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

REVISED VERSION

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40 **ABSTRACT**

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

52

53 ***Keywords:***

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

55 **1. Introduction**

56 In recent years, a growing concern is caused by the threats generated by the interaction between
57 natural hazards and technological installations, the so called Natech (Natural-hazard triggered
58 Technological) scenarios [1]. In a number of disastrous natural calamities that stroke heavily
59 industrialized regions in different parts of the world, severe technological accidents followed the
60 natural events, directly affecting the population and causing huge damages to industrial assets [2-4].
61 The World Health Organization in a recent document remarked that, also as a consequence of climate
62 change, both the frequency and the magnitude of natural calamities are growing [5]. This trend rises
63 serious concern that the likelihood and magnitude of Natech events will consequently increase as well
64 [6].

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

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

81 In order to prevent technological accidents or to mitigate their consequences, safety procedures and
82 specific technical solutions are usually adopted, [usually referred to as safety barriers in the technical](#)
83 [literature \[20-41\]](#). Examples of safety barriers are water deluge systems to protect vulnerable
84 equipment from fire, catch basins to prevent liquid spread in case of a spill, foam systems, etc.
85 However, a number of case histories demonstrated the possible ineffectiveness of conventional safety
86 technological measures in case of Natech events, due to the specific conditions caused by the impact
87 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].

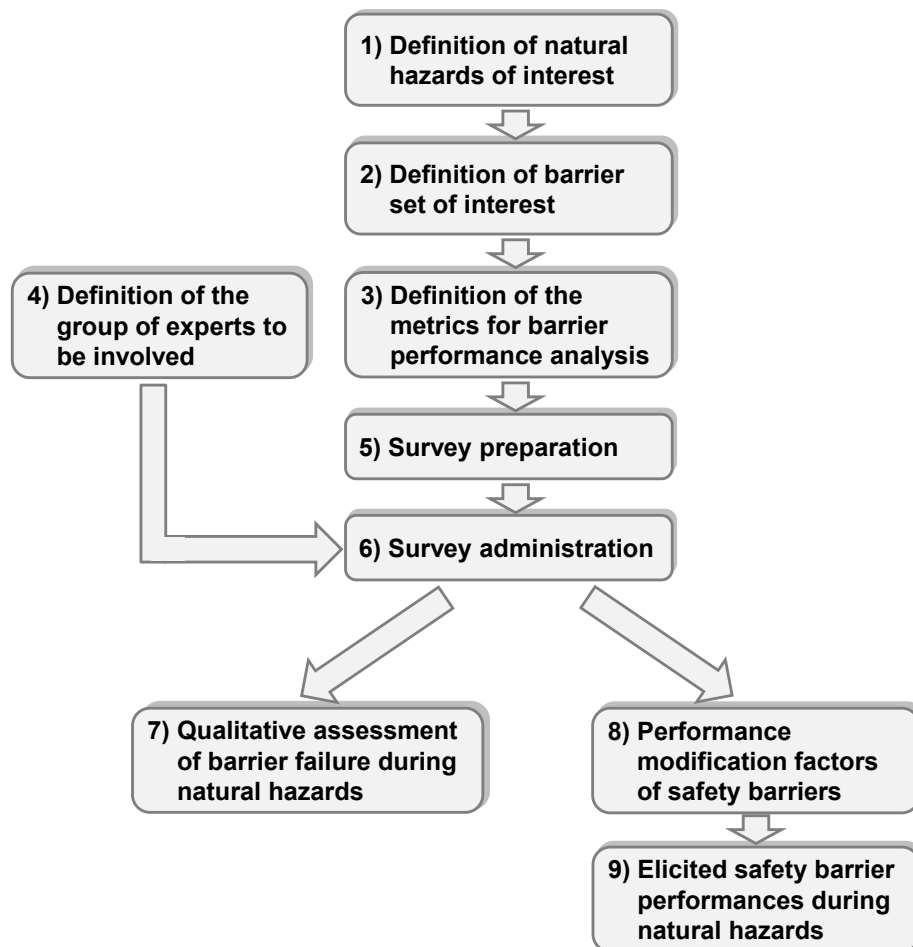
187 The effectiveness parameter, accounting for the quality of the performed barrier function, is not
188 assessed in standard LOPA studies [20, 39], and needs to be estimated considering performance data

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.).

206 However, in order to focus the elicited group of experts and to limit the complexity of the survey, the
207 decision was taken to limit this study to the analysis of these two significant categories of events.
208

209 **3.2 Definition of a set of reference safety barriers**

210 The second starting point of the study was the definition of a set of safety barriers to be analysed (step
211 2 in Fig. 1). This is needed both to limit the extension of the study and to allow the preparation of a
212 reference scheme and a description of the function of each safety barrier considered, to support the
213 expert elicitation. In the present study, only technical active and passive safety barriers were
214 considered. The choice to exclude organizational and procedural barriers is motivated by need to limit
215 the complexity of the study and to the high site specificity of their performances (e.g., presence of
216 internal emergency teams, distance of the plant from closest firefighter station, presence of specific
217 plans for natural disaster), that undermines the general validity of the performance parameters
218 obtained. On the contrary, baseline values for active and passive technical barriers are mostly related
219 to system architecture, thus are linked to the inherent structure of the safety system. Indeed, according
220 to lessons learnt from previous accidents, some specific failure patterns can be identified [55].

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

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

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

244
 245 **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.

246
 247 **3.3 Metrics for performance analysis of safety barriers**

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

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

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

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

259 Thus, in case of active barriers, the modification factor $\phi_{j,i}$ is used to determine a tailored value of
260 $PFD_{j,i}$ starting from a baseline $PFD_{0,i}$ reported by literature sources [52, 58, 59]:

$$261 \quad PFD_{j,i} = 1 + (\phi_{j,i} - 1)(1 - PFD_{0,i}) \quad (1)$$

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

$$263 \quad \eta_{j,i} = \eta_{0,i} \quad (2)$$

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

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

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

$$268 \quad \eta_{j,i} = (1 - \phi_{j,i}) \eta_{0,i} \quad (3)$$

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

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

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

275

276 **3.4 Expert elicitation**

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

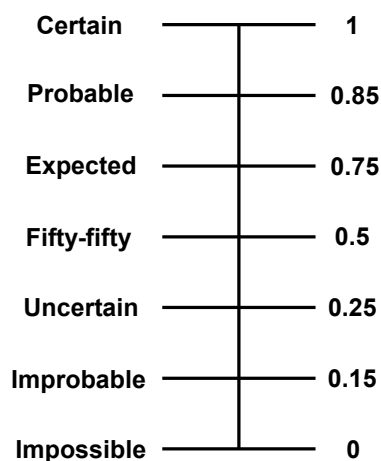
285 The actual number and background of experts answering the survey are reported in Section 4. An ad-
286 hoc survey has been prepared (step 5 in Fig. 1) and administered to the group of experts (step 6 in

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

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

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

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



308
309 **Figure 2:** Verbal scale adopted in the survey and corresponding quantitative translation adopted in the analysis
310 of the answers.

311 **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.

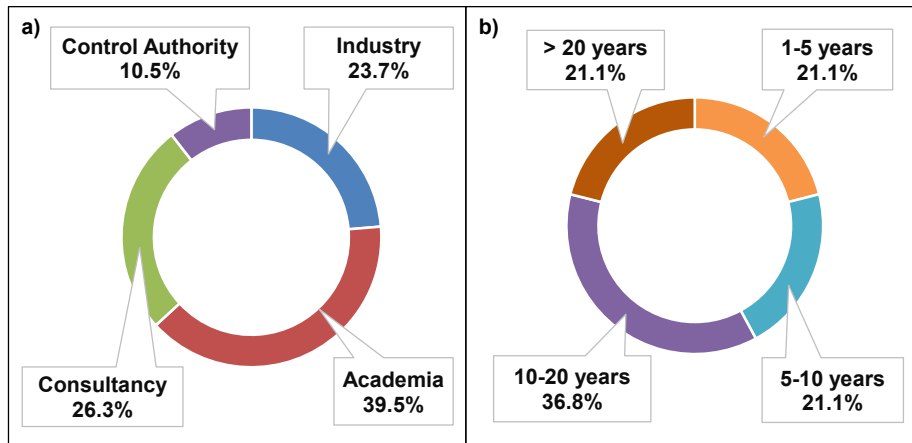
333 Elicited modification factors are then implemented in the proposed metric to assess active and passive
334 safety barrier expected performances during the reference natural hazards (step 9 in Fig. 1).

335

336 **4. Results and Discussion**

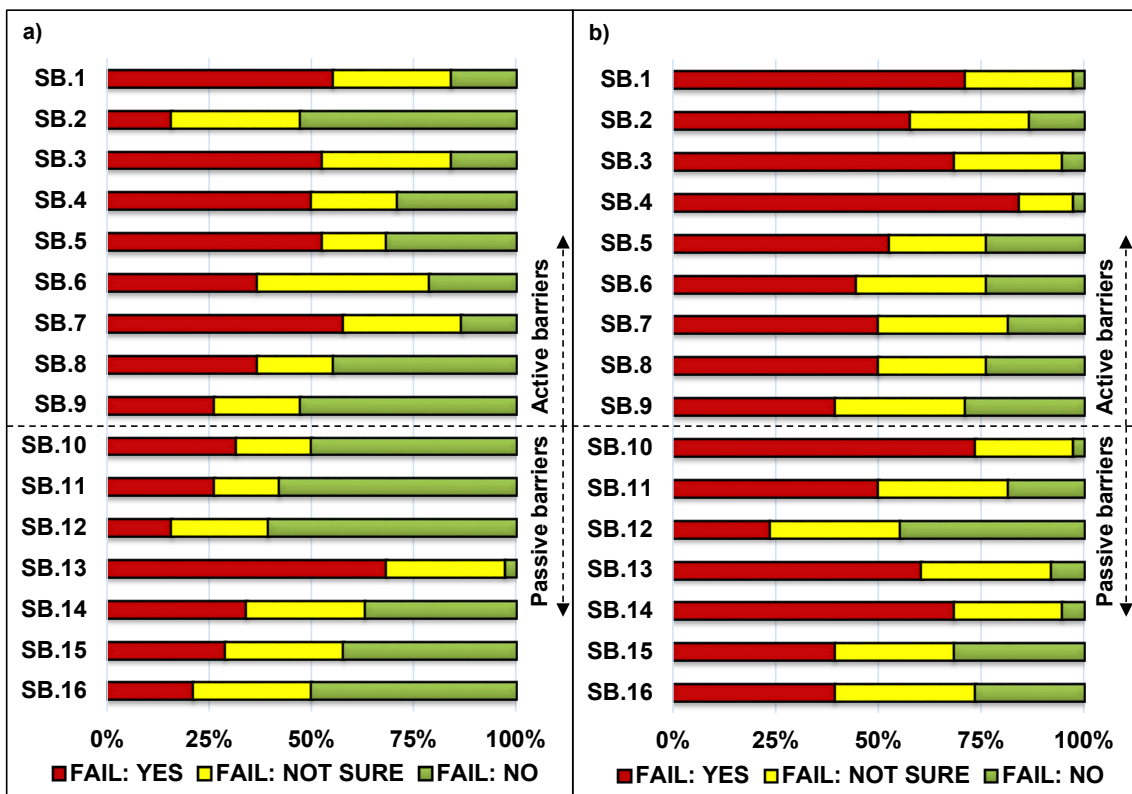
337 **4.1 Results of the survey**

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).



343
344 **Figure 3: Summary of professional background (a) and year of experience (b) of the pool of experts.**

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



350
351 **Figure 4: Results obtained from the survey concerning the likelihood of barrier failure or unavailability in the**
352 **case of the impact of (a) flood or (b) earthquake. The key to barrier ID is reported in Table 1.**

353

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).

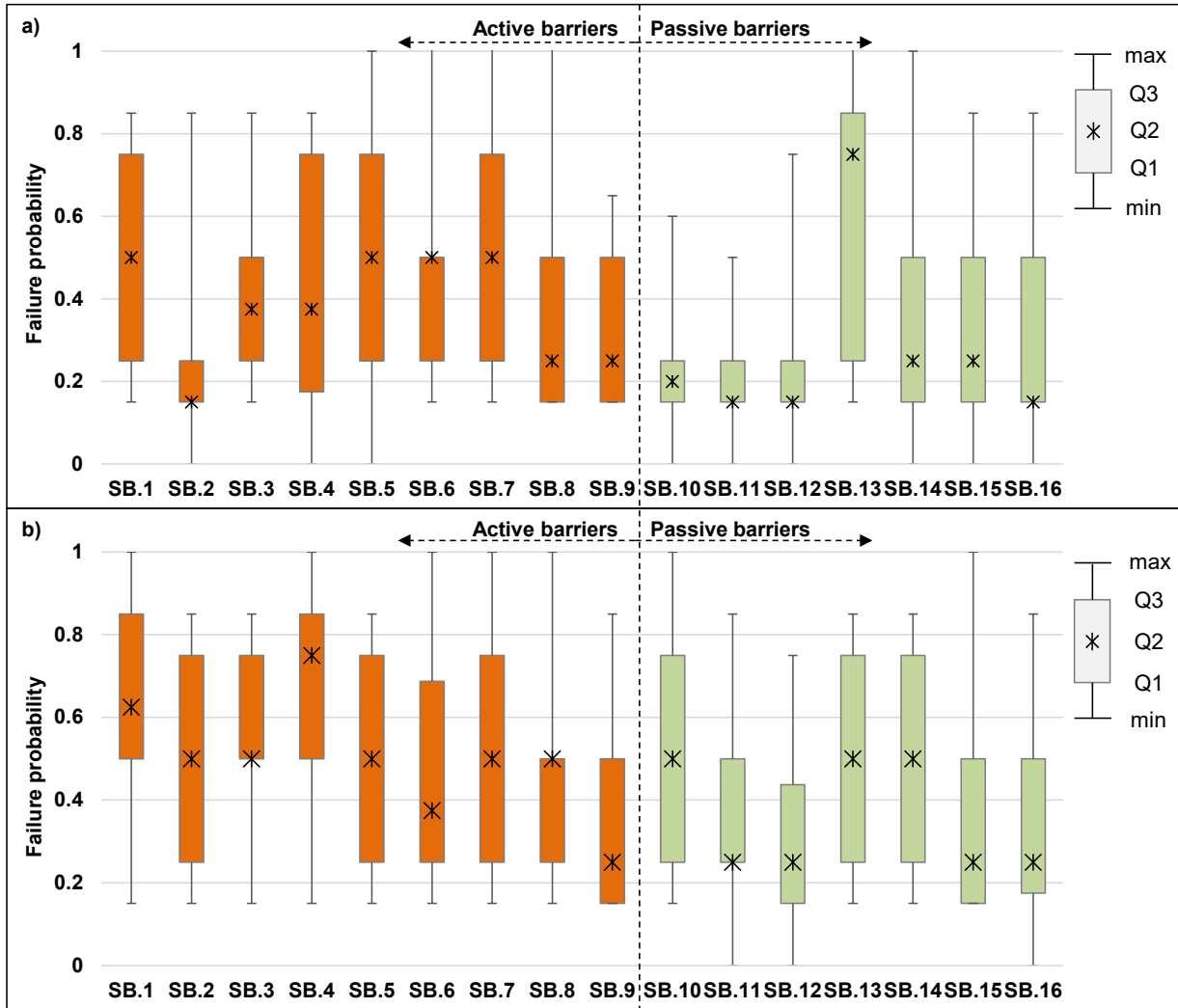
410

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

421 the distribution in case of disperse judgments: the influence of outliers on the variation of the mean
 422 value is rather elevated in the set of data obtained, while the median of the distribution is less affected
 423 by outliers, thus better representing the central tendency of data [63, 64].
 424



425
 426 **Figure 5: Results obtained from the elicitation of performance parameter ϕ for (a) floods and (b) earthquakes**
 427 **(Q1= higher value for the 1st quartile, Q2= highest value for the 2nd quartile (median value of the**
 428 **dataset), Q3= highest value for the 3rd quartile. Orange = Active barrier, Green = passive barrier. 0:**
 429 **failure impossible; 1: failure certain; see Fig. 2 for quantitative translation criteria of verbal scales).**
 430 **The key to safety barrier ID is reported in Table 1.**

431
 432 Distributions of the performance parameters during floods are presented in Fig. 5a. The most
 433 vulnerable active systems identified by the experts are the inert gas blanketing system (SB.1),
 434 hydrants (SB.5), fire activated valves (SB.6), and fire and gas detectors (SB.7), with median values
 435 of the elicited performance parameter of about 0.5. As evident from Fig. 4a, some of these items were
 436 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.

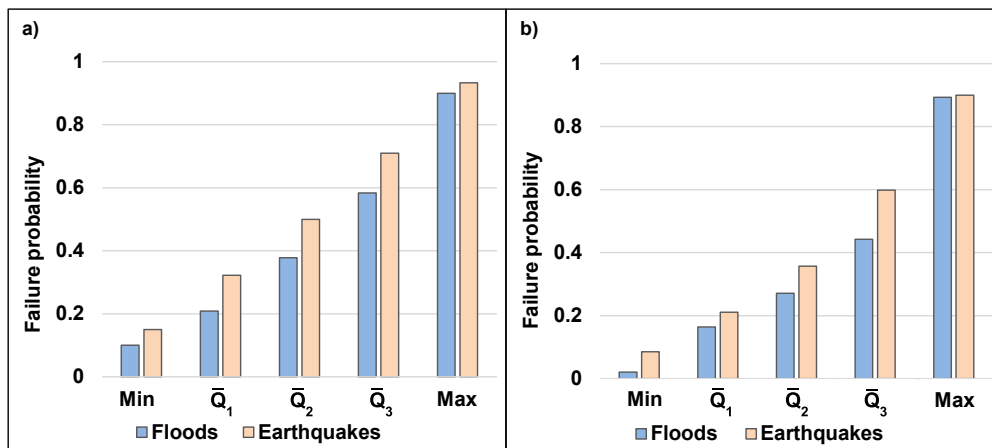
461 Passive barriers are deemed to be significantly affected by seismic loads in 3 out of 7 cases, with the
462 most critical items being firewalls (SB.10), bunds and catch basins (SB.13), and emergency
463 blowdown line (SB.14): median value is of 0.5 for each of the three distributions. For this subset 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 1st, 2nd, and 3rd 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 1st quartile, \bar{Q}_2 = average median
 491 value, \bar{Q}_3 = average highest value in the 3rd 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,

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

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

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

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

530

531 **5. Conclusions**

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

540

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681
682
683

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

687

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. 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>

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 st quartile = 0.25 2 nd quartile = 0.5 3 rd 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 st quartile = 0.15 2 nd quartile = 0.15 3 rd 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 st quartile = 0.25 2 nd quartile = 0.375 3 rd 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 st quartile = 0.175 2 nd quartile = 0.375 3 rd quartile = 0.75 Maximum = 0.85 Average = 0.439 Sample Std.Dev. = 0.279
Hydrants	SB.5	0.5	Minimum=0 1 st quartile = 0.25 2 nd quartile = 0.5 3 rd quartile = 0.75 Maximum = 1 Average = 0.493 Sample Std.Dev. = 0.308
Fire activated valves	SB.6	0.5	Minimum=0.15 1 st quartile = 0.25 2 nd quartile = 0.5 3 rd 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 st quartile = 0.25 2 nd quartile = 0.5 3 rd quartile = 0.75

			Maximum = 1 Average = 0.537 Sample Std.Dev. = 0.281
SDVs	SB.8	0.25	Minimum=0.15 1 st quartile = 0.15 2 nd quartile = 0.25 3 rd quartile = 0.5 Maximum = 1 Average = 0.343 Sample Std.Dev. = 0.238
BDVs	SB.9	0.25	Minimum=0.15 1 st quartile = 0.15 2 nd quartile = 0.25 3 rd quartile = 0.5 Maximum = 0.85 Average = 0.318 Sample Std.Dev. = 0.222
Fire walls	SB.10	0.2	Minimum=0 1 st quartile = 0.15 2 nd quartile = 0.2 3 rd quartile = 0.25 Maximum = 0.85 Average = 0.282 Sample Std.Dev. = 0.245
Blast walls	SB.11	0.15	Minimum=0 1 st quartile = 0.15 2 nd quartile = 0.15 3 rd quartile = 0.75 Maximum = 0.85 Average = 0.274 Sample Std.Dev. = 0.240
Fireproofing	SB.12	0.15	Minimum=0 1 st quartile = 0.15 2 nd quartile = 0.15 3 rd 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 st quartile = 0.25 2 nd quartile = 0.75 3 rd 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 st quartile = 0.15 2 nd quartile = 0.25 3 rd quartile = 0.5 Maximum = 1 Average = 0.334 Sample Std.Dev. = 0.236
Mounding tanks	SB.15	0.25	Minimum=0 1 st quartile = 0.15 2 nd quartile = 0.25 3 rd quartile = 0.5 Maximum = 0.85 Average = 0.357 Sample Std.Dev. = 0.275
Burying tanks	SB.16	0.15	Minimum=0 1 st quartile = 0.15

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			2 nd quartile = 0.15 3 rd 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 st quartile = 0.5 2 nd quartile = 0.625 3 rd 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 st quartile = 0.25 2 nd quartile = 0.5 3 rd 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 st quartile = 0.5 2 nd quartile = 0.5 3 rd 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 st quartile = 0.5 2 nd quartile = 0.75 3 rd quartile = 0.85 Maximum = 1 Average = 0.620 Sample Std.Dev. = 0.246
Hydrants	SB.5	0.5	Minimum=0.15 1 st quartile = 0.25 2 nd quartile = 0.5 3 rd 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 st quartile = 0.25 2 nd quartile = 0.375 3 rd 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 st quartile = 0.25 2 nd quartile = 0.5 3 rd quartile = 0.75 Maximum = 1 Average = 0.480 Sample Std.Dev. = 0.264
SDVs	SB.8	0.5	Minimum=0.15 1 st quartile = 0.25

			2 nd quartile = 0.5 3 rd quartile = 0.5 Maximum = 1 Average = 0.433 Sample Std.Dev. = 0.246
BDVs	SB.9	0.25	Minimum=0.15 1 st quartile = 0.15 2 nd quartile = 0.25 3 rd quartile = 0.5 Maximum = 0.85 Average = 0.368 Sample Std.Dev. = 0.236
Fire walls	SB.10	0.5	Minimum=0.15 1 st quartile = 0.25 2 nd quartile = 0.5 3 rd quartile = 0.75 Maximum = 1 Average = 0.514 Sample Std.Dev. = 0.271
Blast walls	SB.11	0.25	Minimum=0 1 st quartile = 0.25 2 nd quartile = 0.25 3 rd quartile = 0.5 Maximum = 0.85 Average = 0.405 Sample Std.Dev. = 0.257
Fireproofing	SB.12	0.25	Minimum=0 1 st quartile = 0.15 2 nd quartile = 0.25 3 rd 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 st quartile = 0.25 2 nd quartile = 0.5 3 rd 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 st quartile = 0.25 2 nd quartile = 0.5 3 rd quartile = 0.75 Maximum = 1 Average = 0.530 Sample Std.Dev. = 0.234
Mounding tanks	SB.15	0.25	Minimum=0.15 1 st quartile = 0.15 2 nd quartile = 0.25 3 rd quartile = 0.5 Maximum = 1 Average = 0.411 Sample Std.Dev. = 0.259
Burying tanks	SB.16	0.25	Minimum=0 1 st quartile = 0.175 2 nd quartile = 0.25 3 rd quartile = 0.5 Maximum = 0.85 Average = 0.391 Sample Std.Dev. = 0.251

