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Assessment of safety barrier performance in the mitigation of domino scenarios caused by Natech events

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**Assessment of safety barrier performance  
in Natech scenarios**

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***REVISED VERSION***

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## ABSTRACT

The impact of natural hazards on chemical and process facilities may lead to catastrophic technological accidents defined as Natech events. In the present study, a performance assessment of safety barriers during extreme natural events as floods and earthquakes was carried out. Assessing the performance of safety barriers during such complex scenarios is a key issue to identify the final consequences and the evolution of Natech events. Due to the scarcity of available data, an anonymous survey was carried out, involving more than 40 experts of different nationalities and background. Categories of safety barriers highly vulnerable to the impact of natural events were identified. Baseline values for performance modification factors describing how barrier performance may be affected by floods and earthquakes were obtained from the expert elicitation procedure. The results may support the probabilistic analysis of Natech scenarios, in order to achieve a more accurate assessment of final consequences and of possible escalation.

### ***Keywords:***

Natech; Safety barriers; Natural hazards; Performance Assessment; Expert elicitation

## 1. Introduction

In recent years, a growing concern is caused by the threats generated by the interaction between natural hazards and technological installations, the so called Natech (Natural-hazard triggered Technological) scenarios [1]. In a number of disastrous natural calamities that stroke heavily industrialized regions in different parts of the world, severe technological accidents followed the natural events, directly affecting the population and causing huge damages to industrial assets [2-4]. The World Health Organization in a recent document remarked that, also as a consequence of climate change, both the frequency and the magnitude of natural calamities are growing [5]. This trend rises serious concern that the likelihood and magnitude of Natech events will consequently increase as well [6].

Chemical and process installations are among the most critical infrastructures which could be targeted by natural hazards. Indeed, as a consequence of structural damage to facilities, loss of containment of hazardous substances is likely to take place. The incidence of Natech events was estimated to be as high as 5% out of the total of records reported in industrial accident database up to about 20 years ago [3]. However, such figures are presumably even higher nowadays, due to the increasing frequency of natural hazards linked to climate change [7-9]. For instance, Hurricane Harvey had an unprecedented intensity which has been directly linked to climate change [10], and triggered a multitude of Natech events and massive hazmat releases from shutdown procedures [11].

The main criticalities characterizing Natech scenarios are related to the broad impact area that natural events generally have. For instance, floods and earthquakes have the potential to cause the simultaneous failure of different equipment items in a process installation, leading to multiple loss of containment events and to complex accident scenarios [12-14]. Previous studies demonstrated how accidents developing from natural hazards have to potential to cause severe fires, explosions, toxic dispersion and environmental contamination [15-18]. Furthermore, Natech accidents are likely to escalate generating cascading events involving surrounding equipment, or domino effect [19], further exacerbating the already catastrophic consequences of the initial scenario.

In order to prevent technological accidents or to mitigate their consequences, safety procedures and specific technical solutions are usually adopted, [usually referred to as safety barriers in the technical literature](#) [20-41]. Examples of safety barriers are water deluge systems to protect vulnerable equipment from fire, catch basins to prevent liquid spread in case of a spill, foam systems, etc. However, a number of case histories demonstrated the possible ineffectiveness of conventional safety technological measures in case of Natech events, due to the specific conditions caused by the impact of the natural event [42-44, 4, 11].

88 Despite the growing interest in the analysis of Natech scenarios and the recognized criticalities related  
89 to the performance of safety barriers, systematic approaches for the analysis of the performance of  
90 safety barriers in Natech scenarios are lacking. Thus, in the present study, a specific analysis was  
91 carried out to understand the behaviour of safety barriers during Natech events, in order to derive  
92 quantitative criteria for their expected performance. Due to the scarcity of data, available information  
93 was analysed with the support of an expert elicitation procedure. The reasons why an expert elicitation  
94 procedure was selected for the purpose are manifold. First of all, given the novelty of the problem  
95 addressed and the unavailability of quantitative information on safety systems failure during Natech  
96 events, expert judgment constitutes a solid starting point to face the issue [45]. Moreover, an  
97 analogous methodology has been successfully employed for determination of indicators estimating  
98 performances of protection systems in the context of physical security of process installation [46].  
99 Finally, expert elicitation has been recognized in the literature to be particularly suitable for issues  
100 which are not practically measurable despite a theoretical basis is present [47]. Thus, a reference set  
101 of safety barriers was defined and their expected performance under the impact of a natural event was  
102 analysed both qualitatively and quantitatively. The qualitative analysis was carried out to evidence  
103 criticalities and to highlight the most vulnerable items. *The quantitative assessment was based on a  
104 method developed in previous studies, dedicated to accident escalation quantitative risk assessment  
105 (QRA) [30-32]. The method incorporates the concepts of availability and effectiveness to express the  
106 level of confidence of the barriers [22-24], and adopts a LOPA (layer of protection analysis) approach  
107 [20].*

108 In the following, the basic concepts of safety barriers and the methodology adopted for performance  
109 quantification are introduced (Section 2). The expert elicitation procedure and the proposed  
110 methodology to tailor barrier performance data accounting for the impact of natural hazards are  
111 discussed in Section 3. The main results of the study, together with a discussion on their applicability  
112 and limitations are provided in Section 4. Conclusions are given in Section 5.

113

## 114 **2. Schematization and assessment of safety barriers**

115 *The concept of safety barrier is used within the process industry referring to measures to protect  
116 vulnerable assets (e.g., people, environment, reputation, etc.) against hazards posed by failures or  
117 deviations of systems [25].*

118 *There is a considerable amount of scientific and technical literature dedicated to barriers and barrier  
119 management [20-41]. Safety barriers may be generically defined as physical and non-physical means  
120 planned to prevent, mitigate or control undesired events or accidents [40]. Within the Norwegian oil  
121 & gas sector, according to [33], safety barriers are defined as: “systems of technical, operational and*

122 *organizational elements, which are intended individually or collectively to reduce the possibility for a specific*  
123 *error, hazard or accident to occur, or which limit its harm/disadvantages”.*

124 This definition is quite similar to the one developed within the ARAMIS framework, where safety  
125 barriers are defined as technical and organizational solutions provided to directly serve safety  
126 functions, which, in turn, are technical or organizational actions intended to prevent, avoid or control  
127 the occurrence of hazardous events, or to mitigate their consequences [22-24]. The concept of barrier  
128 function, that is, barrier design purposes, is shared by multiple literature sources [22-34, 40], and is  
129 necessary to distinguish without ambiguity between functions and how they are practically  
130 accomplished through the implementation of barrier systems. More specifically, Svenson [34] defines  
131 “barrier function” each task implemented by barrier systems to arrest accident evolution. Sklet [40]  
132 defines barrier functions as functions planned to prevent, control, or mitigate undesired events,  
133 recalling the definition proposed within the ARAMIS framework [22-24]. A comprehensive review  
134 of terminology commonly used in the field of barrier management can be found elsewhere [40].

135 Given the quite broad definitions reported above and the multiplicity of sectors in which barrier  
136 conceptualization is applied (for instance, in [41] it is applied for identification of emerging hazards  
137 linked to new technologies such as biogas production), it clearly appears that several criteria may be  
138 adopted to categorize safety barriers. A possibility is to classify barriers based on whether their safety  
139 function is aimed at reducing the frequency of a hazardous event, namely proactive barriers; or to  
140 lessen its outcomes, namely reactive barriers [25]. Reason [35, 36] proposed a universal classification  
141 based on defense-in-depth concepts and on the type of functions implemented by barriers, which is  
142 deemed generally valid for all organizations, regardless of their operating hazards. Another possibility  
143 is provided by Hollnagel [28, 29], who categorizes barriers in:

- 144 • physical and material barrier systems, whose function is expressed by physical means;
- 145 • functional barrier systems, which are based on creation of preconditions impeding actions;
- 146 • symbolic barrier systems, which require interpretation by someone to express their function;
- 147 • incorporeal barriers, which are in fact organizational barriers in the industrial context.

148 The categorization adopted in the following is based on barrier working principle, and has been  
149 widely adopted in previous literature [20-24, 30-32]. Hence, safety barriers are categorized in passive,  
150 active and emergency/procedural barriers.

151 All the systems *that* do not require activation to perform their functions are defined passive barriers  
152 (e.g., pressure relief devices, fireproofing materials, catch basins). On the other hand, active barriers  
153 need activation to perform their functions and are generally more complex systems linked to  
154 subsystems for detection and for signal processing. Fire protection systems such as sprinklers and  
155 water deluge systems (WDS) are common examples of active barriers [48-50]. Lastly,

156 emergency/procedural barriers include procedures and contingency plans developed for responding  
157 to the occurrence of major accident scenarios (e.g., intervention of fire brigades, internal or external  
158 emergency teams) [51].

159 Barriers may be characterized by a number of properties determining their performances. For  
160 instance, according to Hollnagel [28, 29], barrier quality should be evaluated considering a set of  
161 conditions, among which are efficiency, robustness, resource need, and availability. Norwegian  
162 Petroleum Safety Authority highlights that performance requirements must be verifiable and related  
163 to barrier element properties, including aspects as reliability, effectiveness, integrity, functionality,  
164 and robustness among others [33].

165 In order to assess the expected performance of safety barriers during Natech events, a concise  
166 approach to performance quantification is required. A number of methodologies for the assessment  
167 of safety barrier performance through a limited number of parameters have been proposed in the  
168 literature. For instance, among simplified methods it is worth mentioning LOPA, a well-established  
169 framework for barrier performance assessment based on the concept of Independent Protection  
170 Layers (IPLs) [20, 39]. The method proposed in the IEC 61508 [52] for safety instrumented systems  
171 is based on the evaluation of the required safety integrity level (SIL) through a simplified risk-based  
172 approach, which is then specifically tailored for the process sector in the IEC 61511 [53]. A further  
173 approach sharing some common traits with LOPA and IEC 61508 standard is the MIRAS method  
174 proposed within the ARAMIS project [22-24]. More recently, a two-parameter approach was  
175 proposed for the specific framework of domino effect prevention, based on the probability of failure  
176 on demand (PFD) and effectiveness of the barrier [31]. The PFD expresses the probability that the  
177 system is unavailable when it is required to express its safety function, and the effectiveness is the  
178 probability that the barrier successfully performs its escalation prevention function once successfully  
179 activated. Since one of the most critical features of the impact of natural hazards on process facilities  
180 is the possibility that severe cascading scenarios are triggered, this approach was adopted in the  
181 present study.

182 PFD values for simple components can be found in technical literature, while in the case of complex  
183 systems (such as active safety barriers) the PFD has to be evaluated through fault tree analysis (FTA)  
184 considering system architecture [54], or, in the absence of data, through simplified risk-based  
185 approaches such as the Risk Graph [52,53]. A comprehensive set of baseline reliability data sources  
186 are reported by Necci et al. [54].

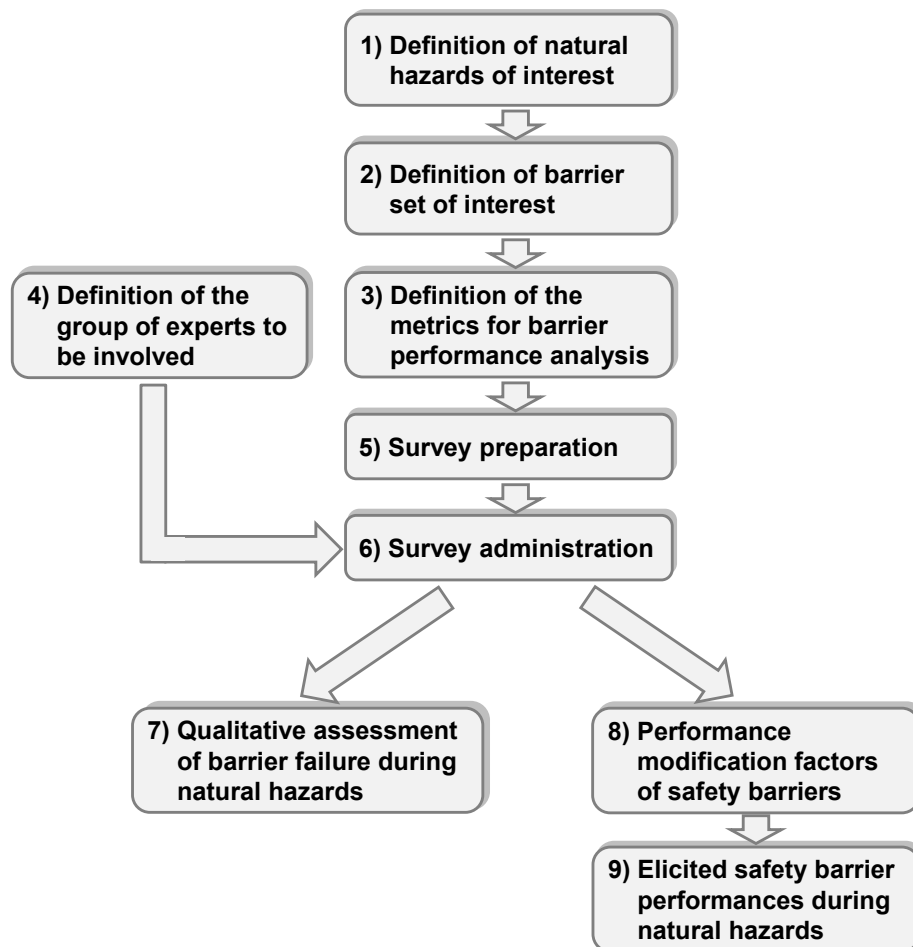
187 The effectiveness parameter, accounting for the quality of the performed barrier function, is not  
188 assessed in standard LOPA studies [20, 39], and needs to be estimated considering performance data

189 dependent of the type of system, as well as on operational management, system installation and  
190 maintenance [30, 32].

191

### 192 3. Methodology

193 In order to investigate the performance of safety barriers in Natech scenarios, a specifically developed  
194 approach was applied. The steps of the study carried out are summarized in Fig. 1. Each step of the  
195 approach is discussed in the following.



196

197 **Figure 1: Flowchart of the approach adopted in this study for barrier performance estimation in Natech events.**

198

199

#### 200 3.1 Natural events considered in the study

201 In step 1, the boundaries of the study were set to define the detail of the activity and to make affordable  
202 the elicitation process. In particular, it was decided to limit the study to the impact of earthquakes and  
203 floods. These were selected since they are the natural events that more frequently triggered severe  
204 Natech accidents [1]. In perspective, the approach developed may be applied to assess barrier  
205 performance in case of other types of natural events (e.g. tsunamis, lightning, tornados, etc.).



However, in order to focus the elicited group of experts and to limit the complexity of the survey, the decision was taken to limit this study to the analysis of these two significant categories of events.

### **3.2 Definition of a set of reference safety barriers**

The second starting point of the study was the definition of a set of safety barriers to be analysed (step 2 in Fig. 1). This is needed both to limit the extension of the study and to allow the preparation of a reference scheme and a description of the function of each safety barrier considered, to support the expert elicitation. In the present study, only technical active and passive safety barriers were considered. The choice to exclude organizational and procedural barriers is motivated by need to limit the complexity of the study and to the high site specificity of their performances (e.g., presence of internal emergency teams, distance of the plant from closest firefighter station, presence of specific plans for natural disaster), that undermines the general validity of the performance parameters obtained. On the contrary, baseline values for active and passive technical barriers are mostly related to system architecture, thus are linked to the inherent structure of the safety system. Indeed, according to lessons learnt from previous accidents, some specific failure patterns can be identified [55].

The definition of the set of barriers to consider was based on a preliminary evaluation of equipment items and substances most frequently involved in earthquake and flood triggered accidents based on past accident events. Indeed, it has been highlighted that atmospheric tanks storing an elevated inventory of flammable liquids (e.g., petroleum products) are particularly vulnerable during earthquakes and floods [16, 56], and escalation due to fire may be critical during such Natech incidents, as confirmed by relevant case histories (see Section 1). These findings constituted the drivers for the selection of the set of safety barrier considered. Indeed, since one of the main criticalities of Natech events triggered by flood and earthquakes is the high possibility of accident escalation through domino effect, the investigated barrier set is mainly composed of escalation prevention systems. Moreover, fire protection systems constitute a significant part of the set also because these systems are required in accepted standards on fire protection of petroleum storages (e.g., see [57]).

It is worth specifying that the analyzed set of barriers is not aimed at providing an exhaustive and complete list of possible technological solutions for escalation prevention, rather it is composed of barriers which, based on past accident analysis, may be prone to fail following the impact of natural events. For example, PSVs, despite being the most common passive safety barrier to prevent vessel overpressure, have not been included in the analysis since, due to their features, their failure was never reported in available data on Natech scenarios.

The final set of selected safety barriers considered in the analysis is composed of the 16 items listed in Table 1, which also reports a short description and an identification code (SB.k, with k=1,...,16). Items SB.1-SB.9 are active barriers, while SB.10-SB.16 are passive barriers. It is worth noting that the Emergency Blow-Down (EBD) line was considered passive since it is constituted of pipework (and possibly a KO drum) which are always in place, not needing an activation.

**Table 1: Safety barriers considered in the survey prepared for expert elicitation**

Safety barrier	Barrier ID	Classification [20]	Short description
Inert-gas blanketing system	SB.1	Active	System for inert gas delivery to storage tanks to prevent the possible formation of flammable atmospheres.
Automatic rim-seal fire extinguishers	SB.2	Active	Automatic foam delivery system for prompt extinguishment of rim-seal fires developing in the roof area of atmospheric storage tanks.
Fixed / Semi-fixed foam systems	SB.3	Active	Systems for tank fire extinguishment by means of foam/water delivery.
WDS / Water Curtains / Sprinklers	SB.4	Active	Systems for water delivery during fire, either for flame extinguishment or critical asset protection (e.g., LPG vessels).
Hydrants	SB.5	Active	Water sources for fire brigades located in multiple areas of the plant.
Fire activated valves	SB.6	Active	Valves activating in case of fire nearby.
Fire and gas detectors	SB.7	Active	Field sensors for detection of flames and gases.
SDVs	SB.8	Active	Isolation valves activating during emergency situations.
BDVs	SB.9	Active	Depressurization valves activating during emergency situations.
Fire walls	SB.10	Passive	Physical barriers for fire protection.
Blast walls	SB.11	Passive	Physical barriers for blast protection.
Fireproofing	SB.12	Passive	Coating materials for fire protection.
Bunds / Catch basins	SB.13	Passive	Physical systems for liquid retaining in case of spill.
Emergency Blowdown line to flare stack	SB.14	Passive	Line for flaring employed during emergency situations.
Mounding tanks	SB.15	Passive	Locating vessels into gravel/ground mounds for fire protection.
Burying tanks	SB.16	Passive	Locating vessels underground for fire protection.

### 3.3 Metrics for performance analysis of safety barriers

Failure modes, which have been highlighted by past accident analysis, constitute the basis of the definition of the metric for performance parameter adjustment (step 3 in Fig. 1).

A performance modification factor  $\phi_{j,i}$  was defined, expressing the plausibility that, during j-th natural hazard, the i-th safety barrier will not be available, due to direct impact of the natural event on the facility.

Based on the analysis of past accident and of failure modes, natural hazards are supposed to affect the availability of active barriers (and in turn their PFD), but to have a negligible effect on the

effectiveness of such category of barriers. On the contrary, in case of passive barriers the effectiveness is the only parameter which is supposedly modified (e.g., the effective capability of catch basins to retain liquid spills), since barriers belonging to this category do not need to be activated and the concept of PFD is not applicable.

Thus, in case of active barriers, the modification factor  $\phi_{j,i}$  is used to determine a tailored value of  $PFD_{j,i}$  starting from a baseline  $PFD_{0,i}$  reported by literature sources [52, 58, 59]:

$$PFD_{j,i} = 1 + (\phi_{j,i} - 1)(1 - PFD_{0,i}) \quad (1)$$

with  $\phi_{j,i} \in [0,1]$ . The effectiveness for this category of barriers is assumed to be unmodified:

$$\eta_{j,i} = \eta_{0,i} \quad (2)$$

where  $\eta_{0,i}$  is the baseline value for barrier effectiveness, independent of the natural event considered.

It is worth noting that according to Eq. (1),  $PFD_{j,i}$  is a linear function of the factor  $\phi_{j,i}$ .

In case of passive technical safety barriers, the performance characterization of  $i$ -th passive barrier during  $j$ -th natural hazard may be calculated as follows:

$$\eta_{j,i} = (1 - \phi_{j,i}) \eta_{0,i} \quad (3)$$

with  $\phi_{j,i} \in [0,1]$ . According to Eq. (3), the effectiveness  $\eta_{j,i}$  is a linear decreasing function of  $\phi_{j,i}$ .

In case the natural hazard does not affect the integrity of the barrier (i.e.,  $\phi_{j,i} = 0$ ) the performance parameter of the barrier corresponds to its original baseline value,  $\eta_{0,i}$ .

A reference set for the baseline values of the safety barriers considered is proposed in previous studies (see [31, 54] and references cited therein). However, the selected baseline data sources do not affect the conceptual framework developed in the present study.

### 3.4 Expert elicitation

An extended group of experts of different nationalities (from Europe, US, Canada, and Asia) was invited to participate in a specific on-line survey in order to obtain information on the expected performance of the reference set of safety barriers defined in the two categories of Natech events selected for the study. Experts of different nature were involved in the survey, involving both academics, i.e. scholars in the field of process safety and industrial design; and practitioners, such as targeting consultancy directors, members of control authorities, facility managers (step 4 in Fig. 1). *Involving experts with heterogeneous background is useful to cover all relevant aspects of the subject matter, thus enhancing the completeness of results [45].*

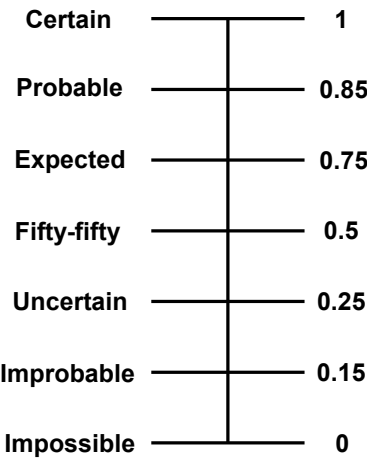
The actual number and background of experts answering the survey are reported in Section 4. An ad-hoc survey has been prepared (step 5 in Fig. 1) and administered to the group of experts (step 6 in

Fig. 1) through the Google Form web-app. The transcription of the survey form can be found in Appendix A.

Together with the survey, a brief description of each considered barrier was provided to the experts. Given the heterogeneous background of the expert pool, a preliminary section to investigate the background of respondents has been included in the survey. The number of years of experience, together with the belonging institution have been asked. *It should be noted that information on status/background of experts is asked in favor of thorough documentation, and it is deemed a suitable trade-off between anonymity and objectivity in this kind of studies [45].*

For both the natural events considered, two questions regarding each safety barrier were asked. Experts were requested to express their opinion on the possibility that the safety barrier could be affected by the specified natural event. A short qualitative answer was required: “YES”, “NO”, “NOT SURE” (e.g., “Do you think in case of floods impacting process facilities, the automatic rim-seal fire extinguisher could be damaged and could be unavailable in case of demand?”). Experts were also given the possibility to leave the question unanswered.

The second question concerned the expert’s opinion on the likelihood of the safety barrier failure as an immediate consequence of the natural event considered. Experts were asked to provide an answer through the verbal scale presented in Fig. 2. The verbal scale was later translated in numerical values according to the association shown in Fig. 2. The choice of adopting a verbal scale with a background translation to numerical values was preferred to directly requiring to experts a numerical answer since this approach, since it was successfully applied in several previous studies, and generally helps respondents providing answers more intuitively [60].



**Figure 2:** Verbal scale adopted in the survey and corresponding quantitative translation adopted in the analysis of the answers.

### 3.5 Assessment of performance modification factors

312 Answers to the qualitative part of the survey were firstly analysed in order to perform a preliminary  
313 qualitative assessment of barrier failure (step 7 in Fig. 1). Since categorical answers were posed to  
314 respondents in this part (see Section 3.4), a simple statistical analysis was sufficient to obtain the  
315 percentage of experts agreeing on whether each barrier would fail or not (or being not sure). Results  
316 are then compared with those obtained from the quantitative questions in terms of performance  
317 modification parameters to check their coherence.

318 Modification factors to be used in Eqs. (1) and (3) in order to update the baseline figures for safety  
319 barrier performance in case of Natech accidents caused from flood and earthquakes were obtained  
320 from the elaboration of quantitative expert answers (step 8 in Fig. 1). After the quantitative translation  
321 using the verbal scale in Fig. 2, expert judgments for each barrier were combined to obtain a  
322 distribution of values for the modification factor by a linear weighting procedure, associating the  
323 same weight to each expert. Even if possibly oversimplified, that applied is the most common and the  
324 simplest approach for averaging results obtained from multiple sources. More refined methods, for  
325 instance supra Bayesian combination, have not been applied since they would have required an  
326 elevated computational effort [61], without providing any added value to results due to the elevated  
327 degree of uncertainty of the study.

328 The results were analyzed comparing distributions obtained for different barriers. However,  
329 performance parameters need to be expressed concisely to be suitable for risk analysis. Thus, to  
330 summarize the information obtained for each barrier, the median value of each distribution has been  
331 chosen as a statistical indicator representing performance modification factor (step 8 in Fig. 1). In  
332 Section 4.3 this choice was further discussed.

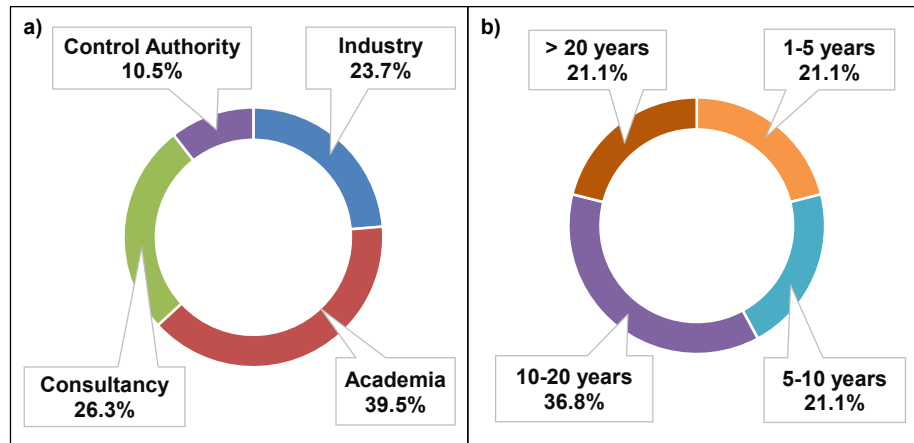
333 Elicited modification factors are then implemented in the proposed metric to assess active and passive  
334 safety barrier expected performances during the reference natural hazards (step 9 in Fig. 1).

335

## 336 **4. Results and Discussion**

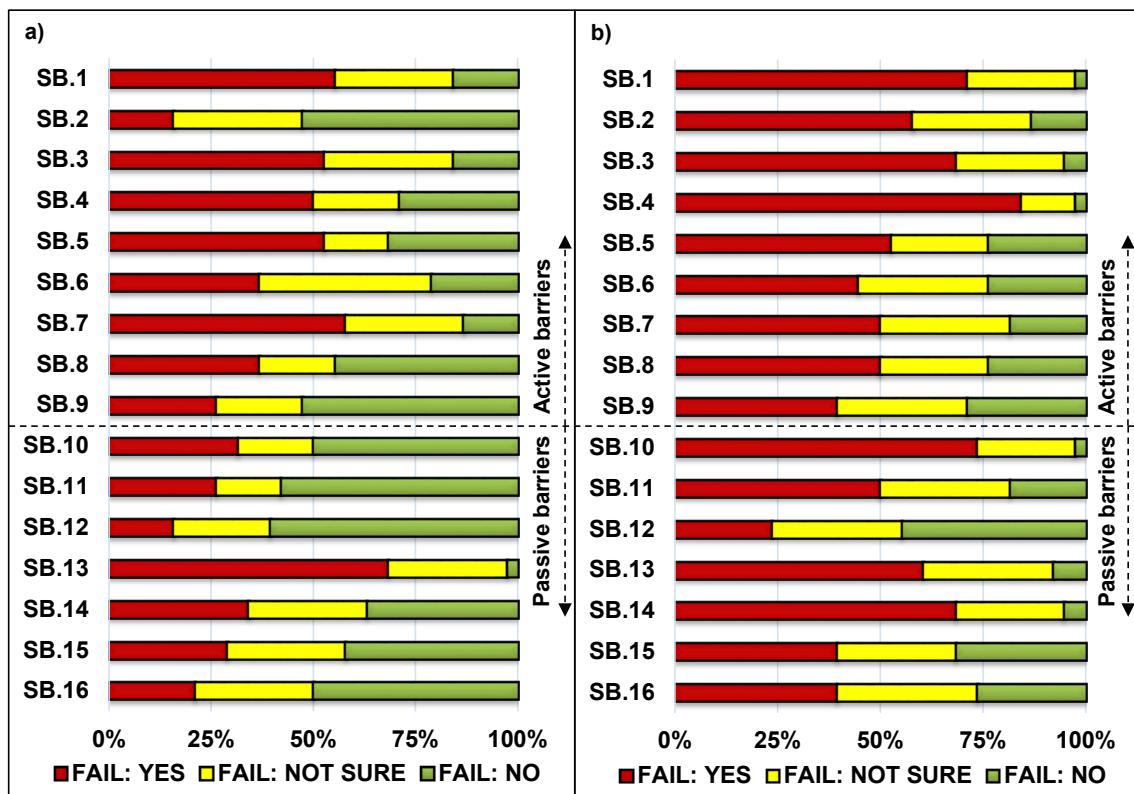
### 337 **4.1 Results of the survey**

338 The survey was answered by 41 experts. The final number of answers considered is of 38, since 3  
339 respondents declared not to have specific experience within the context of safety barriers and their  
340 answers were not further considered. The final number of involved experts was considered  
341 satisfactory, in agreement with some literature studies (e.g., see [62]). Fig. 3 summarizes the  
342 professional background (panel a) and the years of experience of the pool of respondents (panel b).



**Figure 3: Summary of professional background (a) and year of experience (b) of the pool of experts.**

Qualitative results obtained from the analysis of the answers to the first type of question for each barrier (concerning if the barrier would likely be affected by the impact of the natural event) are reported in Fig. 4. Missing answers were associated to the “Not sure” category in Fig. 4, since it was assumed that a missing answer could be interpreted as an uncertainty of the expert in determining an answer.



**Figure 4: Results obtained from the survey concerning the likelihood of barrier failure or unavailability in the case of the impact of (a) flood or (b) earthquake. The key to barrier ID is reported in Table 1.**

354 Qualitative results on failure of safety barriers in case of floods are presented in Fig. 4a. As it can be  
 355 noted from the figure, active safety barriers (SB.1 to SB.9) are in general perceived by experts to be  
 356 more vulnerable to floods with respect to passive safety barriers (SB.10 to SB.16). Indeed, more than  
 357 half of the experts indicated that 5 active barriers out of 9, and 1 passive barrier out of 7 would be  
 358 damaged and unavailable during flooding scenarios. The active barriers recognized as likely to be  
 359 unavailable in the case of a flood by most of experts are mainly complex systems for fire prevention  
 360 and mitigation, that is, inert gas blanketing systems (SB.1), foam systems (SB.3), sprinklers and water  
 361 deluge systems (SB.4), hydrants for fire brigades (SB.5), and detection devices as fire & gas detectors  
 362 (SB.7). Automatic rim-seal fire extinguishers (SB.2) have been considered unlikely to be affected by  
 363 most experts, presumably due to their position, above floating roofs of atmospheric storage tanks. An  
 364 elevated uncertainty is present concerning the impact of floods on fire activated valves (SB.6),  
 365 probably due to the high specificity of such safety systems. Both SDVs and BDVs (SB.7 and SB.8,  
 366 respectively) have been considered to be unaffected by most of experts, reflecting the fact that these  
 367 systems are usually designed fail-safe.

368 For what concerns passive barriers, it is clear that the most critical items perceived by experts are  
 369 bunds and catch basins (SB.13). Interviewed experts seem to have clear in mind the possibility that  
 370 these systems may be overtopped by floodwaters, annealing the possibility to express their safety  
 371 function of retaining possible liquid spills, as it was also highlighted by past accident analysis [16].  
 372 The other passive barriers seem not to be significantly affected by floodwaters according to experts'  
 373 opinion.

374 Finally, it is worth remarking that if uncertainty is conservatively associated to likelihood of failure  
 375 (i.e., considering the sum of "fail" and "not sure" answers) the failure of 12 out of 16 items is deemed  
 376 plausible by more than 50% of experts.

377 Qualitative results on the failure of safety barriers in the case of earthquakes are presented in Fig. 4b.  
 378 It is clear from the figure that in most cases the failure of the barriers due to seismic events is expected  
 379 by the majority of experts.

380 Among active barriers, the only items which in experts' opinion are unlikely to fail (Fail % lower  
 381 than 50) are fire activated valves (SB.6) and BDVs (SB.9). The criticality of active fire protection  
 382 systems has been strongly highlighted. Indeed, these systems are those considered more vulnerable  
 383 among the investigated set of active barriers. For instance, WDS and sprinklers (SB.4) are expected  
 384 to be damaged in an earthquake by about 85% of respondents, while the failure of both foam systems  
 385 (SB.3) and inert gas blanketing systems (SB.1) is expected by about 70% of experts. These systems  
 386 are composed of a pipework distribution network (i.e., for delivering firefighting water, foam, or inert

387 gas, respectively), which may be vulnerable during seismic events, as evidenced by past Natech  
388 accident analysis [56].

389 Among passive barriers, a total of 4 out of the 7 systems present in the selected set of safety barriers  
390 were considered likely to fail by more than half of the experts in the pool. The most critical events  
391 resulted firewalls (SB.10), emergency blowdown lines (EBD line) (SB.14) and bunds and catch  
392 basins (SB.13) whose failure in case of earthquake is expected respectively by 74%, 68% and 60%  
393 of the experts participating in the survey. The criticality of the EBD line evidenced by the survey is  
394 probably due to the importance given by experts to the elevated vulnerability of piping during seismic  
395 events, emerging from accident analysis [56]. As expected, firewalls, bunds and catch basins may be  
396 particularly prone to structural failures due to seismic loads. The extensive damages to concrete dikes  
397 during Koaceli Earthquake (1999) (see Section 1) is an example confirming the vulnerability to  
398 earthquakes of these safety barriers [42].

399 When the results obtained for earthquakes (Fig. 4b) are compared to those obtained in the case of  
400 floods (Fig. 4a), it clearly emerges that the consulted experts consider the failure of the set of technical  
401 safety barriers considered more likely in the case of an earthquake than in the case of a flood. Indeed,  
402 if only 6 items are considered likely to fail by more than 50% of experts in the case of a flood, when  
403 earthquake is considered this number rises to 11. On average, active barriers have been assessed likely  
404 to fail by about 43% of experts during floods, and by about 58% of experts during earthquakes. A  
405 similar trend is found for passive barriers, with an average of 33% of experts considering failure likely  
406 in case of floods, and 51% in case of earthquakes.

407 Nevertheless, both in the case of floods and of earthquakes, experts agree that passive barriers are  
408 generally more robust than active barriers, despite few specific cases (e.g., catch basins are likely to  
409 be submerged by floodwaters).

410

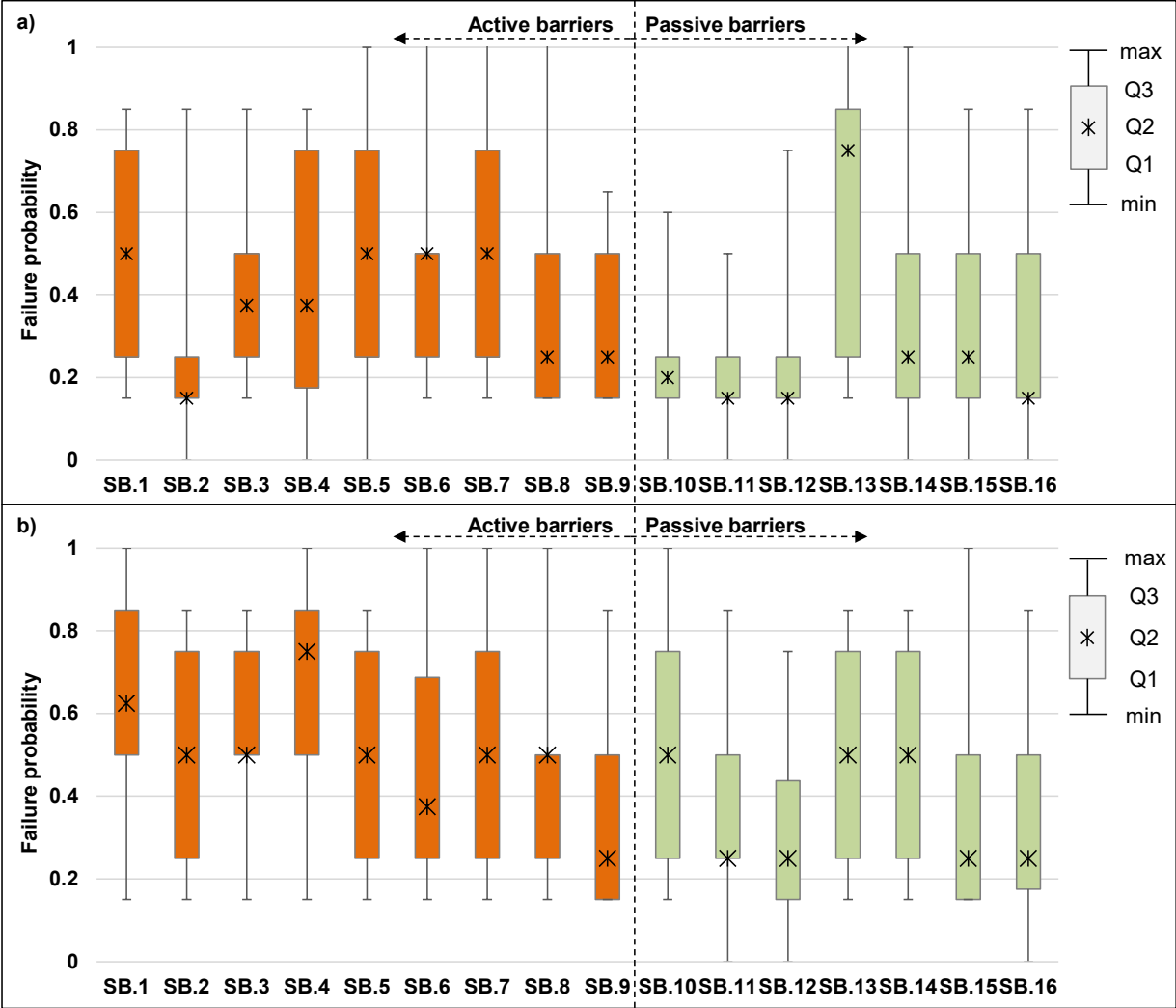
#### 411 **4.2 Barrier performance modification factors**

412 The analysis of the answers obtained to the second set of questions, requiring the experts to express  
413 a verbal graduation of the likelihood of barrier failure during natural hazards, allowed gathering a  
414 distribution of the modification factors  $\phi_{j,i}$  by the procedure described in Section 3.5. The  
415 distributions of the elicited performance modification parameter are reported in Fig. 5 in the concise  
416 form of boxplots. Further details on the results, and a detailed description of the distributions obtained  
417 for each barrier are presented in Appendix B.

418 In coherence with previous studies (see [46]), assuming the median value of each distribution as the  
419 value for the performance modification factor is suggested. The adoption of the mean value as a  
420 statistical indicator in this case is not considered the best choice, since it is not fully representative of



the distribution in case of disperse judgments: the influence of outliers on the variation of the mean value is rather elevated in the set of data obtained, while the median of the distribution is less affected by outliers, thus better representing the central tendency of data [63, 64].



**Figure 5:** Results obtained from the elicitation of performance parameter  $\phi$  for (a) floods and (b) earthquakes (Q1= higher value for the 1<sup>st</sup> quartile, Q2= highest value for the 2<sup>nd</sup> quartile (median value of the dataset), Q3= highest value for the 3<sup>rd</sup> quartile. Orange = Active barrier, Green = passive barrier. 0: failure impossible; 1: failure certain; see Fig. 2 for quantitative translation criteria of verbal scales). The key to safety barrier ID is reported in Table 1.

Distributions of the performance parameters during floods are presented in Fig. 5a. The most vulnerable active systems identified by the experts are the inert gas blanketing system (SB.1), hydrants (SB.5), fire activated valves (SB.6), and fire and gas detectors (SB.7), with median values of the elicited performance parameter of about 0.5. As evident from Fig. 4a, some of these items were recognized as critical by the majority of experts also in the qualitative answers.

437 It should be remarked that the distributions of answers have a high dispersion for some items. For  
 438 instance, figures for WDS and sprinkler systems (SB.4) show a large disagreement among  
 439 respondents (i.e., median of 0.375, Q1 and Q3 of 0.175 and 0.75 respectively), despite they had been  
 440 deemed likely to fail by the majority of experts in the qualitative part of the survey. The same issue  
 441 affects the set of the most vulnerable items (SB.1, SB.5 and SB.7). The possible reasons of such  
 442 distributions are probably due to differences considered by the experts in the layout of complex  
 443 systems as active barriers.

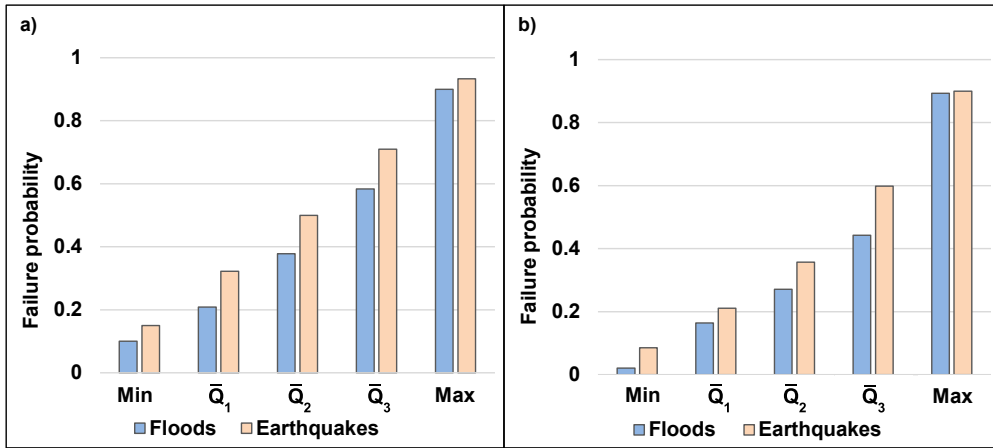
444 Automatic rim-seal fire extinguishers (SB.2), SDVs (SB.8) and BDVs (SB.9) show low values of the  
 445 modification parameter (respectively of 0.15, 0.25 and 0.25), highlighting their expected resilience to  
 446 floods. It should also be noted that the distribution elicited for SB.2 is peculiarly narrow, indicating  
 447 that the majority of experts agree on the scarce vulnerability of this barrier.

448 Among passive barriers, the catch basins and bunds (SB.13) are by far the items showing the highest  
 449 value of modification factor (0.8). This result was expected, since the large majority of experts had  
 450 already identified the vulnerability of such retaining systems during floods. The other passive barriers  
 451 investigated have been assessed to be only slightly affected by floodwaters, showing low values of  
 452 the performance modification parameter (apart from SB.13, the average median value is of about 0.2).  
 453 The distributions of the performance parameter for each barrier considering earthquake are shown in  
 454 Fig. 5b. In this case the most vulnerable items are by far the gas blanketing system (SB.1) and WDS  
 455 and sprinklers (SB.4), with median values of 0.625 and 0.75, respectively. These results are in line  
 456 with the qualitative answers (see Fig. 4b), highlighting that experts are clearly oriented concerning  
 457 the vulnerability of these systems in the case of earthquakes. Most of the other active barriers are  
 458 considered as well likely to be affected by earthquakes, showing median values of 0.5 in 5 out of 7  
 459 cases. Surprisingly, different figures result for SVDs (SB.8) with respect to BDVs (SB.9), in spite of  
 460 the similarity of such safety systems.

461 Passive barriers are deemed to be significantly affected by seismic loads in 3 out of 7 cases, with the  
 462 most critical items being firewalls (SB.10), bunds and catch basins (SB.13), and emergency  
 463 blowdown line (SB.14): median value is of 0.5 for each of the three distributions. For this subset of  
 464 barriers, the effectiveness is halved with respect to their expected performance during standard  
 465 operating conditions. Again, the results are in line with those obtained from qualitative answers. The  
 466 category of passive barriers is associated to an average performance modification parameter equal to  
 467 0.36, lower than that corresponding to the set of active systems considered (equal to 0.5), confirming  
 468 that such category of barriers is considered more resilient to earthquakes.

469 In order to compare the quantitative performance results obtained for floods and earthquakes, the  
 470 average distribution of position parameters was calculated for the entire set of barriers investigated.

471 More specifically, the following parameters were calculated for floods and earthquake: the average  
 472 over the entire set of barriers of the minimum and maximum value (Min and Max) and of the highest  
 473 figure in the 1<sup>st</sup>, 2<sup>nd</sup>, and 3<sup>rd</sup> quartiles ( $\bar{Q}_1$ ,  $\bar{Q}_2$ , and  $\bar{Q}_3$  respectively) of the distributions.  
 474 The results are reported in Fig. 6. From the figure it clearly emerges that the investigated barriers are  
 475 deemed in general more vulnerable to earthquakes than to floods. Indeed, considering earthquakes,  
 476  $\bar{Q}_2$  is of 0.5 for active barriers and 0.375 for passive ones, while the corresponding values for floods  
 477 are of 0.378 and 0.271 respectively. Fig. 6 further confirms that the investigated active barriers are  
 478 considered to be more vulnerable to both natural hazards than passive barriers. It should also be noted  
 479 that the difference among the impact of floods and earthquakes is slightly higher for active barriers  
 480 than for passive barriers, in general. Indeed, the average difference in performances among  $\bar{Q}_1$ ,  $\bar{Q}_2$   
 481 and  $\bar{Q}_3$  parameters, is of 0.12 for active barriers and 0.1 for passive barriers.  
 482 The differences between the average position of outliers (i.e., Min and Max position parameters) have  
 483 not been assessed in the comparison since they express the extreme points of each distribution, which  
 484 in some cases are determined by the judgment of a limited group of experts in disagreement with the  
 485 majority. For instance, the distribution elicited for automatic rim-seal fire extinguisher (SB.2) in case  
 486 of floods, shows a maximum value of 0.85, which has been expressed only by 2 experts out of 38  
 487 analysed, while the really narrow distribution confirms general agreement among respondents.



488  
 489 **Figure 6:** Average parameters of the distributions calculated for (a) active barriers and (b) passive barriers.  
 490 Min = average minimum value,  $\bar{Q}_1$  = average higher value in the 1<sup>st</sup> quartile,  $\bar{Q}_2$  = average median  
 491 value,  $\bar{Q}_3$  = average highest value in the 3<sup>rd</sup> quartile, Max = average maximum value.

### 492 4.3 Discussion

493 The modification parameters elicited from the survey in perspective may be considered as a first step  
 494 to assess safety barrier performance in probabilistic QRAs of Natech events [14]. However, due to  
 495 the scarcity of data, this study only represents a first exploration of the topic and important limitations,

in particular when quantitative data are of interest, should be considered. Actually, in order to maintain a general validity of the assessment, it was decided to ask experts to consider a “plausible” intensity of natural hazards. Indeed, defining the characteristics and the intensity of natural hazards would have restricted the applicability domain of the study. On the one hand, the absence of intensity specification is thus in favor of a more general validity of the study. On the other hand, it also limits the direct applicability of results in the quantitative assessment of specific scenarios. The modification parameters obtained should be thus considered as generic baseline values. Site-specific values for quantitative assessment studies need to be derived from tailoring procedures, based on more detailed data both on the intensity of the natural event and on the specific features of the safety barrier considered.

An additional limitation of the present study is the inherent uncertainty affecting expert elicitation procedures. Experts may be unable to properly express their knowledge within the framework of the prepared survey, or they may be not confident with the verbal scale they were provided of. It is also possible that experts would have preferred to express their opinions on the likelihood of barrier failures through numerical distributions. For instance, some authors suggest to employ the Classical Model to better characterize judgment features, thus requiring experts to provide their subjective parameter distributions for each surveyed item in terms of 5<sup>th</sup>, 50<sup>th</sup> and 95<sup>th</sup> percentiles [65]. However, this procedure would have made the survey harder to be completed by experts, and was considered inappropriate considering the scarcity of data and the explorative nature of the present study. Furthermore, the combination of the distributions obtained would have required a proper assessment of the relative weights of expert knowledge, which was not practically feasible.

Some analyzed safety systems show a wide dispersion of the answer distributions, indicating a limited agreement among experts. One of the possible causes may be the technical complexity of some systems analyzed. In particular, for active barriers, a more refined analysis can be required to obtain reliable results. A possibility may be to study these systems through more sophisticated approaches considering the impact of natural hazards in each relevant subsystem. For instance, a failure mode and effect analysis (FMEA) could be used to assess which subsystems are critical during natural hazards, and what is the effect of damages to parts of system architecture [55].

The present study was limited to the analysis of technical barriers. However, this limitation derived only from the need to limit the number of barriers considered in the survey to limit the time required to the experts to complete it, and also from the background of selected experts. Procedural barriers and emergency measures may be assessed as well within the proposed framework. Indeed, during natural hazards the actions of plant operators and emergency teams, may be heavily hindered due to the high stressing environment and the complexity of scenarios [4].

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**5. Conclusions**

In the present study, the performances of common safety barriers adopted in chemical and process plants during natural hazards have been investigated by expert elicitation. Some safety barriers were identified as having a critical vulnerability to natural hazards. Baseline values to describe how the performance of safety barriers is modified during floods and earthquakes were obtained from the expert elicitation procedure. These parameters may support the probabilistic analysis of Natech scenarios, in order to achieve a better estimate of final consequences and possible domino effects. The results lay the basis for an improved risk-informed decision making on proactive strategies enhancing the safety of chemical and process plants against natural disasters.

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## 684 **Appendix A**

685 The present appendix reports the transcription of the form adopted to carry out the expert elicitation.  
 686 The form is reported in Table A.1

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688 **Table A.1 Transcription of the survey form**

<p>The scope of the present questionnaire is to gather experts' opinions on the possibility that several common safety barriers used in chemical and process plants could fail if impacted by natural events. The safety barriers considered are described in the file that you received attached to the e-mail including the link to the survey.</p> <p>The survey is limited to the impact of generic FLOOD and SEISMIC events (i.e., EARTHQUAKES) affecting the site where the barrier is present. The term "generic" in this context means that the opinion has to be expressed independently of the intensity of the event: in answering the questions you should evaluate how plausible is the failure of a protection measure in case of such events. It must be remarked that the present elicitation is to gather performance estimates: you should assess the plausibility of barrier failure and/or inefficient response considering its architecture (e.g., subsystems, dependence on power-grid connection, position of pumps, pipework, fail-safe design, etc.).</p> <p>In case you do not know (or you are not familiar with) a specific system mentioned in the survey, you can skip the question. In case you know the system, but you are not sure about the answer you can skip the question as well.</p> <p>In line with EU research standards, this survey is strictly anonymous. This research is purely of an academic nature, it is only intended to further and improve knowledge on the performance of protection measures adopted in industrial facilities.</p> <p><u>Personal information</u></p> <p>You are kindly asked to answer to a couple of questions for understanding your background.</p> <p>1. Which kind of institution do you belong to?          Answers: [Academia/Industry/Consultancy/Other: (specify).....]</p> <p>2. How many years of experience do you have in the context of safety barrier management?          Answers: [No experience/ From 1 to 5/From 5 to 10/From 10 to 20/More than 20]</p> <p><u>SBI. Inert Gas Blanketing System</u></p> <p>With inert gas blanketing system we refer to the whole system for padding tanks containing flammable liquids, comprising the inert supply tank, and the relative distribution piping.</p> <p>3. Do you think in case of flood event impacting process facilities, the inert gas blanketing system could be damaged and could be unavailable in case of demand?          Answers: [YES/NO/NOT SURE]</p> <p>4. Based on your experience and judgement, how likely do you think it is that the inert gas blanketing system is unavailable in case of demand, as immediate consequence of flood event?          Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]</p> <p>5. Do you think in case of seismic event impacting process facilities, the inert gas blanketing system could be damaged and could be unavailable in case of demand?          Answers: [YES/NO/NOT SURE]</p>
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6. Based on your experience and judgement, how likely do you think it is that the inert gas blanketing system is unavailable in case of demand, as immediate consequence of seismic event?

Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]

#### SB.2 Automatically Actuated Rim-Seal Fire Extinguishers

With automatically actuated rim-seal fire extinguishers we refer to a safety system against rim-seal fires located on the roof of flammable liquid storage tanks.

7. Do you think in case of flood event impacting process facilities automatically actuated rim-seal fire extinguishers could be damaged and could be unavailable in case of demand?

Answers: [YES/NO/NOT SURE]

8. Based on your experience and judgement, how likely do you think it is that automatically actuated rim-seal fire extinguishers are unavailable in case of demand, as immediate consequence of flood event?

Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]

9. Do you think in case of seismic event impacting process facilities automatically actuated rim-seal fire extinguishers could be damaged and could be unavailable in case of demand?

Answers: [YES/NO/NOT SURE]

10. Based on your experience and judgement, how likely do you think it is that automatically actuated rim-seal fire extinguishers are unavailable in case of demand, as immediate consequence of seismic event?

Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]

#### SB.3 Fixed/Semi-Fixed Foam Systems

With fixed/semi-fixed foam systems we refer to systems for tank fire extinction by providing water-based foam to the fire area.

11. Do you think in case of flood event impacting process facilities fixed/semi-fixed foam systems could be damaged and could be unavailable in case of demand?

Answers: [YES/NO/NOT SURE]

12. Based on your experience and judgement, how likely do you think it is that fixed/semi-fixed foam systems are unavailable in case of demand, as immediate consequence of flood event?

Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]

13. Do you think in case of seismic event impacting process facilities fixed/semi-fixed foam systems could be damaged and could be unavailable in case of demand?

Answers: [YES/NO/NOT SURE]

14. Based on your experience and judgement, how likely do you think it is that fixed/semi-fixed foam systems are unavailable in case of demand, as immediate consequence of seismic event?

Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]

#### SB.4 Water Deluge System / Water Curtains & Sprinklers

With water deluge system, water curtains we refer to safety systems to mitigate the risk posed by external fire to critical areas where the fire shall not spread. With sprinklers we refer to the system providing water to burning area.

15. Do you think in case of flood event impacting process facilities water deluge system, water curtains & sprinklers could be damaged and could be unavailable in case of demand?

Answers: [YES/NO/NOT SURE]

16. Based on your experience and judgement, how likely do you think it is that water deluge system, water curtains & sprinklers are unavailable in case of demand, as immediate consequence of flood event?

Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]

17. Do you think in case of seismic event impacting process facilities water deluge system, water curtains & sprinklers could be damaged and could be unavailable in case of demand?

Answers: [YES/NO/NOT SURE]

18. Based on your experience and judgement, how likely do you think it is that water deluge system, water curtains & sprinklers are unavailable in case of demand, as immediate consequence of SEISMIC event?

Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]

#### SB.5 Hydrants

With hydrants we refer to sources where fire brigades can connect firehoses to deliver water to burning areas. The system of firefighting water distribution to hydrants can be supposed the same to provide water to WDS and sprinklers.

19. Do you think in case of flood event impacting process facilities hydrants could be damaged and could be unavailable in case of demand?

Answers: [YES/NO/NOT SURE]

20. Based on your experience and judgement, how likely do you think it is that hydrants are unavailable in case of demand, as immediate consequence of flood event?

Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]

21. Do you think in case of seismic event impacting process facilities hydrants could be damaged and could be unavailable in case of demand?

Answers: [YES/NO/NOT SURE]

22. Based on your experience and judgement, how likely do you think it is that Hydrants are unavailable in case of demand, as immediate consequence of seismic event?

Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]

#### SB.6 Fire Walls

With fire walls we refer to physical barriers to protect assets from fire.

23. Do you think in case of flood event impacting process facilities fire walls could be damaged and could be unavailable?

Answers: [YES/NO/NOT SURE]

24. Based on your experience and judgement, how likely do you think it is that fire walls are unavailable, as immediate consequence of flood event?

Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]

25. Do you think in case of seismic event impacting process facilities fire walls could be damaged and could be unavailable?

Answers: [YES/NO/NOT SURE]

26. Based on your experience and judgement, how likely do you think it is that fire walls are unavailable, as immediate consequence of seismic event?

Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]

#### SB.7 Blast Walls

With blast walls we refer to physical barriers resistant to blast waves.

27. Do you think in case of flood event impacting process facilities blast walls could be damaged and could be unavailable?

Answers: [YES/NO/NOT SURE]

28. Based on your experience and judgement, how likely do you think it is that blast walls are unavailable, as immediate consequence of flood event?

Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]

29. Do you think in case of seismic event impacting process facilities blast walls could be damaged and could be unavailable?

Answers: [YES/NO/NOT SURE]

30. Based on your experience and judgement, how likely do you think it is that blast walls are unavailable, as immediate consequence of seismic event?

Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]

#### SB.8 Fireproofing

With fireproofing we refer to specific coating material intended to protect equipment from fire.

31. Do you think in case of flood event impacting process facilities fireproofing could be damaged and could be ineffective?

Answers: [YES/NO/NOT SURE]

32. Based on your experience and judgement, how likely do you think it is that fireproofing is ineffective, as immediate consequence of flood event?

Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]

33. Do you think in case of seismic event impacting process facilities fireproofing could be damaged and could be ineffective?

Answers: [YES/NO/NOT SURE]

34. Based on your experience and judgement, how likely do you think it is that fireproofing is ineffective, as immediate consequence of seismic event?

Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]

#### SB.9 Bunds / Catch Basins

With bunds / catch basins we refer to physical barriers around tanks storing hazardous liquids, sized to retain the whole content of the tank preventing liquid spread. Concrete, earth, or steel are used to build these structures.

35. Do you think in case of flood event impacting process facilities bunds / catch basins could be damaged and could be ineffective?

Answers: [YES/NO/NOT SURE]

36. Based on your experience and judgement, how likely do you think it is that bunds / catch basins are ineffective, as immediate consequence of flood event?

Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]

37. Do you think in case of seismic event impacting process facilities bunds / catch basins could be damaged and could be ineffective?

Answers: [YES/NO/NOT SURE]

38. Based on your experience and judgement, how likely do you think it is that bunds / catch basins are ineffective, as immediate consequence of seismic event?

Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]

#### SB.10 Fire Activated Valves

With fire activated valves we refer to valves activated through melting elements or by heat detectors. The valves instrument air to operate correctly.

39. Do you think in case of flood event impacting process facilities fire activated valves could be damaged and could be unavailable in case of demand?

Answers: [YES/NO/NOT SURE]

40. Based on your experience and judgement, how likely do you think it is that fire activated valves are unavailable in case of demand, as immediate consequence of flood event?

Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]

41. Do you think in case of seismic event impacting process facilities fire activated valves could be damaged and could be unavailable in case of demand?

Answers: [YES/NO/NOT SURE]

42. Based on your experience and judgement, how likely do you think it is that fire activated valves are unavailable in case of demand, as immediate consequence of seismic event?

Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]

#### SB.11 Fire and Gas Detectors

With fire and gas detectors we refer to sensors located in the field to detect fire, heat, smoke, or gas leaks, cabled to an alarm in control room.

43. Do you think in case of flood event impacting process facilities fire and gas detectors could be damaged and could be unavailable?

Answers: [YES/NO/NOT SURE]

44. Based on your experience and judgement, how likely do you think it is that fire and gas detectors are unavailable, as immediate consequence of flood event?

Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]

45. Do you think in case of seismic event impacting process facilities fire and gas detectors could be damaged and could be unavailable?

Answers: [YES/NO/NOT SURE]

46. Based on your experience and judgement, how likely do you think it is that fire and gas detectors are unavailable, as immediate consequence of seismic event?

Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]

#### SB.12 Shut Down Valves (SDVs)

With shut down valves (SDVs) we refer to fail-close valves aimed at the isolation of the equipment when activated. SDVs may be activated manually or by process/local/emergency shut-down logic.

47. Do you think in case of flood event impacting process facilities shut down valves (SDVs) could be damaged and could be unavailable in case of demand?

Answers: [YES/NO/NOT SURE]

48. Based on your experience and judgement, how likely do you think it is that shut down valves (SDVs) are unavailable in case of demand, as immediate consequence of flood event?

Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]

49. Do you think in case of seismic event impacting process facilities shut down valves (SDVs) could be damaged and could be unavailable in case of demand?

Answers: [YES/NO/NOT SURE]

50. Based on your experience and judgement, how likely do you think it is that shut down valves (SDVs) are unavailable in case of demand, as immediate consequence of seismic event?

Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]

#### SB.13 Blow Down Valves (BDVs)

With blow down valves (BDVs) we refer to fail-open valves venting process fluid to flare, aimed at providing a fast depressurization of the equipment. BDVs may be activated manually or by emergency shut-down logic.

51. *Do you think in case of flood event impacting process facilities blow down valves (BDVs) could be damaged and could be unavailable in case of demand?*

Answers: [YES/NO/NOT SURE]

52. *Based on your experience and judgement, how likely do you think it is that blow down valves (BDVs) are unavailable in case of demand, as immediate consequence of flood event?*

Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]

53. *Do you think in case of seismic event impacting process facilities blow down valves (BDVs) could be damaged and could be unavailable in case of demand?*

Answers: [YES/NO/NOT SURE]

54. *Based on your experience and judgement, how likely do you think it is that blow down valves (BDVs) are unavailable in case of demand, as immediate consequence of seismic event?*

Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]

#### SB.14 Emergency Blow Down (EBD) line to flare stack

The BDV is activated to depressurize equipment through opening a line to flare stack. The EBD line connecting the equipment to the flare is likely to have a flash KO drum for liquid separation.

55. *Do you think in case of flood event impacting process facilities the emergency blow down (EBD) line to flare stack could be damaged and could be unavailable?*

Answers: [YES/NO/NOT SURE]

56. *Based on your experience and judgement, how likely do you think it is that the emergency blow down (EBD) line to flare stack is unavailable in case of demand, as immediate consequence of flood event?*

Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]

57. *Do you think in case of seismic event impacting process facilities the emergency blow down (EBD) line to flare stack could be damaged and could be unavailable?*

Answers: [YES/NO/NOT SURE]

58. *Based on your experience and judgement, how likely do you think it is that the emergency blow down (EBD) line to flare stack is unavailable, as immediate consequence of seismic event?*

Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]

#### SB.15 Mounding storage

With mounding storage we refer to locating tanks into above-ground piles of gravel/earth (i.e., mounds) for protection from external fire.

59. *Do you think in case of flood event impacting process facilities mounds protecting the tanks could be damaged and could become ineffective in protecting tanks in case of fire?*

Answers: [YES/NO/NOT SURE]

60. *Based on your experience and judgement, how likely do you think it is that the protection given by mounds becomes ineffective, as immediate consequence of flood event?*

Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]

61. *Do you think in case of seismic event impacting process facilities mounds protecting the tanks could be damaged and could become ineffective in protecting tanks in case of fire?*

Answers: [YES/NO/NOT SURE]

62. *Based on your experience and judgement, how likely do you think it is that the protection given by mounds becomes ineffective, as immediate consequence of seismic event?*

Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]

#### SB.16 Burying storage

With burying storage (underground) we refer to positioning storage tanks below ground level.

63. *Do you think in case of flood event impacting process facilities the protection given by earth covering buried tanks could be compromised?*

Answers: [YES/NO/NOT SURE]

64. *Based on your experience and judgement, how likely do you think it is that the protection given by earth covering buried tanks becomes ineffective, as immediate consequence of flood event?*

Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]

65. *Do you think in case of seismic event impacting process facilities the protection given by earth covering buried tanks could be compromised?*

Answers: [YES/NO/NOT SURE]

66. *Based on your experience and judgement, how likely do you think it is that the protection given by earth covering buried tanks becomes ineffective, as immediate consequence of seismic event?*

Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]

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# Appendix B

The detail of the distributions obtained from experts' answers are reported in Table B.1 for floods and in Table B.2 for earthquakes.

**Table B.1: Description of performance parameter distribution for each safety barrier for floods. The reader can refer to Table 1 for concise barrier descriptions and classification.**

Safety barrier	Barrier ID	Performance estimate factor	Distribution description
Inert-gas blanketing system	SB.1	0.5	Minimum=0.15 1 <sup>st</sup> quartile = 0.25 2 <sup>nd</sup> quartile = 0.5 3 <sup>rd</sup> quartile = 0.75 Maximum = 0.85 Average = 0.441 Sample Std.Dev. = 0.259
Automatic rim-seal fire extinguishers	SB.2	0.15	Minimum=0 1 <sup>st</sup> quartile = 0.15 2 <sup>nd</sup> quartile = 0.15 3 <sup>rd</sup> quartile = 0.25 Maximum = 0.85 Average = 0.284 Sample Std.Dev. = 0.217
Fixed / Semi-fixed foam systems	SB.3	0.375	Minimum=0.15 1 <sup>st</sup> quartile = 0.25 2 <sup>nd</sup> quartile = 0.375 3 <sup>rd</sup> quartile = 0.5 Maximum = 0.85 Average = 0.434 Sample Std.Dev. = 0.236
WDS / Water Curtains / Sprinklers	SB.4	0.375	Minimum=0 1 <sup>st</sup> quartile = 0.175 2 <sup>nd</sup> quartile = 0.375 3 <sup>rd</sup> quartile = 0.75 Maximum = 0.85 Average = 0.439 Sample Std.Dev. = 0.279
Hydrants	SB.5	0.5	Minimum=0 1 <sup>st</sup> quartile = 0.25 2 <sup>nd</sup> quartile = 0.5 3 <sup>rd</sup> quartile = 0.75 Maximum = 1 Average = 0.493 Sample Std.Dev. = 0.308
Fire activated valves	SB.6	0.5	Minimum=0.15 1 <sup>st</sup> quartile = 0.25 2 <sup>nd</sup> quartile = 0.5 3 <sup>rd</sup> quartile = 0.5 Maximum = 0.85 Average = 0.418 Sample Std.Dev. = 0.238
Fire and gas detectors	SB.7	0.5	Minimum=0.15 1 <sup>st</sup> quartile = 0.25 2 <sup>nd</sup> quartile = 0.5 3 <sup>rd</sup> quartile = 0.75

			Maximum = 1 Average = 0.537 Sample Std.Dev. = 0.281
SDVs	SB.8	0.25	Minimum=0.15 1 <sup>st</sup> quartile = 0.15 2 <sup>nd</sup> quartile = 0.25 3 <sup>rd</sup> quartile = 0.5 Maximum = 1 Average = 0.343 Sample Std.Dev. = 0.238
BDVs	SB.9	0.25	Minimum=0.15 1 <sup>st</sup> quartile = 0.15 2 <sup>nd</sup> quartile = 0.25 3 <sup>rd</sup> quartile = 0.5 Maximum = 0.85 Average = 0.318 Sample Std.Dev. = 0.222
Fire walls	SB.10	0.2	Minimum=0 1 <sup>st</sup> quartile = 0.15 2 <sup>nd</sup> quartile = 0.2 3 <sup>rd</sup> quartile = 0.25 Maximum = 0.85 Average = 0.282 Sample Std.Dev. = 0.245
Blast walls	SB.11	0.15	Minimum=0 1 <sup>st</sup> quartile = 0.15 2 <sup>nd</sup> quartile = 0.15 3 <sup>rd</sup> quartile = 0.75 Maximum = 0.85 Average = 0.274 Sample Std.Dev. = 0.240
Fireproofing	SB.12	0.15	Minimum=0 1 <sup>st</sup> quartile = 0.15 2 <sup>nd</sup> quartile = 0.15 3 <sup>rd</sup> quartile = 0.25 Maximum = 0.85 Average = 0.261 Sample Std.Dev. = 0.252
Bunds / Catch basins	SB.13	0.75	Minimum=0.15 1 <sup>st</sup> quartile = 0.25 2 <sup>nd</sup> quartile = 0.75 3 <sup>rd</sup> quartile = 0.85 Maximum = 1 Average = 0.597 Sample Std.Dev. = 0.275
Emergency Blowdown line to flare stack	SB.14	0.25	Minimum=0 1 <sup>st</sup> quartile = 0.15 2 <sup>nd</sup> quartile = 0.25 3 <sup>rd</sup> quartile = 0.5 Maximum = 1 Average = 0.334 Sample Std.Dev. = 0.236
Mounding tanks	SB.15	0.25	Minimum=0 1 <sup>st</sup> quartile = 0.15 2 <sup>nd</sup> quartile = 0.25 3 <sup>rd</sup> quartile = 0.5 Maximum = 0.85 Average = 0.357 Sample Std.Dev. = 0.275
Burying tanks	SB.16	0.15	Minimum=0 1 <sup>st</sup> quartile = 0.15

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			2 <sup>nd</sup> quartile = 0.15 3 <sup>rd</sup> quartile = 0.5 Maximum = 0.85 Average = 0.289 Sample Std.Dev. = 0.230
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**Table B.2 Description of performance parameter distribution for each safety barrier for earthquakes. The reader can refer to Table 1 for concise barrier descriptions and classification.**

Safety barrier	Barrier ID	Performance estimate factor	Distribution description
Inert-gas blanketing system	SB.1	0.625	Minimum=0.15 1 <sup>st</sup> quartile = 0.5 2 <sup>nd</sup> quartile = 0.625 3 <sup>rd</sup> quartile = 0.85 Maximum = 1 Average = 0.607 Sample Std.Dev. = 0.238
Automatic rim-seal fire extinguishers	SB.2	0.5	Minimum=0.15 1 <sup>st</sup> quartile = 0.25 2 <sup>nd</sup> quartile = 0.5 3 <sup>rd</sup> quartile = 0.75 Maximum = 0.85 Average = 0.489 Sample Std.Dev. = 0.255
Fixed / Semi-fixed foam systems	SB.3	0.5	Minimum=0.15 1 <sup>st</sup> quartile = 0.5 2 <sup>nd</sup> quartile = 0.5 3 <sup>rd</sup> quartile = 0.75 Maximum = 0.85 Average = 0.571 Sample Std.Dev. = 0.238
WDS / Water Curtains / Sprinklers	SB.4	0.75	Minimum=0.15 1 <sup>st</sup> quartile = 0.5 2 <sup>nd</sup> quartile = 0.75 3 <sup>rd</sup> quartile = 0.85 Maximum = 1 Average = 0.620 Sample Std.Dev. = 0.246
Hydrants	SB.5	0.5	Minimum=0.15 1 <sup>st</sup> quartile = 0.25 2 <sup>nd</sup> quartile = 0.5 3 <sup>rd</sup> quartile = 0.75 Maximum = 0.85 Average = 0.482 Sample Std.Dev. = 0.282
Fire activated valves	SB.6	0.375	Minimum=0.15 1 <sup>st</sup> quartile = 0.25 2 <sup>nd</sup> quartile = 0.375 3 <sup>rd</sup> quartile = 0.6875 Maximum = 0.85 Average = 0.445 Sample Std.Dev. = 0.262
Fire and gas detectors	SB.7	0.5	Minimum=0.15 1 <sup>st</sup> quartile = 0.25 2 <sup>nd</sup> quartile = 0.5 3 <sup>rd</sup> quartile = 0.75 Maximum = 1 Average = 0.480 Sample Std.Dev. = 0.264
SDVs	SB.8	0.5	Minimum=0.15 1 <sup>st</sup> quartile = 0.25

			2 <sup>nd</sup> quartile = 0.5 3 <sup>rd</sup> quartile = 0.5 Maximum = 1 Average = 0.433 Sample Std.Dev. = 0.246
BDVs	SB.9	0.25	Minimum=0.15 1 <sup>st</sup> quartile = 0.15 2 <sup>nd</sup> quartile = 0.25 3 <sup>rd</sup> quartile = 0.5 Maximum = 0.85 Average = 0.368 Sample Std.Dev. = 0.236
Fire walls	SB.10	0.5	Minimum=0.15 1 <sup>st</sup> quartile = 0.25 2 <sup>nd</sup> quartile = 0.5 3 <sup>rd</sup> quartile = 0.75 Maximum = 1 Average = 0.514 Sample Std.Dev. = 0.271
Blast walls	SB.11	0.25	Minimum=0 1 <sup>st</sup> quartile = 0.25 2 <sup>nd</sup> quartile = 0.25 3 <sup>rd</sup> quartile = 0.5 Maximum = 0.85 Average = 0.405 Sample Std.Dev. = 0.257
Fireproofing	SB.12	0.25	Minimum=0 1 <sup>st</sup> quartile = 0.15 2 <sup>nd</sup> quartile = 0.25 3 <sup>rd</sup> quartile = 0.4375 Maximum = 0.75 Average = 0.314 Sample Std.Dev. = 0.234
Bunds / Catch basins	SB.13	0.5	Minimum=0.15 1 <sup>st</sup> quartile = 0.25 2 <sup>nd</sup> quartile = 0.5 3 <sup>rd</sup> quartile = 0.75 Maximum = 0.85 Average = 0.464 Sample Std.Dev. = 0.249
Emergency Blowdown line to flare stack	SB.14	0.5	Minimum=0.15 1 <sup>st</sup> quartile = 0.25 2 <sup>nd</sup> quartile = 0.5 3 <sup>rd</sup> quartile = 0.75 Maximum = 1 Average = 0.530 Sample Std.Dev. = 0.234
Mounding tanks	SB.15	0.25	Minimum=0.15 1 <sup>st</sup> quartile = 0.15 2 <sup>nd</sup> quartile = 0.25 3 <sup>rd</sup> quartile = 0.5 Maximum = 1 Average = 0.411 Sample Std.Dev. = 0.259
Burying tanks	SB.16	0.25	Minimum=0 1 <sup>st</sup> quartile = 0.175 2 <sup>nd</sup> quartile = 0.25 3 <sup>rd</sup> quartile = 0.5 Maximum = 0.85 Average = 0.391 Sample Std.Dev. = 0.251



