems and equipment which have not been specifically designed for seismic loads should not be arbitrarily assumed to fail under earthquake loads. SCEs are expected to differentiate between likely and unlikely interactions based on their judgment and on past earthquake experience. Special attention needs to be given to the seismic interaction of electrical cabinets containing relays. If the relays in the electrical cabinets are essential (the relays should not chatter during an earthquake), then any impact on the cabinet is considered as an unacceptable seismic interaction and cause for identifying that item of equipment as an outlier.

3.3.3.6. Equipment class evaluations

A screening guideline which has to be satisfied to evaluate the seismic adequacy of an item of equipment is to confirm that (1) the equipment characteristics are generally similar to the earthquake experience equipment class or the generic seismic testing equipment class and (2) the equipment meets the intent of the specific caveats, procedures, or guidelines for the equipment class. Table V lists all the equipment classes contained in the DOE Seismic Evaluation Procedure and the type of evaluation for each class. In addition to the classes of equipment in the SQUG GIP, there are eleven additional classes of equipment developed for application at DOE facilities.

The 20 equipment classes from the SQUG GIP are contained in Chapter 8 of DOE/EH-0545 [15] which lists the caveats that permit the use of the Reference Spectrum and/or GERS to define the seismic capacity of the equipment classes. Since the procedures in Chapter 8 are from the SQUG GIP, they were independently reviewed by the Senior Seismic Review and Advisory Panel (SSRAP) as part of the SQUG programme and were approved by the NRC. For the 20 equipment classes from the SQUG GIP, extensive use of earthquake experience and test data permits the rigorous definition of the equipment capacity and evaluation of the seismic adequacy of the equipment. The equipment capacity is compared to the seismic demand as discussed earlier.

Chapters 9 and 10 of DOE/EH-0545 [15] contain equipment class evaluations based on screening procedures. The procedures for the classes of equipment in Chapter 9 are from Revision 2 of the SQUG GIP, while the procedures developed for three other DOE classes of equipment are provided in Chapter 10. Procedures for the three classes from the SQUG GIP were independently reviewed by SSRAP as part of the SQUG programme and were approved by the NRC with a safety evaluation report. The three classes of equipment with screening procedures developed for the DOE are piping, HVAC ducts, and unreinforced masonry (URM) walls.

TABLE V. EQUIPMENT CLASS EVALUATIONS IN THE DOE SEISMIC EVALUATION PROCEDURE

Section	Equipment Class	Type of Evaluation
	ELECTRICAL EQUIPMENT	
8.1.1	Batteries on Racks	SQUG GIP Caveats
8.1.2	Motor Control Centres	SQUG GIP Caveats
8.1.3	Low-Voltage Switchgear	SQUG GIP Caveats
8.1.4	Medium-Voltage Switchgear	SQUG GIP Caveats
8.1.5	Distribution Panels	SQUG GIP Caveats
8.1.6	Transformers	SQUG GIP Caveats
8.1.7	Battery Chargers and Inverters	SQUG GIP Caveats
8.1.8	Instrumentation and Control Panels	SQUG GIP Caveats
8.1.9	Instruments on Racks	SQUG GIP Caveats
8.1.10	Temperature Sensors	SQUG GIP Caveats
	MECHANICAL EQUIPMENT	
8.2.1	Fluid-Operated / Air-Operated Valves	SQUG GIP Caveats
8.2.2	Motor-Operated / Solenoid-Operated Valves	SQUG GIP Caveats
8.2.3	Horizontal Pumps	SQUG GIP Caveats
8.2.4	Vertical Pumps	SQUG GIP Caveats
8.2.5	Chillers	SQUG GIP Caveats
8.2.6	Air Compressors	SQUG GIP Caveats
8.2.7	Motor-Generators	SQUG GIP Caveats
8.2.8	Engine-Generators	SQUG GIP Caveats
8.2.9	Air Handlers	SQUG GIP Caveats
8.2.10	Fans	SQUG GIP Caveats
10.2.1	HEPA Filters	General Guidelines
10.2.2	Glove Boxes	General Guidelines
10.2.3	Miscellaneous Machinery	General Guidelines
	TANKS	
9.1.1	Vertical Tanks	Screening Procedure
9.1.2	Horizontal Tanks and Heat Exchangers	Screening Procedure
10.3.1	Underground Tanks	General Guidelines
10.3.2	Canisters and Gas Cylinders	General Guidelines
	PIPING, RACEWAY, AND DUCT SYSTEMS	
9.2.1	Cable and Conduit Raceway Systems	Screening Procedure
10.1.1	Piping	Screening Procedure
10.1.2	Underground Piping	General Guidelines
10.4.1	HVAC Ducts	Screening Procedure
	ARCHITECTURAL FEATURES AND COMPONENTS	
10.5.1	Unreinforced Masonry (URM) Walls	Screening Procedure
10.5.2	Raised Floors	General Guidelines
10.5.3	Storage Racks	General Guidelines

For these procedures which represent the state-of-the-art for screening techniques to evaluate the seismic performance of piping, HVAC ducts, and URM walls, the DOE Steering Group had an independent review performed as discussed earlier. The screening procedures contain a summary of the equipment class descriptions and parameters based on earthquake experience data, test data, and analytical derivations. An item of equipment normally has the same general characteristics as the equipment in the evaluation procedures. The intent of this rule is to preclude items of equipment with unusual designs and characteristics which have not demonstrated seismic adequacy in earthquakes or tests. The screening procedures cover those features which experience has shown can be vulnerable to seismic loads. These procedures are a rigorous step-by-step process through which the important equipment parameters and dimensions are determined, seismic performance concerns are evaluated, the equipment capacity is determined, and the equipment capacity is compared to the seismic demand.

Chapter 10 of DOE/EH-0545 [15] also contains general guidelines or “good practice” for equipment classes not covered in the previous two sections. The guidelines are intended to provide cost-effective and achievable techniques for increasing the seismic capacity of the equipment classes. For these guidelines, the DOE Steering Group had an independent review performed.

The general guidelines for evaluating the seismic adequacy of the equipment classes in Chapter 10 cover those features which experience has shown can be vulnerable to seismic loads. These procedures provide practical guidelines and reference to other documents which can be used to implement an equipment strengthening and upgrading programme. Enhancements to the sections of Chapter 10 that contain general guidelines are planned as DOE/EH-0545 [15] is revised.

3.3.3.7. Relay functionality review

As part of the seismic evaluation of equipment in DOE facilities, it may be necessary to perform a relay seismic functionality review. The purpose of this review is to determine if the equipment listed on the SEL could be adversely affected by relay malfunction in the event of a DBE and to evaluate the seismic adequacy of those relays for which malfunction is unacceptable. The term “relay malfunction” is used to designate relay chatter or inadvertent change-of-state of the electrical contacts in a relay, contractor, motor starter, or switch. The purpose of Chapter 11 of DOE/EH-0545 [15] is to provide an overview of the relay evaluation procedure and describe the interfaces between other evaluation activities and the relay evaluation. In the DOE/EH-0545 [15], three screening methods for establishing the seismic capacity of relays, a list of low ruggedness relays, and two methods for determining the scaled seismic demand on relays mounted in cabinets or other structures are provided.

3.3.3.8. Outlier identification and resolution

Items listed in the SEL that do not pass the screening criteria contained in DOE/EH-0545 [15] are considered outliers and need to be evaluated further. Since the screening guidelines are intended to be used as a generic basis for evaluating the seismic adequacy of equipment at DOE facilities, an outlier may be shown to be adequate for seismic loads by performing additional evaluations such as the seismic qualification techniques currently being used in some DOE facilities. These additional evaluations and alternate methods have to be thoroughly documented to permit independent review. As discussed in Chapter 12 of DOE/EH-0545 [15], outlier resolution may be somewhat open-ended in that several different options or approaches are available to evaluate the seismic adequacy of the equipment. The most appropriate method of outlier resolution will depend upon a number of factors such as (1) which of the screening criteria could not be met and by how much, (2) whether the discrepancy lends itself to an analytical evaluation, (3) how extensive the problem is in the facility and in other facilities, or (4) how difficult and expensive it would be to modify, test, or replace the subject items of equipment.

3.3.4. Conclusion

The approach used in the DOE Seismic Evaluation Procedure for evaluating the seismic adequacy of equipment in DOE facilities is consistent with the intent of DOE Order 420.1, the approach in the SQUG GIP, and the approach developed for the EPRI Seismic Margins Assessment Programme [11].

With DOE/EH-0545 [15], safety analyses and facility-specific efforts to seismically evaluate systems and components are done in a efficient and consistent manner. In addition, the evaluation will satisfy DOE-specific requirements for assuring adequate measures for the protection of public health and safety, for on-site worker life safety, for protection of the environment, and for investment protection for seismic hazards.

Based on applications at DOE facilities of the methodology in DOE/EH-0545 [15], seismic screening evaluations using experience data is a technical necessity and is the most economically attractive of the options to evaluate existing equipment and distribution systems [61].

3.4. Experience with the application of indirect methods by regulatory bodies

Regulatory experience in the field was collected from participants of the following countries: Armenia, Lithuania, Russia, Ukraine, Hungary, Slovakia, representing the regulatory action for WWER and RBMK plants. In some countries (Hungary and Slovakia) the regulatory body already reviewed the seismic re-evaluation projects and the relevant technical documents; in the other countries the regulatory action is currently dealing with the preparation of general requirements and guidelines. The most relevant comments from the regulatory experience can be summarized as in the following:

- In general the seismic re-evaluation process is regulated by a set of regulatory requirements (at a very high level) and by a “technical criteria” document which in some cases was endorsed by the regulatory body (Armenia, Slovakia) and enforced as technical requirement (Armenia), while in other cases it was just developed by the Utilities as answer to the regulatory requirements and then reviewed by the regulator.
- In all cases the regulatory review stopped at the “criteria document” level and therefore it did not directly reviewed the application of such principles to the specific plant situation
- In some cases the regulatory review concluded that the technical documentation was not completed and clear and therefore a detailed review of the seismic qualification process was not even possible
- In no cases did the regulatory body carry out a “Peer Review” of the qualification process, with direct involvement of independent experts in the walkdown and in training of operators

- Often the seismic qualification is in connection with the life extension of the plant: a generic lack of regulatory requirements does not allow to distinguish between urgent safety issues and medium term investment-recovery issues

3.5. Experience with the application of indirect methods by utilities

Experience with the application of "indirect methods" to the plants was collected from participants of the following countries: Hungary (Paks NPP), Bulgaria (Kozloduy NPP), Slovakia (Bohunice and Mochovce NPP), representing the experience in WWER plants.

In some countries (Hungary and Slovakia) the seismic re-evaluation programmes are in an advanced implementation status and the experience gained could be really useful to optimize the process in the other countries. The most relevant comments from the experience of the utilities can be summarized as in the following:

- The seismic qualification has always been influenced by some non-safety issues like life extension policy, availability of contractors, replacement vs. qualification costs, etc. Therefore the approach followed in the different countries is not the same, particularly in the definition of the equipment to be qualified (the so called SSEL) which showed very different number of equipment: from 20 000 to 5 000 for the same unified WWER plants. Nevertheless, a general common approach to the problem of the seismic qualification with "indirect methods" was recognized and it is mainly based on the application of qualitative approaches and extensive engineering judgement. The GIP approach has been the common basis for all the applications, with some extension to specific classes of SSCs, as described above.

- In all cases the RLE was selected coincident with the SL-2, and the decision for upgrading was taken when HCLPF values were found lower the RLE.

- The FRS were evaluated by analysis and the "40 foot" rule have never been applied. The uncertainty related to the soil properties was considered through "envelope" of three different analyses with different values of the soil properties and then "broadening". It was recognized that the approach is too conservative and in the most recent applications the envelope was actually skipped.

- In many cases, a specific task for FRS analysis and modification was carried out to clean the values from conservatism typical of the structural analysis.

- The application of seismic qualification methods was always aimed at the evaluation of the seismic ruggedness of the plant to the SL-2, and not to the evaluation of the relevant safety margin. However, many plants started a seismic PRA for the analysis of the "old" and "new" safety margin to seismic events as a final confirmation of the benefit of the implemented upgrading measures.

- In general the seismic re-evaluation process was regulated by a unified criteria document which in the case of the qualification of the equipment and components reflects the US practice based upon walkdowns and indirect criteria.

- All the plants who implemented such programme used more than one foreign contractor and engineering consultant for the qualification of equipment and components, with a large involvement of local subcontractors for the execution of the walkdown, for the detailed capacity evaluation, for the design of the upgrading. This large number of contractors and sub contractors (about 30 in some cases!) developed their tasks according to international standards, to national standards and to local engineering practices. Moreover large interface problems arose among the contractors for data transfer (e.g.: calculation of FRS and SSC qualification), responsibility of different contractors and configuration control at the interface between different disciplines (e.g.: anchorage of a mechanical component to a concrete structure).

- In some countries complementary testing programmes were carried out on electrical equipment (mainly relays) and mechanical components (tanks) to support the qualification of the “outliers” from the walkdown. In some other cases replacement with new components was considered more effective and convenient.

- Often the quality of documentation, the contractor QA manual, the contractor review system were not homogeneous and consistent among the contractors. Therefore some difficulties were recorded in the detailed technical review by both the Project managers and by the Regulators and in general it appears difficult to appreciate the final conservatism of the qualification process.

- Moreover, the application of a qualitative approach for the qualification of SSCs implies a very stringent training process to limit the operator dependency on the final results. The responsibility of the training procedures has been always left to the contractors.

- The acquisition of the “as-is” situation of all the plants was very difficult and uncertain due to the very frequent lack of a stringent configuration control system for the plant. Such lack of basic information often requested an additional preliminary task for the recognition of the plant. Also the quality of construction was very difficult to be evaluated in many cases and particularly for anchorage: the reliability of the whole qualification process suffered of such difficult estimation which in some cases suggested the replacement.

- Some lack of technical, well proven qualification procedures (particularly for I&C equipment) was probably at the base of extensive and expensive replacement tasks

- A generic lack of clarity in the procurement procedures do not clarify the differences between criteria to be applied to existing SSC to be re-qualified and criteria for the replacement of existing SSC. In fact very often the replacement procedures require the seismic qualification of the new equipment, but they do not require its qualification respect to the anchorage criteria and interaction criteria

- Many plants decided to deal with ageing issues with dedicated Ageing Management Programmes (AMP), separated by the qualification programmes. Therefore the qualification tasks always referred to the nominal situation of the SSC and their anchoring and they did not include any ageing consideration in the reference configuration to be qualified.

4. COMPARISON OF THE SELECTED METHODOLOGIES

4.1. General

Some key aspects have been identified in re-evaluation procedures for a detailed comparison, as shown in Fig. 8. They are analysed in the following with reference to the three selected approaches.

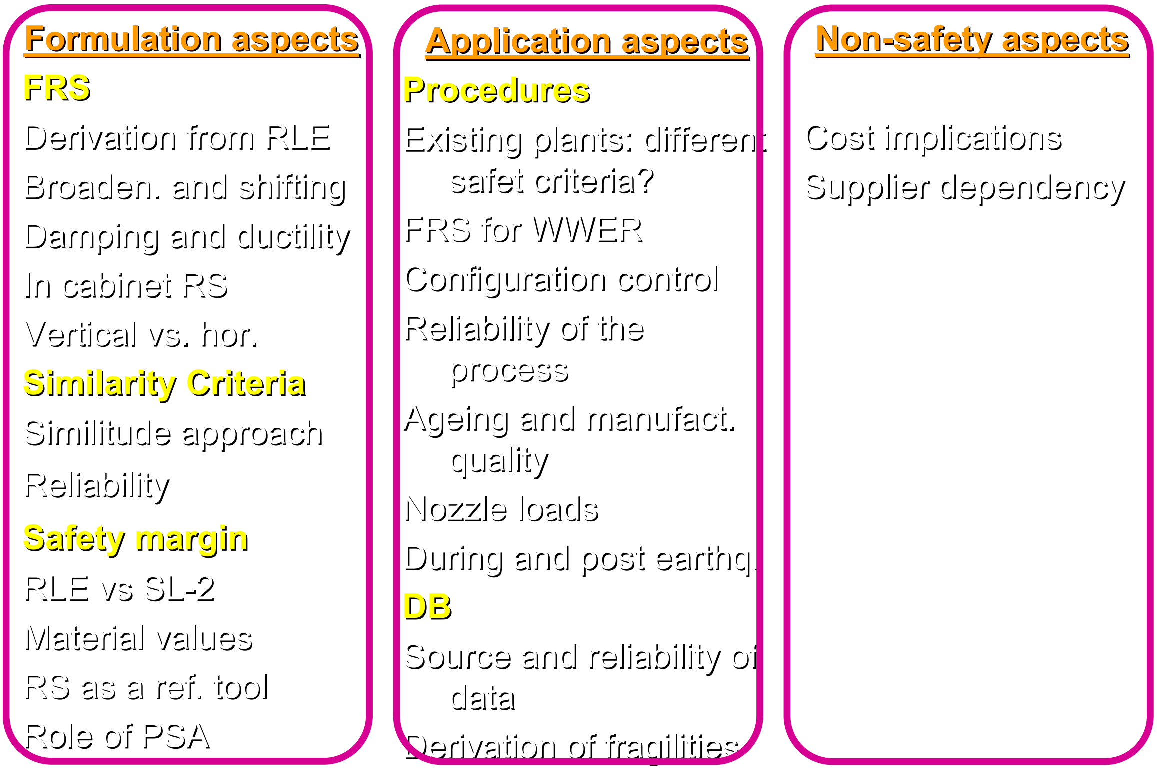


FIG. 8. Key issues in the re-evaluation aspects.

The basic concern for such a comparison is the reference to the general approach where the component qualification has to be used: in fact in many cases methodologies like SMA, PSA etc. have been used for the qualification of existing plants, while their original development was just associated to the analysis of the plant performance for earthquakes beyond the design basis. Such a different context demands for a consistency analysis at the high level, with potential consequences on the detailed procedures followed for component qualification.

In particular, the following original reference application framework [11–14] need to be kept in mind, according to the engineering practice:

- **Design criteria**: they should be rigorous and conservative, oriented to licensing basis. In some cases they may allow the use of similarity criteria for equipment verification, but they require explicit analysis for piping (charts only for the small bore)
- **Margins methodologies**: they should be less conservative than design and intended to assess capacity beyond licensing basis. They should use margin screening methodologies, screening walkdown and bounding analysis (especially for piping). They

are usually not accepted for design basis in US where they have been developed. A seismic margin review studies answer to the question of whether the capacity of the plant exceeds target earthquake input selected for review typically designated as a Seismic Margin Earthquake, SME or Review Level Earthquake, RLE. It is assumed that the regulatory agency and the plant owner jointly select this earthquake level. The objective is to investigate the ability of the plant to withstand the effects of the Seismic Margin Earthquake with high confidence and to identify seismic vulnerabilities if any. This is accomplished using the results and insight obtained from past Margin Assessments, review of data on actual performance of structures and equipment in recorded strong motion earthquakes, and analytical qualification and test data.

- **PSA**: it is performed to quantify risk and identify the major contributors, but it is also an alternative to margins evaluation. It requires some deterministic analyses of structures and equipment. Generic fragilities are used for equipment screened using margins methods. Piping are screened by walkdown and generic fragilities are used. Only selected fragility analyses are carried out. Resources are focused on low capacity, high risk items. The large uncertainties in the seismic hazard curves used in a PSA evaluation make decisions regarding seismic adequacy difficult. The large number of systems and components to be considered in a external event seismic PSA limit the attention paid to the more critical components and systems in the plant and generally require a significantly greater expenditure of resources as compared to a Seismic Margin Assessment, SMA, particularly for high level RLE. For low level RLE, a PSA might be even cheaper than a SMA procedure as attention is paid only to the most critical items.

Therefore in the comparison, the specific reality of WWER and RBMK plants (where most of such GIP based procedures have been developed) has to be kept in mind. This concept can provide part of the justification of the differences between GIP and the other methods, particularly in the definition of the seismic input, but also in the component qualification.

It has also to be noted that while existing design methods have inconsistent safety factors, margins criteria provides for more consistency in safety factor policy and PSA even attempts to quantify the real margin in development of fragilities to support “risk informed” decisions. In this sense the application of margins methods or PSA to existing structures might represent a more engineering oriented approach, not necessarily more liberal than the design approach, but surely more balanced in the location of the conservatism in order to avoid unnecessary upgrading.

Particularly, design methods require the greatest margin for ductile structural failures (as yield is usually taken as reference capacity), lower margin, but better defined, for brittle failures and do not provide a margin at all in the qualification by test. Margins approaches allow reduction in seismic loads for ductile failure modes (through the use of ductility) and use penalty factors for tested components.

The most recent design procedures (such as many “Unified Utility Requirements”) apply also margins methods to the design of new facilities, thanks to the better control on the design margins.

4.2. Approach to GIP extension

4.2.1. Basic questions

This section intends to discuss how the three methods under review answer the following questions:

(1) Were other equipment classes added to the traditional GIP selection?
(2) Is the addition of new classes (if any) based on an upgrading of the experiment databases or on other criteria?
(3) How new caveats have been developed for the new classes?

4.2.2. Method 1

It applies the SQUG-GIP (bounding spectra). The GIP equipment classes and items have been extended to appropriate modifications (ModGIP category) and supplements (NonGIP category).

ModGIP may refer to plant-specific topics or to NPP type-specific topics. Related to the US nuclear power plants, it accounts for deviations in material, design and quality. ModGIP criteria catalogues have been elaborated for anchorage verification, for cable tray verification, and for seismic interaction evaluation. The criteria are based on simple calculations or on tests, respectively.

NonGIP covers those topics not treated in the SQUG-GIP. The NonGIP criteria catalogues are elaborated applying simple calculations as well as small computer programmes, taking plant-specific items like seismic excitation into account. NonGIP criteria are presented in piping evaluation guidelines, piping support criteria catalogues and HVAC ducts criteria catalogues.

The evaluation of the quality of welding is carried out on a qualitative base.

Relays have been totally replaced bypassing the qualification problem for the existing ones.

4.2.3. Method 2

Original GIP caveats have been modified (for example for the low pressure valves and motor operated valves).

New equipment classes have been added to GIP, namely: cable trays (addressed by simple calculations), heat exchangers (addressed with dedicated procedures for interaction, anchorage and integrity evaluation), small bore piping and large diameter (only cold). Validation of the new caveats was carried out on the base of an upgraded GIP database that was completed with many experience data from WWER component testing. The validation reports are not publicly available.

Nozzle loads and anchorages have been addressed by simplified analysis based on testing and conservative assumptions. Special conservative rules were developed for equipment with natural frequencies in the range 8 - 12 Hz.

A “generic procedure” is kept updated on the basis of the continuous implementation.

4.2.4. Method 3

Some caveats of the original GIP have been modified to comply with different limitations in terms of frequencies in the comparison of capacity versus demand.

New screening procedures have been added to the traditional 20 GIP classes, without developing new caveats, for the following equipment: glove boxes, filters, vertical tanks, underground tanks, storage racks, canisters, gas cylinders, HVAC, computer floors, unreinforced masonry. Such procedures were independently reviewed by expert teams before being inserted in the final methodology.

Based on GIP, some procedures for the review of the anchorages have been upgraded and new procedures for relays qualification developed.

All modifications to GIP were peer-reviewed and also the additional guidelines were validated with additional test and independent reviews.

4.3. Evaluation of floor response spectra

4.3.1. Basic questions

This section intends to discuss how the three methods under review answer the following questions:

1. Are the FRS evaluated explicitly or some engineering rules are applied?
2. Which is the range of FRS broadening and shifting?

4.3.2. Method 1

Starting from the reference time history analysis of the building structure carried out with median soil properties, the FRS are generated at the different floor elevations and then broadened by $\pm 15\%$. This procedure will be preferred.

Alternatively, the mathematical model soil properties are varied (minimum, mean, and maximum soil stiffness values). In this case, no broadening of the FRS will be applied.

4.3.3. Method 2

FRS coming from numerical analyses (unbroadened) were modified according to the following effects:

- mass ratio effects (excitation is reduced depending on the mass ratio supported equipment/supporting structures; Newmark approach is used)
- ductility
- in conjunction to ductility reduction, +15%/-50% peak shifting is recommended
- clipping of sharp FRS peaks [55]
- uncertainty in the modelling and local vibration effect (usually filtered by the grid of the finite element model used for the overall structure). It was included by shifting the peaks following ASCE [53]

4.3.4. Method 3

FRS are evaluated following ASCE 4-98 [53] and therefore applying peak shifting.

Moreover, two factors are applied to in structure response spectra:

- a scale factor, to account for the performance category [15] assigned to the item
- an experience data factor, to account for the influence of the procedure used in the capacity evaluation. The margin between the design and ultimate failure values are contained in this factor, according to the use of experience data or to the use of test data

4.4. Seismic capacity

4.4.1. Basic questions

This section intends to discuss how the three methods under review answer the following questions:

(1) How seismic capacity is evaluated?

(2) Which criteria are used for demand versus capacity comparison?

4.4.2. Method 1

GIP bounding spectra is applied.

4.4.3. Method 2

More detailed criteria than GIP ones were developed for comparison of seismic capacity versus demand.

Bounding spectrum (BS) is used with the following adaptations:

- used for structures with massive shear walls (reactor building); for others, in structure response spectra are to be computed
- additional conservatism introduced : the use of BS is restricted to equipment whose frequency > 12 Hz (GIP stays)
- for a specific set of rugged equipment, the capacity is said to be BS 0.5 g (GIP says BS 0.33 g)

4.4.4. Method 3

GIP criteria for comparison of demand versus capacity were modified as this method requires to demonstrate the ability to achieve probabilistic performance goals, as defined in [15].

Moreover, there are two exceptions to the requirement of enveloping the seismic demand over the entire frequency range of interests. They limit such comparison to the range of the lowest natural frequency and some narrow peaks in the demand spectrum may exceed the capacity spectrum.

4.5. Management of the safety margin

4.5.1. Basic questions

This section intends to discuss how the three methods under review answer the following questions:

(1) Which is the safety margin in the seismic hazard?
(2) Which is the margin in structural and soil material?
(3) Where the safety margin of the procedures is embedded?
(4) Do the proposed technique allow an explicit evaluation of the overall safety margin of the facility before and after the upgrading?
(5) Is PSA required? Is it a complement to GIP based rules, a confirmation or a review tool?

4.5.2. Method 1, 2, 3

All the methods agree that conservatism mainly lies in the selection of RLE, in material properties, in load combinations, in ductility values, in the bounding spectrum (it is a median-minus-one- standard-deviation), in the performance goals.

The selection of RLE is not considered part of the methods: in the WWER plants, it was always selected at the same level of SL-2.

Uncertainties in the seismic input are addressed by means of the envelope over a set of time histories artificially generated from the selected spectrum.

Soil material properties are considered at their median values.

Loading combinations are referred to normal operation only, with coefficients equal 1.0.

Structural properties are considered at code values, except damping which is at the median value.

The overall safety margin can be evaluated only with the PSA methodology which provides also the contributions to the safety margin. The safety margin of the qualification of the single item by similarity is evaluated in SMA methods only as a lower bound.

PSA is in general additional to GIP based procedures and it is developed with the following goals:

- to evaluate the effect of upgrading
- to prioritize the upgrading measures
- to confirm the results of the SMA techniques
- to compare the risks of the facility with other risks in the country
- to support “risk informed” decisions on maintenance and control of the modifications

4.6. Re-evaluation versus design–ageing aspects

4.6.1. Basic questions

This section intends to discuss how the three methods under review answer the following questions:

(1) Is there any difference between re-evaluation of existing facilities and criteria for the design of new ones?
(2) How are ageing and maintenance quality considered in the re-evaluation process?

4.6.2. Method 1

Re-evaluation relies upon some differences with the design: median value for structural damping (instead of the code values), ductility and one value for soil stiffness combined with FRS broadening (rather than the envelope of three analyses within a broad range for stiffness).

Ageing is evaluated by walkdown and testing of the anchorage (25% of the bolts). For piping, 1 mm thickness is removed for all carbon steel pipe sections in order to check for the ageing effect in the thickness.

4.6.3. Method 2

Same as method 1.

Ageing is evaluated by walkdown, measure of the actual size of anchorage and torque check. With such an approach also the installation procedures and QA are assessed. An ageing management programme is also desirable to deal with such phenomena in a proper and continuous way.

Loading (live loads) according to normal operation only.

4.6.4. Method 3

Different criteria for hazard evaluation allow 10–20% of reduction in the seismic demand.

The use of performance categories accounts for the safety margin in the qualification of equipment that in other methods is not addressed in a probabilistic way.

4.7. Databases

4.7.1. Basic questions

This section intends to discuss how the three methods under review answer the following questions:

(1) Which information is available in the databases?
(2) Are databases essential for the application of the procedures?

4.7.2. Method 1

The GIP database was used implicitly, never directly, through application of GIP caveats.

4.7.3. Method 2

A new database with both seismic experience data and test data has been developed for WWER components, collecting data from WWER countries experience. New caveats for new equipment classes have been developed.

Some original GIP caveats have been modified for application to WWER type components.

4.7.4. Method 3

GIP database was acquired and extensively used for the validation of the caveats for DOE classes.

Extensive experience from recent earthquakes is now available, but it was neither yet implemented in the GIP database nor used for validation of the caveats for added classes. A permanent programme for such updating is already defined.

4.8. Overview of the comparison

Item	GIP	Method 1	Method 2	Method 3	IAEA TG
N. of equipment classes	20 (all the rest has to be tested or analysed). Relays are included. Tanks, heat exchangers and cable raceways have analytical screening procedures. No buildings, no piping, no passive systems, no primary loop, no fail safe items. SEL contains only items verifiable by experience!! (i.e. a subset of the items required for hot shutdown)	20 GIP classes. HVAC, small bore piping, anchorage and nozzle loads have simplified analytical design procedures. Relays are replaced. Modified interaction and anchorage procedures	20 GIP classes with modified caveats based upon extended databases. HVAC, filters, cable supporting structures, tanks, heat exchangers have simplified analytical design procedures. GIP DB was not used. WWER data complemented GIP data	20 GIP classes, some caveats modified and peer reviewed. Added screening procedures, not caveats, and guidelines. DB to be extended with other experience data	17 GIP classes, WWER classes to be qualified by dynamic testing and/or analysis. Includes guidelines for all items in SSEL, RCS, structures and piping.
FRS broadening/shifting	Design or median centred (median soil)	Median soil analysis, averaging on the floor +-15% broadening	peak reduction (15%) + broadening + reduction for mass ratio and ductility effects	peak shifting (ASCE) + performance category and test quality effect	Envelope over FRS calculated with 0.67 - 1.5 soil stiffness
Seismic capacity	BS>SSE and GERS>1.5*1.5*SSE Anchorage Interactions	GIP bounding spectra	GIP bounding spectra or spectra from experience database	GIP bounding spectra or spectra from experience database	GIP
Structural ductility	NO	YES	YES	NO	YES
In cabinet FRS	Special procedure for relays with in cabinet amplification factors	YES	YES	YES	YES
Vertical versus horizontal FRS	Not explicitly considered: implicit in the experience and test data. For anchorage checks, the vertical comp. is 2/3 of the horizontal	As GIP	As GIP	As GIP	As GIP
RLE versus hazard (SL-2)	median shape (NUREG) anchored at 84% Pga or 84% shape (NUREG) anchored at SSE or RG1.60 anchored to SSE or other spectra 84%	vertical is 2/3 of hor.	Not part of the procedure: negotiable	median shape (NUREG) or site specific, with mean Pga	Median shape (NUREG) with 84% Pga. RLE=SL-2
Structural material properties	code values	code values (95 percentile), median structural damping and ductility	code values, median for masonry	code values ± 20% according to strain	best estimate damping, ductility. Use of the code ultimate strength

Soil material properties	best estimate	median	median	median	best estimate
Seismic interaction	Only mechanical (no fire, flood, explosion, impairment of operator action)	GIP	Complete	Complete	Complete
PSA	Not considered	Not considered	Fragilities provided as a spin-off of the experience database	Not part of the procedure	Recommended
Peer review	YES	Through QA	Through QA	Formally implemented and regulated	YES
Differences with design	Only SSEL is concerned, SSE is not combined with other loads, 72 hours rule, one redundancy	As GIP + no enveloping of soil stiffness, reference only to normal operation	As in method 1	As in method 1 + hazard exceedance probability twice the design one (10-20% less seismic loads)	As GIP + ultimate strength for materials, median damping and soil properties.
Ageing	No mention	By walkdown and standard tests on piping thickness	By walkdown and through ageing management programme (AMP)	Through AMP	
Database	GIP, peer reviewed	GIP, but not used	Modified GIP, used for new caveats and outlier solution	GIP, used to validate caveats. Database to be extended in the future, data already available	GIP

5. GUIDELINES FOR FURTHER APPLICATIONS

5.1. General

The results of the comparison of the three selected methods are the background for the development of plant specific technical guidelines for seismic re-evaluation of existing plants. Many of these documents have been developed in recent years with the IAEA umbrella [24-27], and new ones are going to be developed. Some technical documents collect the Member State experience [62, 63] and some others are under review to include re-evaluation issues [64, 65] In the following, some suggestions and guidelines are collected for use by utilities and regulatory bodies, in a general attempt of an improvement of the seismic safety of new and existing plants in Member States.

It is not practical to apply rigorous design basis methodologies to all components in existing NPPs with incomplete seismic qualification. Normally the more practical methods discussed in previous sections are adapted to achieve the goal of the owner/operator. The owner/operator should decide whether the goal is to establish a design basis such as in the SQUG programme for resolution of USI A-46, establish a defined level of plant HCLPF as is done in seismic margins study, quantify risk by performing a seismic PSA or achieve a performance goal such as defined in the US DOE/EH-0545 [15] procedures. Each method will require some extension and modification to cover all equipment to be addressed.

There are some differences in the procedures that will result in differences in seismic reliability. However, any of the methods previously described, appropriately extended, modified and applied, will result in substantial improvement and acceptable seismic reliability if all of the criteria are satisfied. The owner/operator should also decide the extent of the seismic re-evaluation and upgrading. As a minimum all equipment required to achieve a safe shutdown and mitigate a design basis accident needs to be included. Optional equipment might be selected to assure integrity and cooling of the spent fuel pool, isolation and cooling of containment and confinement of radioactive waste products. The methodologies and procedures should, of course, have the concurrence of the regulatory authorities.

Recently high concern was expressed by many utilities due to the high costs of the implementation of such procedures, especially for very low seismicity sites where the Review Level Earthquake at a 10^{-4}/year or 10^{-5}/year probability of exceedance level generally would not exceed 0.1g to 0.12g pga. SMA procedures which have been developed for moderate 0.12g to 0.33g and high >0.33g pga sites are quite burdensome, expensive and provide very little cost benefit when applied to low seismicity sites particularly when such plants have had little or no original seismic design. As a result, new procedures are under development for such low seismicity sites that could be evaluated with criteria similar to what is applied in this report.

An important point of developing and applying any methodology or procedures for re-evaluation is that the personnel be properly trained, that a quality assurance programme is established and applied and that peer review by qualified experts be implemented at all stages of the re-evaluation and upgrade programme.

Even though this report is focused on qualification of equipment and certain other non-building structure commodities, the selection of the earthquake and the development of development of floor response spectra are an integral part of the process so guidance is provided for these two categories also.

5.2. Selection of the reference earthquake

IAEA Safety Guides on seismic hazard [5], provides general guidance for the selection of an SL2 earthquake. The SL2 earthquake is equivalent to the Safe Shutdown Earthquake defined in the US. The most up to date guidance for developing a SSE (SL2 earthquake) is contained in US Regulatory guide 1.165 [19]. In that Regulatory Guide the hazard is developed by probabilistic means and is defined as a 1E-5 median earthquake. 1 E-5 is also the requirement of German regulators. Other NPP owners have elected to base their re-evaluation on a 1E-4 mean earthquake. The US DOE performance based re-evaluation criteria is based on a 1E-4 mean hazard for the highest performance category (Category 4). Regardless of the methodology and frequency of occurrence and confidence level selected, the earthquake is conservatively defined by qualified specialists and concurred with by the appropriate regulatory authorities. It is compatible with the objectives of the seismic re-evaluation.

If a seismic PSA is selected, the hazard should have a full probabilistic description. The minimum description would be as described in Chapter 1. PGA is defined at 15, 50 and 85th percentile non-exceedance probabilities, along with the mean value, out to a recurrence frequency of less than about 1E-8 per year (Fig. 9). In addition, the spectral ordinates are defined as a uniform hazard spectrum for at least the 1E-4 and 1E-5 recurrence frequency.

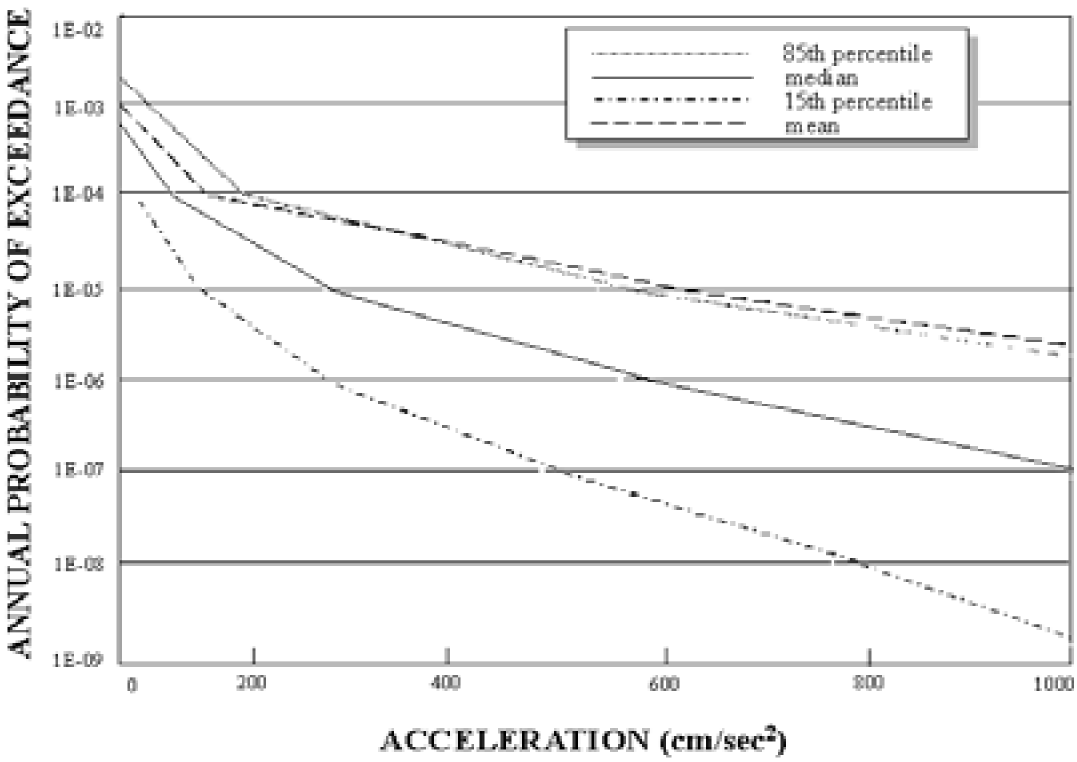


FIG. 9. Probabilistic distribution of seismic PGA.

5.3. Development of floor response spectra

Floor response spectra normally represent median response to the selected ground motion. ASCE 4-98 [53] provides guidance on development of FRS as does NUREG-0800 [21] and Regulatory Guide 1.122 [22]. For soil sites, variations in soil shear stiffness need to be addressed and the results of the variations enveloped, but not necessarily broadened any further. Alternatively, the individual spectra for the variations in soil properties may be peak shifted so that the spectral peak coincides with the dominant frequency of the system. A third alternative is to develop probabilistic FRS and use the 50th percentile value. An efficient and acceptable method for accomplishing this is by a Latin Hypercube Experimental Design Procedure. Probabilistic spectra were developed in this manner for several of the IPEEE evaluations in the US and the methodology was accepted by the US regulators. The development of probabilistic spectra is more labour intensive than deterministic methods but results in much more realistic FRS that are generally lower than best estimate (median centred) spectra that result from deterministic methods described for design or seismic margins studies.

5.4. Evaluation methodology

To date, no operating NPPs outside DOE have applied the DOE criteria.

To date, most re-evaluations of existing NPPs have applied the GIP as far as it is applicable, with some extensions in some cases. Some NPPs have applied seismic margins methodology, but the formal procedures are not in the public domain, and requiring a license for use. Some NPPs have selected seismic PSA for re-evaluation. Our recommendations will focus primarily on the use of the GIP since margins and PSA can be derived from the GIP methods as well.

Also the DOE criteria are an extension of the GIP but recast into a format to achieve performance goals. If the DOE GIP based procedures were to be used for re-evaluation of existing NPPs, some portions would require recasting to focus on definition a HCLPF, or else the end procedure would have to be a probabilistic performance goal.

Modifications and extensions of the GIP have been performed to accommodate conditions that the standard GIP does not cover or excludes. Modifications have included:

- Addition of criteria for HVAC ducting, vertical tanks, horizontal tanks
- Modifications to cable raceway systems to address plant specific conditions
- Modifications to anchorage criteria to address plant specific conditions
- Modifications to caveats to increase voltage from 4.16 kv to 6.3 kv
- Elimination of the method A ground spectra comparison for certain structures
- Increases in the minimum frequency for GIP screening.
- Increases in the screening levels for inherently rugged mechanical equipment

In general, the users of the GIP have found that the procedures are applicable to most mechanical equipment. Although there are no examples of identical equipment of the same manufacturers in the official SQUG database, comparisons of important features such as dynamic characteristics, materials of construction, geometry, etc. suggest that the GIP rules are applicable to NPPs outside the US. This is important since most equipment to be addressed are valves which usually fall within the GIP guidelines. In some NPPs, electrical and I&C cabinets have been found to be very flexible due to conditions identified in the GIP as outliers. These conditions are the lack of continuous sheet metal siding, shallow depth and insufficient support of internal panels. In cases where the GIP caveats have been met for electrical and I&C panels, subsequent testing has verified the initial GIP screening decisions. However, active devices within the cabinets such as relays, breakers, switches, switches, etc. cannot be verified using the GIP due to the unknown behaviour under shaking. These devices almost always require testing to demonstrate their capacity.

If modifications or extensions to the GIP are made, they should be justified by backup analyses or by the collection and processing of testing and experience data. An important issue in qualification testing or in the use of existing test data is that a single test at the level of the required demand does not demonstrate an adequate margin. In this respect, the use of seismic experience data consists of multiple natural tests and can be statistically shown to be more reliable than a single specific test. For this reason, in performing seismic margins assessments or seismic PSAs, the HCLPF from a single test is reduced from the test level. It is recommended that if components are qualified by test or by similarity to other equipment that has been tested, that the test response spectrum exceed the required response spectrum by a factor of 1.5 in order to verify an adequate margin.

If seismic experience is used to establish modifications or extensions to the GIP, the procedures to establish the capacity normally follow the guidance of ASME QME-1 2000 (Draft) [16] and IEEE 344, 1987 [17]. ASME QME-1 [16] and the latest draft for IEEE 344 [17] specify the minimum number of earthquakes and components that should be included and provides weighting functions to arrive at the capacity.

Since the application of the GIP or similar procedures to qualify equipment that is not included in the SQUG GIP database, and any modifications or extensions of the GIP will be outside of the original intent of the GIP for application to US NPPs with US equipment, it is important that these modifications and extensions be justified and reviewed by experts familiar with the development of GIP methods.

It is further important that peer review be conducted at all stages of the re-evaluation and upgrading. This includes review of the criteria to be applied, the development of the seismic hazard, the development of FRS, the application of the re-evaluation criteria and the design and implementation of the upgrades.

5.5. Proposals for procedure improvements

- Application of GIP procedure to non-GIP equipment (equipment that is not from the USA) are better addressed by validation studies: these aspects cannot be regarded as "supplier intellectual property". Documentation on the validation of classes, caveats, databases have to be available as part of the project QA and subjected to deep reviews.
- It is desirable that the concept of an evaluation of the safety margin applied to the qualification of equipment be emphasized in the development of qualification procedures. The proposal of the "performance goals" is an interesting attempt to interpret such need and should be extended to generic procedures.
- Aspects related to vertical seismic motion should be clarified and not left to the implicit assumptions of GIP.

- Combination of seismic loads with non-seismic loads needs to be clarified: many test data already combine them implicitly, but in a non-traceable way.
- The evaluation of the equipment fragilities from the databases or from the properties of generic equipment classes needs to be emphasized. An associated uncertainty also needs to be evaluated.
- Aspects related to the SSEL development are to be clarified: there is a too large difference in real implementation (from few thousands of items up to 20 000–30 000) that gives the impression of a different approach to safety. "Safe shutdown (hot or cold)" and other safety requirements in case of an earthquake (before, during and after) are to be clarified and made consistent with the general IAEA requirements [4]. Moreover, it should be clarified that similarity procedures are not considered applicable to some key components such as the "primary loop" items. Therefore, it is desirable that the limitations to the use of such procedures be set up clearly at the beginning of the project.
- The evaluation of the final safety margin of the upgraded facility should be emphasized. Only one method currently allows a realistic evaluation (implicitly) without development of a PSA. The use of similar approaches (such as "performance criteria") should be encouraged, also for application to facilities other than NPPs.
- Experience databases should be extended with available data and continuously maintained.
- More rigorous procedures for FRS evaluation should be developed, which avoid large conservatism and very much connected to the real structural layout and site conditions. Many procedures use the broadening while others use the envelope in the range 0.5-2. "Caveats" for the applications of the very many broadening, shifting, clipping procedures should be developed to avoid too high, unnecessary qualification demands to the equipment items whose safety margin is sometimes difficult to be proved.
- The uncertainties in FRS evaluation should be addressed explicitly, through statistics or through more realistic structural analyses with sensitivity extensions to the influence of the real scattering in soil data. Such uncertainties strongly affect the qualification process sometimes making the evaluation of the overall safety margin rather difficult

5.6. Proposal for improved implementation and regulatory review

As an outcome of previous analysis of the experience in Member States, a list of recommendations have been discussed at the meeting, as a guideline for further implementations of seismic qualification programmes.

The regulatory requirements should clearly identify the target of the requested action, with a precise distinction among:

- evaluation of the SSCs seismic ruggedness of the seismic safety related SSCs
- evaluation of the safety margin of the plant to seismic actions
- development of a PRA as a confirmation of the previous tasks

The requirements should also identify the reference standards, if any, for the development of such tasks.

The basic documents to be requested are:

- the "unified criteria document for the seismic qualification", with proof of the caveats in use and documentation of their consistency with available databases, validation of additional screening rules, guidelines and simplified calculation charts
- the project QA document, with specification on the mechanisms for independent review of the implementation, for the peer review of the methods, as in [65], for the evaluation of the compatibility of different methods used in the same project, for the selection of responsible technical team, for the project team structure and responsibilities
- the independent review document on the application of the selected methodologies

Training is a key component for a correct application of such similarity criteria: even if some discrepancies are expected between evaluations carried out by different experts, a clear training programme on criteria and methodologies for a correct application might limit the differences in the conclusions. Therefore the training programme should be part of the review by the regulatory body as guarantee for a sound application of the procedures discussed in this report.

Moreover, the peer review has been recognized as a key tool for the assessment of the qualification procedures: their intrinsic qualitative nature prevents any late review on the results and requires a precise involvement of the regulator during the qualification process. Its review in fact cannot stop at the "unified criteria" level, but should be applied at any stage of the process.

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PART II — SEISMIC DESIGN AND RE-EVALUATION OF PIPING SYSTEMS

6. EXPERIENCE IN APPLICATION OF CODES FOR PIPING DESIGN

6.1. Introduction

As mentioned in the general introduction, this part collects the main issues identified in the technical seminar held in Pamporovo, Bulgaria (27–30 March 2000) on Seismic Re-evaluation of Piping Systems. In particular, the results of some research programs carried out in USA and France are described, with reference to both the earthquake experience gained after last worldwide earthquakes and the most recent experimental tests in laboratories. The IAEA experience from many review missions in developing Countries is also provided, with emphasis on the re-evaluation of existing facilities built with earlier standards and seismic design bases lower than the current ones.

In many cases the impact of these results on the national design codes for nuclear structures is discussed in relation to current standards and future developments.

6.1. IAEA synthesis on feedback experience from earthquakes

Seismic feedback experience from the most recent big earthquakes is gathered in reports edited by scientific associations such as EERI (Earthquake Engineering Research Institute) or AFPS (Association française du génie parasismique), or by companies such as EPRI (Electric Power Research Institute) or EQE that specializes in earthquake engineering [1-4].

The feedback experience from 28 recent big earthquakes, most of them with magnitudes larger than 6.0, is now publicly available: Spitak (Armenia, 1988), Loma Prieta (California 1989), Northridge (California 1994), Kobe (Japan 1995), Ceyhan-Misis (Turkey 1998) and Kocaeli (Turkey 1999).

The following issues were identified at the seminar as the main responsible of the damage after analysis of the available data, not only in relation to piping systems and components but also to civil engineering structures.

- the regularity of the structure (in-plan as well as in-elevation regularities).
- the quality of the construction. In a quite recent past it was usual to insist on the quality of the reinforcement; it appears also that the bad quality of the concrete itself is a source of major damages.
- the possible specific fragility of some precast systems. On the other hand some precast systems were found to be safe.

Concerning piping systems, it clearly appears from the feedback experience that they survive earthquake shaking motion particularly well, even amplified by the bearing structures. It is worth to mention that most of them were not designed against earthquakes. The observed cases of rupture of piping systems are consequences of differential input motion on excessively rigid pipes. (Other causes are non-mechanical causes as for instance poor maintenance that results in a lack of detection of excessive erosion of the pipe wall.) This very good feedback experience is collected in [5].

The available feedback experience data also covers electrical and I&C equipment. It is known that earthquakes may cause extensive damages to electrical sub-stations because some devices are supported by brittle (made of ceramic) insulators. All the electrical equipment mounted on wheels (for maintenance purpose) are very sensitive to earthquakes except in case some specific devices prevent them to move. Earthquakes non-damaging structures may cause some dysfunctions in systems such as spurious alarms.

For structures and distribution systems (civil structures as well as mechanical engineering structures and piping systems) the main lesson of the feedback experience is that the seismic margins are located in the ductile capacity.

6.2. Experience in the USA

6.2.1. Seismic response of piping

Piping seismic response was reviewed to describe failure mode and design margin based on laboratory test data and field earthquake experience. It was pointed out that the inherent margin in piping systems designed with conservative codes was beneficial to the seismic re-evaluation of existing nuclear power plants.

6.2.1.1. Seismic response behaviour of piping

EPRI and NRC co-sponsored the piping and fitting dynamic reliability (PFDR) [6] programme to provide answers on the question of margins and failure mechanisms in piping systems subjected to dynamic loading.

Both components tests and system tests were performed. The objectives of the component tests were to determine failure mode(s) under dynamic loading, to measure ratcheting and cycles to failure, and to develop engineering understanding of component behaviour. Components tested are 6 in. diameter, sch. 10, 40, 80 elbows, tees, reducers, nozzles, and support connections. Seismic wave input peak was set at 0.5 Hz below component natural frequency at the shake table maximum excitation.

The component tests in general showed that sch. 10 components cracked in 1/2 to 3-1/2 seismic inputs several times of level D, sch. 40 cracked in 1-1/2 to 3-1/2 seismic inputs, and sch. 80 cracked in 5 to 9 seismic inputs. It was observed that dynamic load reversal prevents collapse and thus seismic loads behave like secondary not primary, ratchet failure loads are >>SSE, ratcheting does not impair functionality, and damping for large dynamic loads is higher than what prescribed in [7]. Furthermore, using elastic analysis with 5% damping and $\pm$ 15% broadening is conservative at suggested level D limits and fatigue usage calculations using ASME code [8] rules is also conservative.

The system tests confirmed all the behaviour observed in components tests. It was therefore concluded that it is extremely difficult to have failure in piping with dynamic/seismic loads; piping systems designed based on ASME Section III code rules have large margins.

6.2.1.2. Field experience with pipi ng in seism ic scenarios

In addition to laboratory testing, piping seismic experience was studied. Stevenson and Associates [9] and EPRI [10] did two independent, extensive surveys of power plants and industrial piping earthquake response performance. The peak ground accelerations of these earthquakes ranged from 0.20g - 0.51g with earthquake duration in the range 3.5 - 15 seconds. More than 100,000 feet of pipe (36% high energy) and 40,000 in-line components were surveyed. Most of these plants are non-nuclear.

The survey showed that there was less than 1 piping failure per unit and the causes of observed failures were seismic anchor movement (equipment/branches), non-welded joints, and eroded/corroded pipes. The seismic-induced above-ground power plant piping (B31.1 pipes) failure was not significant for zpga < 0.40 even when such piping was not designed to resist lateral seismic loads. Consequently, earthquakes do not cause inertial failures in welded steel pipe except in regions of high corrosion or erosion.

6.2.1.3. Vertical tanks

Performance of vertical ground mounted storage tanks under actual earthquakes in the field were evaluated by EPRI. It was observed that anchored tanks performed well even though the anchorage might be inadequate per design requirement. For tanks without any anchorage, they showed possibility of overturning and damage under strong motion earthquakes. Thus, any amount of anchorage will add significant improvement to the tank seismic performance.

6.2.2. Piping design code and acceptance

Modern design of nuclear power plant piping systems is governed by Section III, ASME in which margins on fatigue and limit load failures are embedded. Since seismic inertia loading is treated as a primary static loading, the code does not consider the benefit of the short duration, reverse cyclic loading nature of seismic loads. Excessive conservatism in the code thus resulted in higher support requirements and excessive use of snubbers. This could lead to less safe systems due to higher thermal stress from the constraints, reduced access for in-service inspection, and potential failure of snubbers (lock up). However, the margins provided by conservative code criteria in existing plants give room for requalification for earthquakes larger than design basis earthquakes (DBE), or safe shutdown earthquake (SSE).

6.2.2.1. Piping design codes

Piping codes have evolved over the last 80 years from about 100 pages to more than 7,000 page. The 1955 USAS B31.1 [11] code for power piping covers evaluation of pressure, thermal, and dead weight stresses, providing guidance for placing pipe supports. In the latest editions, guidance for evaluation of seismic and fluid transient-inducted stresses was included.

The 1969 USAS B31.7 [12] for nuclear power piping contains more in-depth evaluation for pressure boundary piping, which was subsequently identified as ASME Class 1 non-pressure boundary piping. In 1971, ASME Section III incorporated B31.7 and class 2 and 3 remained the same as B31.1. The 1974 edition was expanded to provide rules for vessels, piping, pumps, valves, etc. There are altogether seven volumes: NA through NG. ASME

Addenda which reflect revisions due to advancement of the state of technology are issued every three years starting from 1972.

The failure modes addressed by the ASME code are: bursting, gross distortion, and elastic instability, progressive failure and fatigue failure. The elastic stress categories are divided into primary stress: cause catastrophic or instantaneous failure; secondary stress: no instantaneous failure but could lead to incremental plastic collapse; and peak stress: contribute to fatigue crack growth.

The ASME [8] code design conditions can be separated into four levels:

- Level A: normal conditions — expected to occur;
- Level B: upset conditions — will probably occur;
- Level C: emergency conditions — infrequent conditions;
- Level D: faulted conditions — low probability of occurrence.

The ASME code does not rule on categorization of loading, nor does it determine combination of loads. These are determined in the NRC Reg. Guide 1.48 [13], design limits and loading combinations for seismic category 1 fluid system components. For nuclear power plant piping systems, the acceptance of design is per satisfying NRC 10 CFR 50 and 10 CFR 100 [14], Standard Review Plan (SRP), Regulatory Guides (R.G.), and IE Bulletins.

The regulatory framework for piping design includes the following:

Regulatory requirements [14]
- Appendix A, 10 CFR part 50
- General Design Criteria 2
- General Design Criteria 4
- Appendix B, 10 CFR part 50
- Appendix A, 10 CFR part 100

Regulatory guidance
- Regulatory Guide (RG) 1.61 [7]
- Regulatory Guide 1.48 [13]
- Regulatory Guide 1.92 [15]
- Regulatory Guide 1.122 [16]
- Standard Review Plan (SRP) 3.7 [17]
- Standard Review Plan 3.9 [17]

Regulatory acceptance
- Design practice can deviate from regulatory guidance with justification bases, but should not violate the rules and regulations.

In the USA, for PWR primary systems, SSE and LOCA do not need to be combined together, based on “leak before break” consideration. For limited cases, decoupling of pipe breaks and SSE for secondary systems was accepted by the US NRC. The basis for decoupling of pipe breaks and SSE is that the probability that both would occur at the same time is extremely low and leakage monitoring can prevent unstable large flaw from occurring.

6.2.2.2. Proposed revisions to ASME Code

The ASME Section III code for piping design prior to the 1994 Addenda was based on static failure mode consideration. The EPRI/NRC [6] tests showed that piping components and systems under cyclic dynamic loading failed in a fatigue ratcheting mode with a much larger margin than the code allowed. Furthermore, the field experience data showed that well engineered piping systems did not fail under larger earthquakes even for those designed with less restrictive codes. The 1994 Addenda which incorporated the new understanding/data within the same framework of linear elastic design approach relaxed the Equation 9 allowable stress from 3 Sm to 4.5 Sm.

However, the US NRC raised questions on the calculation of margin and the progressive large deformation observed in certain thin walled, unpressurized components, and thus did not endorse the code Addenda. Since then ASME has formed a Seismic Working Group to work on to re-evaluate all the test data and formulate revisions that are acceptable both to industry and the regulatory body. The latest ASME Working Group proposed revisions are to change the B2 indices and maintain the same allowable stress, 3 Sm. For elbows, bends and tees, the change of B2 to 2/3 is equivalent to the original proposal of 4.5 Sm allowable stress. For other components and fittings, the new B2s result in either no relaxation or smaller relaxation. The new proposal has achieved a large degree of consensus. It is likely to be approved in 2000.

Based on the EPRI/NRC test programme results and field seismic experience data, in 1989 EPRI (in collaboration with GE) recommended code changes to remove unwarranted conservatism. The most important recommendation is to change the Equation 9 allowable stress from 3.0 Sm to 4.5 Sm and remove the differentiation of OBE and SSE. After many iterations and working through the ASME reviewing hierarchy, the ASME code body approved the proposed changes and published the 1994 Addenda. The US NRC did not endorse the Addenda because of issues related to margin interpretation of certain test data and the progressive deformation mode of certain thin walled unpressurized pipe components. Since 1994, NRC has sponsored further works on test results correlation and understanding and ASME has formed a working group to re-evaluate the test data and the Addenda seeking changes to reach consensus.

The latest proposal formulated by the ASME Working Group is to change the B2 indices and maintain the same allowable stress. For elbows, bends and tees, the allowable stress of 3 Sm combined with a B2 of 2/3 is equivalent to the original proposal of 4.5 Sm allowable stress. For other components and fittings, the relaxations are either smaller or none.

6.2.3. Seismic re-evaluation issues

Seismic re-evaluation requires the consideration of DBE or SSE definition, the load applied to the structure and the force distribution in the structure, and the overall safety margin available in the plant.

6.2.3.1. Seismic hazard modelling

The first step in seismic design or re-evaluation is to define DBE or SSE which requires the understanding of earthquake source mechanism, distribution of sources, the magnitude distribution of each source, the ground motion attenuation and the probability of occurrence. Historical earthquakes and expert judgement play an important role throughout the procedure to define the seismic hazard at a given site, namely the probability of occurrence for a given ground motion level.

The origin of the review level earthquake (RLE) in US was a result of seismicity re-evaluation in the eastern and central United States, and also the inquiry of the US ACRS on ultimate seismic capacity of nuclear power plants. The RLE was defined to be a credible earthquake larger than DBE or SSE, but not a new DBE or SSE. Consequently, plant piping systems do not have to be retrofitted to meet conservative design code requirements under RLE. Instead, plants only need to be evaluated for safety under RLE. The key concept is that plant can be safely shut down without undue risk to public when a low probability RLE occurs. Because of that, more relaxed criteria can be used. Seismic PRA and SMA are two approaches that can be adopted to do RLE evaluations. Whether a plant has to define a new DBE because of newly discovered fault or seismic sources is a decision between the plant owner and its regulatory agency. The implication is that if a new DBE is defined, then design criteria such as those defined in Section 1.2.1 have to be satisfied. In US, RLE is always referred to earthquakes for safety evaluation, not as a new DBE for design.

In US, RLE is used to evaluate the safety of existing nuclear plants for earthquakes larger than DBE or SSE. If new plants are to be constructed at the same site, it is recommended that RLE be used as the DBE for the new plants. However, this is also dependent on how RLE is defined (probability of occurrence) and the agreement between the plant owner and its regulatory body.

6.2.3.2. Soil-structure interaction modelling

The second element in seismic design or re-evaluation is to define loading input into the plant foundation and subsystems for a given control motion anchored to a broad or site specific spectra. The foundation loading input is calculated through soil-structure interaction (SSI) and the subsystem loading input (floor spectra) is calculated through major building response. Since SSI is in general highly non-linear (SSI in general downshifts soil-structure system frequencies and increases soil-structure system damping), conservative acceptance criteria of SSI analysis are imposed resulting in large foundation loading. Since the foundation input dictates the determination of floor spectra, the subsystem design becomes conservative as well.

The US NRC in SRP for a long time required the enveloping of the results using two different SSI analysis methods because of uncertainties in analysis. By calibrating and benchmarking analysis methods using the Lotung earthquake data (sponsored by EPRI and the Taiwan Power Company), the revised SRP accepts results based on one method only if that method has a verification basis.

One additional phenomenon involved in SSI is spatial incoherence. Because of complexities of seismic wave transmission from the source to the site, plane wave passage may not fully account the observed randomness or incoherence in the variation, especially for high frequencies. This incoherence effect will result in spectra peak reduction in the higher frequency range which is beneficial for qualification of equipment mounted on floors.

6.2.3.3. Seismic margin assessment

Basic steps of a seismic evaluation involves steps to define ground motion, define components for which evaluation is needed and determine seismic capacity of components to be compared with acceptance criterion. Acceptable methods in US for Individual Plant Examination for seismic events (IPEEE) [18] are seismic probabilistic risk assessment (SPRA) and seismic margins assessment (SMA). SPRA is probabilistic seismic hazard based which is more complicated and requires special expertise (hazard, fragility, systems PRA). SPRA dose not yield deterministic indication of seismic capability of plant.

The SMA approach is deterministic and more practical. It is experience-based and screening focused on walkdown and practical safety improvement. It does not require hazard data or fragility calculations. It can be performed in house with a short learning curve and it is compatible with SQUG (Seismic Qualification Utility Group) [19] approach which is widely adopted in US for equipment seismic qualification.

One key element of SMA is that a review level earthquake (RLE) should be defined as explained above. SMA is performed to assure that plant can be safely shut down under RLE without posing undue risk to the public. For IPEEE in US, NRC has prescribed RLE to be NUREG/CR-0098 [20] median spectral shape anchored to 0.3g for most plants.

SMA component selection and screening is done by success path logic to achieve and maintain shutdown and component generic seismic ruggedness screening is based on past experience and judgement by evaluators. Extensive plant walkdowns are conducted to verify screening and identify, verify outliers. Their capacity is assessed via deterministic calculations aimed at the evaluation of a “high confidence-of a low-probability-of-failure” (HCLPF). The deterministic plant seismic capacity then is defined in terms of the lowest capacity components. Based on available experience and data, SMA is more practical for RLE below 0.3g peak ground acceleration (pga).

SMA encompasses a multidiscipline effort: system engineers define critical function and components; system operations engineers choose preferred paths to shutdown; and seismic engineers screen components based on generic ruggedness data and make judgements on their specific applicability.

6.2.3.4. Seismic re-evaluation of structures, equipment and components

For re-evaluation of seismic Category 2 and 3 components against RLE, the seismic margin approach only requires two safe shutdown paths. All structures, equipment, components, etc. needed to assure the functionality for safe shut down have to be qualified either by analysis, test or experience data. A screening process should be performed first. Detailed evaluations should follow for those that could not be easily screened out.

If an RLE is defined to be the new DBE, then all the design requirements need to be met. In the USA, that means meeting the requirements and criteria stipulated in the plant Final Safety Analysis Report (FSAR), unless some relaxed requirements can be negotiated with the regulatory agency.

6.2.4. Piping degradation due to corrosion

Power plant piping and equipment are subject to degradation from a variety of mechanisms. Some mechanisms are rather aggressive and can pose a threat to the pressure boundary integrity in months, whereas others may take decades. Some may cause small leaks, whereas others can cause sudden and catastrophic ruptures of high temperature and/or high pressure piping or vessels.

6.2.4.1. Corrosion mechanism and threat

Boric acid corrosion

Boric acid is commonly used for reactivity control and sometimes the secondary circuit of PWR plants to help control IGSCC. The most common threat is accidental leakage onto carbon steel components (e.g., leakage past a valve packing that sprays or drips onto adjacent piping, vessels, etc.).

Cavitation

A type of erosion caused when water near the saturation pressure experiences a large pressure drop. Steam bubbles are formed and then violently collapse when the pressure recovers. The collapse sets off shock waves which cause deformation and subsequent damage. Commonly occurs within and downstream of control valves, orifices, pumps, and sometimes at reducers/expanders and elbows. It can be quite fast acting. It tends to cause sharp, jagged damage.

Droplet impingement

Also called liquid impingement erosion. Caused by water droplets in a moving gas (e.g., steam) eroding material from a parallel or orthogonal surface. It can be fairly fast acting. It tends to cause sharp, jagged damage.

Erosion-corrosion

Caused by erosion of a protective oxide film on a passivated metal followed by corrosion of the base material. Copper and brass alloys are especially susceptible to this damage mechanism. Carbon steel also has some susceptibility. Locations where commonly found include heat exchanger inlets, straight pipes, elbows, and tees.

Flow-accelerated corrosion (FAC)

It occurs in carbon and low alloy steels exposed to moving water or wet steam. It results from dissolution of normally protective oxide layer: layer is reformed and again dissolved in a continuous process. Wall loss tends to occur over a fairly wide area, rates as high as 5 mm/year have been measured in power plants. Commonly found in piping and vessels of steam generation loop. Single phase damage typically appears as small smooth scallops; two-phase damage often appears as tiger stripes.

Flashing

Water near the saturation pressure can flash to steam at locations of high pressure drops most commonly occurs at orifices and control valves. Typically it causes droplet impingement and accelerated FAC downstream.

Fouling

Fouling is commonly found in power plant service water systems. One form occurs on heat exchanger tubes resulting from the inverse solubility3 precipitates out). Another form is caused by microbes attaching to piping, Hx tubes, etc. (form biofilms). It can attract other suspended particles. Fouling can degrade Hx performance, increase flow resistances, accelerate corrosion, interfere with valves, etc.

Fretting

It can occur at contact areas of materials subject to vibration and slip. Pits can be formed where water impurities can concentrate to further accelerate the attack and from which fatigue cracks can nucleate. Sometimes it was found in steam generator and condenser tubes

Galvanic corrosion

Also called “dissimilar metals corrosion”. It occurs when two dissimilar metals are in contact and wetted by an electrolyte. Corrosion of the less noble metal is a function of the distance between them on the electromotive series. It can occur at welded, bolted, or screwed joints. It was also found at pipe hangers wetted by condensation.

General corrosion

It tends to occur over a fairly wide area of a component. Rusting of mild steels is a common example. Rate of corrosion is considered the lowest at which the component will degrade. However, it can be fairly aggressive to carbon steel in salt water/salt air environments.

Intergranular attack (IGA)

A localized attack at the grain boundaries of a metal causing loss of strength and ductility. Sometimes it was found in stainless steel piping and nickel alloy steam generator tubes.

Intergranular stress corrosion cracking (IGSCC)

It is caused by the simultaneous presence of a tensile stress field, a susceptible material, and a corrosive medium (e.g., water). It can occur at fairly low stresses and is characterized by localized fine cracks which can progress though the material. It has been most commonly found in high alloy steels such as BWR recirculation loop piping, nickel alloy steam generator tubes, and in reactor internals.

Microbiologically influenced corrosion (MIC)

It is associated with a biofilm and colonies of different species creating localized chemistry conditions and waste products.

Pitting corrosion

Sulphides and other ions dissolved in oxygenated water can cause pitting in susceptible materials. These include copper alloys, brass, stainless steel, and various nickel alloys. It was commonly found in raw cooling water systems, particularly sea water.

Sedimentation

Suspended solids such as silt and fine grasses can pass through filters and screens of raw cooling water systems. It can settle when they reach areas of low velocity. It can build-up and harden with time, increasing system pressure drop and potentially compromising ability of system to deliver required flow in critical situations.

Solid particle erosion

It occurs when particles suspended in a high velocity fluid strike a component surface. Sometimes it was found in service water and circulating water systems. Approaches to control corrosion require good plant and system design, good material selection and fabrication methods, non-damaging water chemistry, and periodic inspections.

6.2.4.2. Dynamic response of eroded/corroded pipes

Ten eroded/corroded piping components obtained from actual plants were tested in the laboratory under seismic type loading similar to that in the EPRI/NRC PFDRP tests. The worst case component wall thinning is more than 50%. The tests showed that the degraded pipe components remained to have a large margin prior to fatigue ratcheting failure, more than 50% over level D. Depending on the plant DBE or SSE and RLE magnitude, the margin may be even higher, supporting the continued operation and monitoring for maximum benefit.

6.2.4.3. Corrosion of buried piping

Detecting and controlling buried piping corrosion is a difficult task. It is suggested that there should be non-destructive examination techniques available to detect corrosion in buried pipes. Understanding the chemistry of water or flow medium and flow conditions inside the pipe and the chemical characteristics of the soil surrounding is essential in controlling piping corrosion.

6.3. Experience in France

6.3.1. Feedback experience from tests in France

Seismic design of piping systems is a subject of interest in NPP. This is due to the following reasons:

- Large quantity of piping exists in a plant.
- Analysis problems caused by the need to soften piping systems for thermal loads and to stiffen them for seismic one. Adding supports for seismic loads increases thermal loads and potential fatigue problems under normal operating conditions.
- In existing plants many systems are not seismically designed or are designed according to “old” regulations and practices.
- Post earthquake feedback experience shows very clearly that piping systems, even non-seismically designed, are not fragile component; experimental results confirmed these observations.

Existence of significant margins in piping systems designed according to current codes is clearly evidenced; this is associated to the feeling that some practices (e.g. adding supports) are decreasing the overall safety.

In order to better understand this behaviour and to quantify margins, an important R/D programme was launched in France together with the Utility, EDF, the constructing company, Framatome, and the Safety Authority, IPSN [21]. The aim was to propose procedures for accurate non-linear analyses, simplified methods for piping systems calculation and more realistic design criteria.

6.3.1.1. Overall view of the programme

The different tasks were defined in order to get experimental results for component behaviour, dynamic results for systems and to develop analytical methods for non-linear analyses and simplified evaluation capabilities.

6.3.1.2. Static piping tests

A large number of static deformation tests results on piping components exists in the world. Their analysis is the first step in understanding non-linear piping behaviour. A review of existing results was carried out: it allowed quantifying failure modes fatigue, ratcheting, elastic or elastoplastic instability…) deformation capacity, the maximum loads and to compare them with the values allowed by the Code [22]. For this programme it was judged that the most critical components are elbows and that experimental results are needed in the out of plane behaviour. Monotonic and cycling loads with a constant pressure were applied on elbows in stainless steel of the same dimensions that the line described in Section 6.3.1. Non-linear moment displacement curves were compared with analytical calculations using 3D elements, shell elements and global beam type elements taking into account ovalization of the section.

In repeated cyclic tests, fatigue cracks were observed. Code type evaluations showed that the experimental points were higher than fatigue best fit curve; fatigue ratcheting needed not to be considered for the range of parameters of interest.

In general, it was found that the 3Sm limit for faulted conditions in ASME III [8] or RCC-M code [22] are a good representative of maximum load.

The rotation at maximum load was about 10° for stainless steel elbows and 3–5° for Carbon Steel in closure mode; higher values were obtained in opening mode.

6.3.1.3. Dynamic test on stainless steel pipe: ELSA test

A stainless steel pipe (OD=168.3 mm, t=7.11 mm) representative of an RHR pipe on actual plant was tested on the 6 m × 6 m AZALEE Shaking table in the Seismic Laboratory in CEA-Saclay. The system was designed with Code criteria for a table acceleration of about 0.4g for a representative time history. The damping at low amplitude is 0.14%: this low value was due to rigid supports. One dominant mode was present. The test was performed to the maximum capacity of the table about 7 times the design level, without any visible permanent deformation or cracking. The maximum measured strain was 1.2%.

6.3.1.4. Dynamic test on carbon steel pipe: ASG test

A second test was performed with a Carbon steel pipe (OD = 114.3 mm t = 8.56 mm) designed to code criteria for a table acceleration of about g. Here the damping at low amplitude was 1%; this higher value was mainly due to one of the supports which allowed torsional rotation and axial displacement. Some friction was mobilized. As in the previous test, at the maximum capacity of the table neither visible permanent deformation, nor cracking was visible for a maximum strain of 1.2%. Two modes participated to the response.

6.3.1.5. Evaluation of the results by analysis

Non-linear analyses were performed with the finite element code CASTEM2000 [23] developed in CEA, in order to interpret the experimental results: the good comparison of beam type global element analysis with dynamic and static tests confirmed the adequacy of the formulation and it capability to simulate the non-linear behaviour of piping systems until failure.

Simplified methods were tested in order to propose validated methodologies for non-linear design of pipelines. The Hinge method consists of performing successive steps of spectral analyses; each step corresponds to progressive plastification of a part of the line, generally in elbows. This promising method shows the successive formation of hinges and gives the displacement pattern. It is associated to the definition of inelastic spectrum.

Equivalent linearization derived from Caughey approach gives precisely the evolution of equivalent frequency and damping with the input level. For the ELSA line, the damping at failure reaches 14% with a frequency drift of 27%. The application to multimodal structures is still under development.

With non-linear analysis, it is possible to estimate the failure level of both tested lines. For ELSA this level was about 2.7 times the test level where the bending moment was about 10 time less than the value calculated with modal spectral analysis using the initial 0.14% damping value. Using 2% this ratio increases to 3; the damping value to be used for the interpretations is an important parameter.

In conclusion, this programme demonstrated the margins available in the design codes and to verify the capability of numerical codes in the simulation of the non-linear behaviour of pipelines.

6.3.2. Proposal for new criteria in Europe and in France

6.3.2.1. Introduction

The seismic design of piping systems consists in defining supports in order to:

- Protect equipment by limiting the nozzle loads;
- Fix important masses such as valves;
- Limit potential damages, generally by limiting stresses according to code, displacements or accelerations.

These results are usually obtained by using elastic modal analysis with floor response spectra and static evaluation of anchor displacement. However, the stress criteria proposed in design Codes considers that earthquake is a static equivalent loading; the stress criteria are then very stringent. This approach results in design of stiff lines with heavy supports which may be sensitive to fatigue problems associated with thermal expansion. Moreover, the criteria are not representative of actual seismic behaviour. Therefore new criteria resulting from R/D programmes are under study, as explained in the following.

6.3.2.2. Proposal of new French criteria for design

Results from tests in France, Japan and USA has been used to quantify the margins. The moments calculated by linear analysis are too high compared to actual moments: this is due to plastification. It is proposed in Code [22] to reduce the inertial moment due to earthquakes. Examining the test results, a reduction factor of 3 is proposed for a 2% damping linear analysis. If a 10% damping analysis is used, this reduction should be at least 1. In faulted conditions, the proposed equation for acceptance of stresses in the pipe is:

$$B_1\, PD/2_e + B_2(M_p+M_{SI}/r)/Z \leq 3S_m$$

The right hand side is the same as in the present code, due to its good correlation with the static test results. R is the reduction coefficient.

Anchor displacement may be treated in one of the following ways:

(a) Include the moment due to anchor displacement in the previous equation after dividing it by a coefficient representing the "allowable ductility" in displacement; a value of 5 or 7 seems appropriate.
(b) Consider a separate equation which limits the moment due to anchor displacement.

6.3.2.3. Proposal for piping re-evaluation

In the process of seismic re-evaluation, which is different from design, some adaptation of the code may be proposed. It is not recommended to add new supports on an existing line with significant thermal transients. It will increase fatigue problems and decrease the overall reliability. In that case some increase in allowable stress can be taken into account. A factor of 1.5 or 2 could be adequate but it should be justified according to the overall design process. For low safety class, simplified static analysis may be used.

6.3.3. Lessons learnt from recent experience

6.3.3.1. Combination of thermal and seismic stresses

Do we need to combine seismic and thermal stresses? In faulted conditions, it is not required, because the aim is to verify elastoplastic instability, which is due to primary loads only. But this question can be generalized to all secondary loads, such as anchor displacement. In the new French proposal, where seismic inertial loads are considered as partially secondary, the equation above proposed limits to the deformation of the component. Usually, thermal deformation is usually small compared to other loadings, and it may be excluded from the verification.

Another issue concerns the location of postulated breaks which are used for design of pipe whip restraints. Their definition should include the calculation of total stress, which should include thermal loads.

6.3.3.2. Piping systems with buried and unburied parts

The design method for such cases should be adapted according to the specified conditions (embedment depth, material properties, etc.). One possible approach is building a simple finite element model with continuous elastic springs modelling the effect of the soil; numerical values for spring are given in literature. The design should exclude short and rigid parts; the design method should be consistent with this condition.

6.3.3.3. Design of steel piping support structures

The question is to decide if the support structures should be considered part of building structures or part of the piping system: design principles may be different. If they are considered as part of buildings, some ductility may be considered, for instance.

There is a section of ASME III code which is devoted to support structures and which may be used. It has been noticed that it is very conservative, as it requires an elastic behaviour under all loadcases, even thermal. It is a general opinion that the approach can be adapted to adapted to the specific case: for re evaluation, some plastic deformation may be accepted under seismic load provided steel sections and anchoring systems are adequate.

In general, it seems incorrect to consider the supports as part of a building if they do not participate in the equilibrium of horizontal seismic loads.

6.3.3.4. Buckling of piping systems

There are no criteria in the codes of the USA or France concerning the stability (buckling) of long vertical pipe. The idea is that the design should avoid long vertical spans in compression.

6.3.3.5. Anchoring of tanks

It is recommended to anchor equipment subjected to seismic loads, which otherwise may overturn and slide. Some large vertical tanks may be difficult to be anchored if they are supported on ground. For such components, design practices may allow not to anchor them, but a verification of the overturning stability and the displacement at connected pipes is required.

6.4. Analysis of the seismic response of piping system

6.4.1. Analysis of margins in piping systems

As suggested by feedback experience and confirmed by experimentation, ductile structures exhibit large margins against seismic loads. Modelling of simple ductile structures can be carried out in order to analyse these margins and to give interpretations of the experimental results.

A key result of the analyses is that margins not only depend on ductility but also on dynamic effects. For broadband input, such as seismic ground motions, the lower is the eigenfrequency of the structure (versus the central frequency of the input) the larger are the margins. For narrow band input, such as floor motions, larger margins are obtained in case of resonance (frequency of the component tuned on the central frequency of the floor motion); it just means that in these cases the classical elastic approach is the most pessimistic. These analytical results support the interpretation of the experimental results obtained on shaking tables, either in USA or in France.

Therefore inertial forces should not be considered as primary forces and the design criteria of piping systems should be reformulated accordingly. For instance the following formula can be proposed:

$$S_p + t_i\, S_i + t_d\, S_d < S_{ad}$$

with the following notations:

S_p: Stress due to pressure and other permanent loads to be considered
S_i: Stress due to seismic inertial effects
S_d: Stress induced by seismic differential displacements
S_{ad}: Usual admissible stress
t_i : Primary ratio of the inertial stresses
t_d: Primary ratio of the differential displacements stresses

In current criteria, we have (SSE earthquake) t_i =1 and t_d =0. It seems reasonable to propose something like $t_i = 1/(2\mu-1)^{1/2}$ (possibly also frequency dependant) and $t_d = 1/\mu$, where μ is the accepted ductile capacity of the component under consideration.

This approach is supplemented by the analysis of the probability of failure due to plastic instability of a single degree of freedom system. It can be shown that the probability of failure of a brittle system may be divided by a factor 100 to 10000 with a ductile capacity of only 2 to 3 (2 to 3 times the elastic limit strain).

6.4.2. Ratcheting effects

An experimental finding from the tests on shaking tables is that very often the observed failure mode is fatigue ratcheting; this is a cumulative effect of fatigue (cyclic content of the seismic response of the component) and of cumulative plastic strains (combination of the pressure and again of the cyclic content of the response). This failure mode is not the one assumed by the design criteria (where plastic instability is assumed).

A modification of design criteria towards less severe criteria could be acceptable to the extent the fatigue ratcheting failure mode is still prevented. Some formulas were proposed in the literature on the way to modify fatigue criteria so as to take into account ratcheting. However, to this aim it is necessary to develop simple engineering approaches to estimate the cumulative plastic strain induced by the earthquake. Some indications have been developed on this matter. Practically this approach enables to demonstrate that the new design criteria (either in Europe or in USA) are so that ratcheting effects are negligible (despite plastic strains are possible).

6.4.3. Differential displacements

The calculation of the response of a piping system that undergoes different input motions at different supports is a typical problem of the piping design. From the response of the bearing structures it is possible to determine a matrix of correlation of floor motions. This matrix can then be used in a classical type quadratic combination rule.

6.4.4. Other aspects of engineering practice

The flexibility of the piping support may strongly affect the response; the point is to know which support can be regarded as perfectly rigid in the design of the pipe. The amount of steel needed for the construction of the supports directly corresponds to the assigned stiffness. Engineering practice and final installation modalities are very different from one company to another: it would be worthwhile developing a national engineering practice on this point for any project of interest.

For piping systems, aspects other than relevant to seismic design are of interest. Some minimal natural frequency of the piping system may be required as a way to prevent from consequences from flow induced vibrations. Also the physics of water-hammer and its consequences on design criteria should be considered in comparison with the case of the seismic loads, both of them being dynamic loads.

7. LESSONS LEARNT FROM RESEARCH AND OBSERVATIONS

From the feedback experience, it appears that piping systems that are not designed to withstand seismic conditions generally exhibit a satisfactory behaviour, even in case of severe earthquakes. This fact confirms that the usual engineering practice and usual criteria overestimate the damaging capacity of inertial effects. Some failures were nevertheless observed that were due to excessive differential displacement effects, despite the fact that the stresses associated with them are usually regarded as “secondary stresses” in the nuclear design practice.

Concerning design criteria and associated engineering practice for piping systems, the main conclusions on testing on shaking tables are the following ones:

I. Design criteria as the ASME criteria provide very large margins against seismically induced failure, which confirms feedback experience.
II. The possible failure mode is not plastic instability, as postulated by the criteria, but fatigue-ratcheting, which means that the cyclic aspect of seismic stresses plays a key role that is neglected in current practice.

A consequence of the current nuclear design criteria is that the support design are overly conservative compared with current industrial practice (for a pipe that costs 1, the cost of supports is around 0.2 in conventional plants and around 1 in NPPs, depending on the seismic level input). This situation leads to unusually stiff piping systems that cumulate fatigue damage under thermal cycling in normal operation. Therefore, the number and the stiffness of supports should decrease for a better engineering practice; nevertheless it has to be pointed out that, due to the high speed of fluids in piping systems of NPPs, this reduction has to be limited for reasons connected with flow induced vibrations.

It appears that the key for understanding the physical phenomena is the ductile capacity associated to the dynamic behaviour of piping systems. In principle a sound approach to safety should consider the strain field in the components and limit it to a fraction of the ultimate strain. Unfortunately this is not possible for the time being due the engineering culture (education, design criteria and computer codes are based on stress analysis and not on strain analysis) and due to the inherent difficulty to cope with non-linear dynamic systems.

A typical application problem is the assessment of a cracked pipe. It is now well established that a reasonable decrease in the size of the supporting system has only minor effect on the crack propagation. Consequently some adaptations of the nuclear design criteria (ASME, RCC-M, ETC-M) were proposed to take into account the above mentioned phenomena. They now converge to a common form of new criteria which is the one also proposed in the IAEA Safety Report for seismic re-evaluation of existing NPPs [24]. These criteria reduce the contribution of inertial effects in the seismic capacity of the piping system through some reduction factors, while they emphasize the potential contribution coming from the differential displacement of the supports. For this latter effect, some research is still in progress in the engineering community.

8. RECOMMENDATIONS FOR IMPROVED DESIGN METHODOLOGIES

In the development of new guideline documents for seismic re-evaluation of piping [24–25] derived from [26], it is recommended that the following general issues are considered:

(a) Piping re-evaluation criteria should be consistent with the re-evaluation criteria adopted for the bearing structures: in case post elastic behaviour of bearing structures is accepted, it should be accepted for piping systems too, to avoid to upgrade piping systems more than the buildings inside which they are anchored.
(b) The effects of inertial stresses are to be de-emphasized in current design methodologies, while the effects of stresses induced by differential displacements need to be emphasized.

Note that compliance with b) implies compliance with a).

From the implementation point of view, it would be desirable that piping re-evaluation try not to add new supports on an existing correctly operating pipe, even if criteria are violated (to a limited amount). Some more sophisticated methods could be used to justify the as-built situation. New criteria derived from practices in the USA or France are good alternatives in such cases. For low safety class systems, simplified methods (static) should be preferred.

Walkdowns should be performed for piping systems to check that pipes are adequately supported and have sufficient lateral supports. The vulnerable configuration, including degradation, such as corrosion, found in the piping experience data survey and study needs to be carefully checked and avoided. Although guidelines are available, each plant has to develop its own implementation procedure for plant specific applications. The new ASME or French code, if approved, can be used as a reference. It might be useful to identify a core group of piping systems for the purposes of evaluating which methodology can be implemented.

Design procedures should give more emphasis to important subject, highlighted by the analysis of the feedback experience, such as:

(a) erosion and corrosion;
(b) potential defects;
(c) pipe break location (for high energy lines);
(d) flow induced vibrations.

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ABBREVIATIONS

AC	Air Compressor
AH	Air Handlers
BAT	Batteries on Racks
BCI	Battery Chargers and Inverters
BS	Bounding Spectrum (for SMA)
CDF	Core Damage Frequency
CDFM	Conservative Deterministic Failure Margin
CHL	Chillers
DBE	Design Basis Earthquake
DP	Distribution Panels
EG	Engine Generators
FA	Fragility Analysis
FAC	Flow-Accelerated Corrosion
FAN	Fans
FOV	Fluid-Operated Valves
FRS	Floor Response Spectrum
G	Shear Modulus (of soil)
GERS	Generic Ruggedness Spectrum
GIP	Generic Implementation Procedure
GRS	Ground Response Spectra
HCLPF	High Confidence of a Low Probability of Failure
HP	Horizontal Pumps
HVAC	Heating, Ventilation Air Conditioning
I&C	Instrumentation and Control
IGA	Intergranular Attack
IGSCC	Intergranular Stress Corrosion Cracking
IPEEE	Individual Plant Examination of External Events
IR	Instruments on Racks
IRS	In-Structure Response Spectrum
ISRS	In-Structure Response Spectra
LOCA	Loss of Cooling Accident
LVS	Low Voltage Switchgears
MCC	Motor Control Centres
MG	Motor Generators
MIC	Microbiologically Influenced Corrosion
MOV	Motor-Operated Valves
MS	Member States
MVS	Medium Voltage Switchgears
NEP	Non-Exceedance Probability
NOL	Normal Operating Loads
NPP	Nuclear Power Plants
PRA	Probabilistic Risk Assessment
PSA	Probabilistic Seismic Assessment
QA	Quality Assurance
QC	Quality Control
RBMK	Series of Unified Design in former Soviet Union
RG	Regulatory Guide (US standards)
RLE	Review Level Earthquake

SC	Seismic Class
SDS	Seismic Demand Spectrum
SEL	Seismic Equipment List
SEWS	Seismic Evaluation Work Sheet
SL-2	Seismic Level 2
SMA	Seismic Margin Assessment
SME	Seismic Margin Earthquake
SOV	Solenoid-Operated Valves
SPRA	Seismic Probabilistic Risk Analysis
SQUG	Seismic Qualification Utility Group
SRP	Standard Review Plan (US standards)
SRT	Seismic Review Team
SSC	Systems, Structures and Components
SSE	Seismic Safety Earthquake or Safe Shutdown Earthquake
SSEL	Seismic Safety Equipment List
SVDS	Seismic Verification Data Sheet
SWS	Seismic Walkdown Sheet
TG	Technical Guidelines
TRN	Transformers
TS	Temperature Sensors
UHS	Uniform Hazard Spectrum
URM	Unreinforced Masonry
VP	Vertical Pumps
WWER	Series of Unified Design in Former Soviet Union
ZPA	Zero Period Acceleration
ZPGA	Zero Period Ground Acceleration

LIST OF PARTICIPANTS

Technical Co-operation Meeting
Vienna, Austria: 5–8 June 2000

Representatives of safety authorities and utilities

Alejev, A.	Lithuanian Nuclear Power Safety Inspectorate, Lithuania
Bugaev, V.	GOSATOMNADZOR, Russian Federation
Husarcek, J.	Nuclear Regulatory Authority of Slovakia, Slovakia
Janosi, T.	Hungarian Atomic Energy Authority, Hungary
Katona, T	Paks Nuclear Power Plant, Hungary
Krytskyy, V.	State Scientific Technical Center for Nuclear and Radiation Safety, Ukraine
Kuzma, J.	Bohunice NPP, Slovakia
Milanov, M.	Kozloduy Nuclear Power Plant, Bulgaria
Zadoyan, P.	Armenian Nuclear Regulatory Authority (ANRA), Armenia
Zajicek, T.	Mochovce NPP, Slovakia

Engineering consultants and suppliers

Coman, O.	Stevenson & Associates, Romania
Kamm, K.	Siemens AG, Germany
Masopust, R.	Stevenson & Associates, Czech Republic
Murray, R.	Lawrence Livermore National Laboratory, United States of America

Experts designated by the IAEA

Campbell, R.	EQE International Inc., United States of America
Dellopoulos, G.	Westinghouse Energy Systems Europe S.A., Belgium
Duval, C.	EDF, France
Birbraer, A.	ATOMENERGOPROEKT, Russian Federation

Technical Seminar on Seismic Re-evaluation of Piping Systems
Pamporovo, Bulgaria: 27–30 March 2000

Alexandrov, A.	Energoproject
Batishchev, M.	Energoproject
Boyanova, D.	EQE International
Danailov, S.	Enpro Consult
Darvarova, E.	Bulgarian Academy of Science
Davidov, V.	NEK-EAD
Delcheva, V.	Bulgarian Nuclear Safety Authority
Ederov, I.	Enpro Consult
Fouchedjiev, A.	EQE International
Gledachev, I.	Kozloduy Nuclear Power Plant
Grizanov, I.	Risk Engineering

Hui-Tsung Tang	EPRI, United States of America
Ignatiev, N.	Bulgarian Academy of Science
Kancheva, M.	EQE International
Kaneva, A.	Bulgarian Academy of Science
Kasheva, I.	Kozloduy Nuclear Power Plant
Kirilov, K.	Kozloduy Nuclear Power Plant
Kokolichev, S.	Kozloduy Nuclear Power Plant
Koleva, N.	Bulgarian Academy of Science
Kostov, M.	Bulgarian Academy of Science
Krasteva, M.	Kozloduy Nuclear Power Plant
Labbé, P.	International Atomic Energy Agency
Matneshliev, V.	EQE International
Mihailova, V.	Atomenergoinvest
Milanov, M.	Kozloduy Nuclear Power Plant
Nikolov, N.	Kozloduy Nuclear Power Plant
Partalosov, D.	Kozloduy Nuclear Power Plant
Parvanova, S.	EQE International
Peeva, V.	Risk Engineering
Penkova, L.	Risk Engineering
Petrov, Y.	Risk Engineering
Poungov, S.	Kozloduy Nuclear Power Plant
Raichev, R.	Energoproject
Raichev, S.	EQE International
Ribarska, T.	Kozloduy Nuclear Power Plant
Serafimov, V.	Kozloduy Nuclear Power Plant
Simeonova, S.	Bulgarian Academy of Science
Simovski, T.	Energoproject
Slavcheva, K.	Kozloduy Nuclear Power Plant
Spassov, P.	EQE International
Sokolov, D.	Bulgarian Academy of Science
Sollogoub, P.	CEA, France
Stefanov, D.	Bulgarian Academy of Science
Tahir, M.	Risk Engineering
Toneva, S.	Energoproject
Varbanov, G.	Bulgarian Academy of Science
Vasseva, E.	Bulgarian Academy of Science
Zinoviev, I.	Risk Engineering