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ENSI Final Report: Review Approach and Comments Concerning the PEGASOS Refinement Project (PRP) and the PRP Summary Report

Summary

The project „Probabilistische Erdbeben-Gefährdungs-Analyse für KKW-Standorte in der Schweiz" (PEGASOS), which was sponsored by swissnuclear, managed by the Swiss National Cooperative for the Disposal of Radioactive Waste (Nagra), and implemented according to the Senior Seismic Hazard Analysis Committee (SSHAC) methodology at Level 4 (SL4), was completed in 2004. ENSI's review of PEGASOS is documented in HSK-AN-5364 {HSK, 2004}.

The PEGASOS Refinement Project (PRP) was conducted to update and improve PEGASOS based on new data and methods, and to address some of HSK's review comments. PRP was funded and managed by swissnuclear, and was independently reviewed by ENSI. PRP planning started prior to 2008, whereas expert participation commenced in September of 2008 with a Project Kick-Off Meeting and first workshop, WS-1. The Project held a Summary Meeting in May 2013, and submitted its summary report to ENSI in December 2013 {swissnuclear, 2013}.

Under the planned scope of SL4, PRP included subprojects for seismic sources (SP1), ground motions (SP2), site responses (SP3) and hazard calculations (SP4). ENSI conducted participatory and late-stage reviews of these facets of PRP.

ENSI's essential conclusions from its review of PRP are the following:

1. PRP produced valuable new data and methods, added new elements of state-of-the-art in probabilistic seismic hazard assessment (PSHA), and was successful in its principal intent of refining SP2 and SP3.
2. PRP suitably implemented SP4.
3. PRP included valuable initial research and development; this aspect of PRP prolonged the project beyond plan.
4. Software use in PRP was valid as planned; continuing validity of PSHA calculations for Swiss nuclear plants requires post-PRP improvements in the software platform.
5. SP1 of PRP was found to be deficient and not acceptable, and as a consequence the reported PRP hazard results are also not acceptable.
6. SP2 and SP3 models of PRP are suitable for developing hazard results to be further verified using a compatible and accepted SP1.

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Nomenclature

Formulas

f_{Peak}	Vibration frequency at which a response spectrum peaks
G	Shear modulus
G_{Max}	Maximum shear modulus
κ, Kappa	High frequency filter / damping parameter
κ_0, Kappa0	Site (zero-distance) Kappa value
κ_{0_Rock}	Rock partition of κ_0
κ_{0_Soil}	Soil partition of κ_0
M	Magnitude
M_0	Seismic moment
M_L	Local magnitude
M_{Max}	Maximum magnitude
M_W	Moment magnitude
Q	Anelastic attenuation parameter
R_{Rup}	Closest distance to rupture
Sa	Spectral acceleration
σ (Sigma)	Statistical measure of aleatory variation in horizontal ground motion
σ_{Add}	Additional modeled aleatory variation for vertical ground motion (relative to σ for horizontal motion)
σ_0	Stress drop parameter
V_P	Compression wave velocity
V_S	Shear wave velocity
V_{S_30}	Average V_S over 30 meters

Acronyms and Abbreviations

1D, 2D, 3D	One dimensional, two-dimensional, three-dimensional
A05	ENSI-A05
AN	Aktennotiz [Memorandum Report] (of ENSI or HSK)
AS14	Abrahamson and Silva, 2014 (ground-motion model)
AS97	Abrahamson and Silva, 1997 (ground-motion model)
BJF97	Boore, Joyner and Fumal (ground-motion model)
BSSA	Bulletin of the Seismological Society of America
BSSA14	BSSA, 2014 (ground-motion model)
CAV	Cumulative Absolute Velocity
CB14	Campbell and Bozorgnia, 2014 (ground-motion model)
CB03	Campbell and Bozorgnia, 2003 (ground-motion model)
CBR	Center, Body and Range
ECOS	Earthquake Catalog of Switzerland [Erdbebenkatalog der Schweiz]
ECOS-02	Earthquake Catalog of Switzerland, 2002
ECOS-09	Earthquake Catalog of Switzerland, 2009
ECOS-11	Earthquake Catalog of Switzerland, 2009 as published in 2011
EG	Expert Group (of PRP SP1)
EKKB	Ersatz Kernkraftwerk Beznau [Beznau New / Replacement Nuclear Power Plant]
EKKM	Ersatz Kernkraftwerk Mühleberg [Mühleberg New / Replacement Nuclear Power Plant]
EMME	Earthquake Model of the Middle East
ENSI	Eidgenössisches Nuklearsicherheitsinspektorat [Swiss Federal Nuclear Safety Inspectorate]
ENSI-A05	ENSI Guideline „Probabilistic Safety Analysis (PSA): Quality and Scope“
ENSI-RT	ENSI Review Team
EPRI	Electric Power Research Institute
ETH-Z	Eidgenössische Technische Hochschule Zürich [Swiss Federal Institute of Technology in Zurich]
FFS	Finite Fault Simulation
GEM	Global Earthquake Model
GEN	General (Open Item)
GM	Ground Motion

GMM	Ground-Motion Model
GMPE	Ground-Motion Prediction Equation
GR	Gutenberg-Richter
HF	High Frequency
HID	Hazard Input Document
HSK (now ENSI)	Hauptabteilung für die Sicherheit der Kernanlagen [Swiss Federal Nuclear Safety Inspectorate]
Hz	Hertz (cycles per second)
IAEA	International Atomic Energy Agency
IWS	Interface Workshop
IRVT	Inverse Random Vibration Theory
ISC	International Seismological Centre
ITC	Informed Technical Community
KKB	Kernkraftwerk Beznau [Beznau Nuclear Power Plant]
KKG	Kernkraftwerk Gösgen [Gösgen Nuclear Power Plant)]
KKL	Kernkraftwerk Leibstadt [Leibstadt Nuclear Power Plant]
KKM	Kernkraftwerk Mühleberg [Mühleberg Nuclear Power Plant]
KKN	Kernkraftwerk Niederamt [Niederamt Nuclear Power Plant]
L3	Level 3 (SSHAC level)
L4	Level 4 (SSHAC level)
MG	Monitoring Group (NPP-MG)
MLE	Maximum Likelihood Estimate
Nagra	Nationale Genossenschaft für die Lagerung radioaktiver Abfälle [Swiss National Cooperative for the Disposal of Radioactive Waste]
NGA	Next Generation Attenuation
NL	Nonlinear
NPP	Nuclear Power Plant
NPP-MG	Nuclear Power Plant Monitoring Group
NQA-1	ASME Nuclear Quality Assurance-1 Standard
NRC	US Nuclear Regulatory Commission
PEER	Pacific Earthquake Engineering Research Center
PEGASOS	Probabilistische Erdbeben-Gefährdungs-Analyse für KKW-Standorte in der Schweiz [Probabilistic Seismic Hazard Analysis for the Swiss Nuclear Power Plant Sites]

PGA	Peak Ground Acceleration
PGV	Peak Ground Velocity
PMT	Project Management Team
PPRP	Participatory Peer Review Panel (from the SSHAC Implementation Guidelines)
PRP	PEGASOS Refinement Project
PSA	Probabilistic Safety Assessment
PSHA	Probabilistic Seismic Hazard Analysis
PSSM	Point Source Stochastic Model
QA	Quality Assurance
RAI	Request for Additional Information
RT	Review Team (ENSI-RT)
RVT	Random Vibration Theory
R&D	Research and Development
SCR	Stable Cratonic Region
SED	Schweizerischer Erdbebendienst [Swiss Seismological Service]
SHARE	Seismic Hazard Harmonization in Europe
SL3	SSHAC Level 3
SL4	SSHAC Level 4
SSHAC	Senior Seismic Hazard Analysis Committee
SP	Sub-Project
SP1	Sub-Project 1, Seismic Source Characterization
SP2	Sub-Project 2, Ground-Motion Characterization (Rock)
SP3	Sub-Project 3, Site-Response Characterization (Soil)
SP4	Sub-Project 4, Seismic Hazard Calculation
SP5	Sub-Project 5, Hazard-Compatible Time Histories and Spectra
SSA	Seismological Society of America
TDI	Technically Defensible Interpretation
TFI	Technical Facilitator-Integrator
TN	Technical Note (of PRP)
UCERF	Uniform California Earthquake Rupture Forecast
UHS	Uniform Hazard Spectrum (Note: UHS is not used in this document for Ultimate Heat Sink)
USGS	United States Geological Survey
WS	Workshop

1. Introduction

1.1 Background

Site evaluation work related to seismic hazard in Switzerland for commercial nuclear power plants (NPPs) dates back to the early 1960's {Mayer-Rosa, 1993}, at the time when the NPPs were first being licensed and their seismic design bases were established.

In 1975, the first comprehensive seismic hazard study of Switzerland was initiated by the Swiss Federal Nuclear Safety Inspectorate. This study was based on the approach of probabilistic seismic hazard assessment (PSHA) {Cornell, 1968}. Although PSHA is now generally well-established in the earth-science and engineering communities, and is commonly applied in design and analysis of engineered facilities, back in 1975 it was relatively new and still in the early stages of practical application.

Over the time period since first application of the PSHA approach in Switzerland, considerable experience has been gained with its implementation in various countries, and the methodology has advanced rapidly, undergoing noteworthy refinements to keep up with new data and improvements in the related science and engineering disciplines (see, for example: {EPRI, 1989; NRC, 1989; NRC, 1994; IAEA, 2010; and NRC, 2014}). During its maturation stage, some of the most prominent advancements in PSHA took place in the US during the 1980's and 1990's, and culminated in a systematic framework for implementing PSHA studies, which was authored by the Senior Seismic Hazard Analysis Committee (SSHAC) {NRC, 1997} and has described a multi-level characterization of PSHA studies, up to Level 4. [1]

HSK (predecessor to ENSI) undertook seismic hazard review activities, and in 1998 sponsored a seminar with participation of other relevant governmental agencies, Swiss industry, and academia. The seminar resulted in the conclusion that the then-existing (1975) seismic hazard study was no longer state of the art, and thus, a significant update of the seismic hazard was warranted. In 1999, HSK required the Swiss licensees to update their seismic hazard assessments and perform comprehensive evaluation of uncertainties in hazard.

In response to this requirement, Swiss utilities (through funding of swissnuclear and contracting of the Swiss National Cooperative for the Disposal of Radioactive Waste [Nagra] for project management) developed a plan for a new PSHA project for the Swiss NPPs, named "Probabilistische Erdbeben-Gefährdungs-Analyse für KKW-Standorte in der Schweiz" (PEGASOS). The summary report HSK-AN-6252 {HSK, 2007} provides further discussion of the originating regulatory background and motivation leading to the development of the PEGASOS study for assessment of probabilistic seismic hazard of Swiss nuclear power plant (NPP) sites. The report HSK-AN-5364 {HSK, 2004} describes the process and principal findings from the HSK participatory and late-stage reviews of the PEGASOS study.

Subsequent to the PEGASOS study, swissnuclear decided to perform additional PSHA-related work for the Swiss NPPs. This follow-on work was organized as the PEGASOS Refinement Project (PRP), and

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[1] The SSHAC methodology was developed to explicitly acknowledge the uncertain nature of hazard estimates, and has served as basis to help avoid bias in developing central measures of hazard (e.g., median hazard) and to appropriately quantify the dispersion, or variation, in hazard estimates owing to limited data and associated differences in experts' viewpoints as to implications of the limited data. In short, the methodology is intended to capture the center, body and range (CBR) of credible viewpoints of the informed technical community (ITC), and hence, an appropriate representation of the "community view."

is discussed by swissnuclear in ENSI-approved versions of the PRP Plan {swissnuclear, 2011, 2010, 2009b, 2008}. Additionally, with release of ENSI A-05 {ENSI, 2009a}, official regulatory guidance concerning the quality and scope of probabilistic safety assessments (PSAs) specified that seismic hazard studies for nuclear facilities in Switzerland should be conducted according to the highest level of the SSHAC methodology (i.e., SSHAC Level 4 [SL4]) as it was originally documented {NRC, 1997}, and that ENSI should conduct the official review of the seismic hazard study. It is clear that ENSI must make the final decision concerning acceptability of the seismic hazard study, and this fact is also explicitly acknowledged, and taken as an expectation, in the SSHAC methodology itself.

1.2 Report Objectives

The principal objectives of this review report are:

- To provide an overview description of ENSI's review approach and the related activities conducted during the course of the PRP; and
- To document ENSI's concluding review comments and findings (including dispositions concerning study acceptability), made in terms of a net result of the entire review process (i.e., both participatory and late stages), including consideration of the PRP Summary Report.

1.3 Report Overview and Organization

This report continues in Section 2 with an overall summary of ENSI's aims and approach for the review of PRP. Although these are similar as for the PEGASOS review, adjustments in focus applicable to the ENSI review of PRP are noted.

Section 3 then concisely describes the process of ENSI's participatory review, including its closure and development of the final participatory-stage observations (residual findings) that serve as inputs for the late-stage review.

Section 4 provides a summary of specific review comments developed from ENSI's late-stage review activities (which have included examination of the PRP Summary Report and formulation of several requests for additional information [RAIs]). These review comments are intended primarily as notes on strengths and areas of potential improvement of the study, as discovered during the late stage, and they support subsequent late-stage review findings.

Section 5 summarizes ENSI's overall review assessment, starting with a concise general explanation of how the residual findings from the participatory review, as well as observations on potential improvements from the late-stage review, have been finally dispositioned. It then discusses some key comparisons of PRP and PEGASOS from the perspective of refinement. Next, a brief discussion of SL4 conformance is provided, including comments on the perceived quality of SSHAC implementation for the various subprojects. Section 5 concludes with a summary of principal review findings, including ENSI's statements concerning the validity of PRP and applicability of its results.

The final section of this report, Section 6, provides a list of the cited references.

2 Review Approach and Objectives

2.1 Main Review Objectives

As for PEGASOS, PRP was organized according to the following major subprojects:

- Seismic Source Characterization - Subproject No. 1 (SP1)
- Ground Motion Characterization - Subproject No. 2 (SP2)
- Site Response Characterization - Subproject No. 3 (SP3)
- Seismic Hazard Computation - Subproject No. 4 (SP4)

PRP introduced a new (additional) subproject, SP5, for the purpose of developing scenario time histories and response spectra for prospective use in subsequent application studies. As SP1 to SP4 were planned to be implemented according to the SL4 approach, whereas SP5 was not, ENSI's review of PRP only includes subprojects SP1 to SP4 (consistent with ENSI-A05 {ENSI, 2009a}).

ENSI's main objectives for independent technical and process peer review of the PRP are largely the same as those for the peer review of PEGASOS. In particular, where feasible, ENSI sought to provide appropriate review feedback, based on checks that:

1. The PSHA process was properly implemented in accordance with the following:
   a. The approved original and approved updated versions of the PRP Plan (which include modifications deemed necessary during the course of Project fulfillment);
   b. ENSI's PSHA guidelines, as conveyed in ENSI A-05 {ENSI, 2009a}; and
   c. The SSHAC recommendations for a Level-4 PSHA study (according to the original SSHAC guidance {NRC, 1997}).
2. The relevant facts, data, and state-of-the-art methods were considered in the PSHA process.
3. The key intermediate and final products and results of the PRP appear generally reasonable.

2.2 Review Guidance

ENSI's review of PRP was guided heavily by the review experience in PEGASOS, and was conducted in accordance with applicable state-of-the-art guidance and Swiss regulatory guidance, with some specific related elements being described in the following subsections.

2.2.1 SSHAC Level-4 guidelines

The PSHA approach adopted in approved versions of the PRP Plan {swissnuclear, 2011, 2010, 2009b, 2008} is intended as being based to a large degree on the SL4 methodology presented in NUREG/CR-6372 {NRC, 1997}. The following are important aspects of the SL4 methodology:

- It relies on an expert elicitation approach that requires input from multiple credible/knowledgeable experts.
- It requires that uncertainties be addressed systematically, with considerable care, in consideration of lack of knowledge about evaluation processes, models, and limited data that lead to legitimate differences in interpretations.

- It is intended to produce PSHA results that represent the understanding and uncertainty of the relevant informed communities of earth scientists and engineers.

The SSHAC approach also incorporates information pertaining to independent peer review. A principal consideration in the peer review is the identification of potential biases, both technical and judgmental, in the implementation of the PSHA process.

ENSI notes that, since the time of development of the original SSHAC guidelines, related implementation guidance has been proposed in (at least) the following documents: NUREG-2117, Rev. 1 {NRC, 2012} and USGS Open File Report 2009-1093 {USGS, 2009}. ENSI has considered these useful reports, including the lessons learned and related beneficial information thereby documented. Consistent with the current version of ENSI-A05, these documents have not served as official basis for ENSI's review; where potential discrepancies in guidance documents are encountered, ENSI considers the original SSHAC report to generally (and officially) govern.

2.2.2 ENSI's review approach

In accordance with ENSI-A05 and the PRP Plan, ENSI participated as the official reviewer of the PRP. ENSI performed an independent participatory peer review of the PSHA process followed in PRP. Furthermore, as was the case in PEGASOS, there were some specific unique aspects of the PRP Plan (e.g., the explicit treatment of site-response assessment as a separate subproject, SP3) that are not completely covered by the generic SL4 guidance. In addition, ENSI realized that Swiss regulatory practices should be appropriately represented in the review process. Hence, aside from considering the generic SSHAC peer review recommendations, and (informally) the judged-relevant aspects of subsequent SSHAC implementation guidance, ENSI made use of its specific review objectives (Section 2.1) and in some cases developed ad hoc approaches or more prescriptive guidance for implementing its independent participatory peer review of PRP. For example, ENSI undertook its own approach as to: development and implementation of guiding principles to avoid interference with PRP experts (see Section 2.2.3 below); review of the PRP database; process for suggesting and accepting a reasoned/judicious use of Monte Carlo simulation for quantification of uncertainty of intermediate hazard results; review treatment on encountering variances to the original PRP Plan; checking for implementation of the Project's QA guidelines; and other elements of review. Such objectives and guidance followed, to a significant degree, those already developed and documented in the earlier PEGASOS review, but where necessary, procedures were continuously updated / adjusted in accordance with the actual experience realized during the course of the PRP.

During fulfillment of PEGASOS, the project tasks and milestones remained comparatively fixed and transparent, once initially established. Accordingly, it was comparatively straightforward to implement review tasks and schedule so as to directly follow, or shadow, that project. This was not so much the case for the PRP; the PRP schedule was not a fixed target, but was expansive and fluid, and project activities were in a number of important cases not fully transparent. Accordingly, the ENSI review of PRP necessarily adapted fluidity as to schedule, and transitioned in emphasis to the pre-established review roles and activities, with less control around fixed schedule. Additionally, ENSI occasionally made specific request for clarification on various developments within the Project.

Although SL4 guidance suggests participatory and/or late-stage review options, both of these facets were considered essential by ENSI for conducting a complete review, capable of achieving closure or disposition on open review issues. Thus, ENSI's review approach included participatory and late-stage review activities. Owing to a significant number of open items from the participatory review phase, EN-

SI's late-stage review became extensive, and served to confirm findings, to develop additional observations, and to disposition review items to the extent possible. These activities are further discussed in Section 2.4 and Section 2.5 below. In both of these major phases of review, ENSI addressed technical and process issues – with a focus on the latter – as well as any project management and administrative issues that had the potential to adversely impact the hazard assessment and results.

2.2.3 Guiding principles of ENSI's review

ENSI strictly adhered to a set of guiding principles toward achieving a productive review outcome that would not unduly disrupt the PRP. These principles were followed during all facets of the review.

As ENSI intended the review project to proceed without introducing potential conflict or bias, ENSI took care to not influence the expert assessments made in the Project, and did not directly or unnecessarily disrupt the course and schedule of the Project. ENSI also provided related comments to the Project such that other designated observers of the Project would also be discouraged from influencing/biasing the experts or the Project.

The guiding principles are similar to those followed in the PEGASOS review; for convenient reference, they are repeated here:

1. Participants from ENSI should fulfill their responsibilities for regulatory review free of any conflicts of interest, and should endeavor to achieve the intent of regulatory review objectives and related goals (herein stated in Section 2.1).
2. ENSI participants should work together as a team, toward the goal of conveying the collective diversity of ENSI viewpoints in an overall consensus presentation of review observations. Any inconsistencies in review observations should be resolved in a manner consistent with noted ENSI and/or ENSI-RT roles (see Section 2.3 below).
3. ENSI participants should fulfill their review activities in a manner that minimizes undue disruption and direction to the Project as it proceeds, while yet achieving ENSI's review objectives and related goals. In this regard:
    a. Participation of ENSI members at formal PRP workshops and meetings should be observatory only. Following the conclusion of a workshop or meeting session, ENSI may provide informal review comments to the PRP Project Management Team (PMT), provided they are not made in the presence of an elicited expert.
    b. Providing observation and feedback to the Project concerning a significant weakness in performance of a TFI (technical facilitator-integrator), expert, or other Project participant is an important, but sensitive, aspect of ENSI's review role. Such observations should be made only if there is a potential risk that the Project participant may be introducing a bias into the PSHA study, and they should be raised only in situations where the thinking or confidence of an elicited expert will not be influenced.
    c. ENSI participants should take care concerning the timing of their comments. Comments made prematurely in the course of the Project may appear to be directive, whereas comments made too late in the Project may lead to a disruptive regression or digression of the Project to address a review concern.

2.3 Review Team

ENSI appointed a review team (designated as ENSI-RT, or its shortened form "RT") to have principal responsibility for implementing the PRP review project. ENSI-RT served as advisor to ENSI. Although its recommendations are accepted or modified at ENSI's discretion to ensure that the specific intent of ENSI's objectives is achieved, ENSI-RT served as ENSI's principal agency for fulfilling regulatory review of the PRP.

ENSI-RT includes a panel of recognized experts in probabilistic seismic hazard assessment:

- [redacted]ENSI Project Manager);
- [redacted], Eidgenössische Technische Hochschule Zürich [ETH-Z]);
- [redacted] R.T. Sewell Associates, Consulting); and
- [redacted] (Basler & Hofmann AG, Consulting Engineers).

Supplemented by the foundation of having reviewed the PEGASOS study, the expertise of any individual ENSI-RT member typically encompasses multiple aspects of the various scientific and engineering disciplines involved in PSHA, and is consistent with the requirements for peer reviewers, as described in SSHAC guidance. Taken collectively, the multiple areas of strength in expertise among panel members cover the major spectrum of PSHA topics.

The ENSI-RT members all served on HSK-RT for the PEGASOS review (see Section 2.3 of HSK-AN-5364). In their capacity as ENSI-RT participants, they have not represented their individual organizations or just their own viewpoints, but rather, have served as a team of contracted agents for ENSI, with the purpose of facilitating ENSI's review work and developing consensus review products.

The leader of ENSI's "Probabilistic Safety Analysis and Accident Management" Section, Dr. Gerhard Schoen, also observed a significant number of PRP workshops and observed most RT meetings and correspondences.

All ENSI-RT members regularly communicated with the ENSI Project Manager in accordance with their responsibilities and/or concerns regarding technical, management, and/or administrative matters. Although reviewers had principal responsibility for a specified PRP subproject (or subprojects), they also had the mutual responsibilities to stay informed on other subprojects and to communicate any review concerns regarding integration of subprojects. Owing, however, to specific background and circumstances – namely, that the PRP was intended to refine specific aspects of PEGASOS; that the RT members had inherently acquired significant general familiarity with all aspects of the PEGASOS study after review of that project; and that the number of RT members decreased (from five to four) relative to the case in PEGASOS – the review role of each RT participant became significantly more open relative to roles of the same RT members during PEGASOS. In general, all RT members strived to observe as many PRP activities as feasible (regardless of subproject), and to participate in technical understanding and commentary on all aspects of PRP.

All reviewers also participated in reviewing components of the PEGASOS/PRP database that related to fulfillment of their review roles.

2.4 Participatory Review

The participatory review conducted by ENSI included a technical and process peer review. The approach and scope of the review, summary of the technical and process elements, and procedures implemented for resolution of review issues, are described in the following subsections.

A summary list of some specific elements of ENSI's participatory review activities during PRP is provided here:

1. ENSI attended PRP workshops as well as some working meetings and webinars, as observers, and explained review findings in related review debriefing meetings;
2. ENSI developed several workshop review reports (see references {ENSI, 2008} through {ENSI, 2013c} in Section 6);
3. ENSI perused and researched information on the PEGASOS/PRP database;
4. ENSI reviewed key documentation and deliverables of the PRP project;
5. ENSI performed independent qualitative checks of intermediate and final PSHA results;
6. ENSI conducted, as needed, interim discussions with swissnuclear, as well as internal meetings involving ENSI Management and ENSI-RT;
7. ENSI conducted regular, periodic RT meetings, as well as technical meetings with the PMT and TFI; and
8. ENSI provided replies to PRP responses to ENSI comments on workshops, and ENSI maintained a list of open review points and consolidated open items.

2.4.1 Approach and scope of participatory review

The participatory review [2] approach in PRP consisted of two principal and complementary types of activities: (1) observation of the development of expert assessments through workshops, working meetings and elicitation meetings; and (2) structured interactions, as were determined useful, with the PRP PMT and TFI. In executing these activities, ENSI's review considered matters pertaining to process and technical implementation of the PSHA study.

The first type of activity – review observation at instances involving expert discussions and elicitations – made it possible: to assess the validity of the expert evaluation and elicitation process; to verify whether or not bias was being introduced into the PSHA process; to stay regularly informed of the progress of the study; and to gain the familiarity needed to knowledgeably communicate review questions or issues with the PRP PMT.[3] This activity was strictly observational, since it was important that there

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[2] The applicable SSHAC guidance describes a participatory review as follows: "An ongoing review that provides the peer reviewers with full and frequent access throughout the entire project. The process is structured to seek peer-review comments at numerous stages, and includes peer-review interaction with both the study team and, if appropriate, with the consultants and/or experts whose input is important to the final product."

[3] Owing to rapid advancements of a research and development (R&D) nature within the Project, some of which occurred outside the course of normal PRP workshops – and hence, were not fully transparent through observation of workshops alone – ENSI made specific request for an ENSI-PMT Technical Clarification Meeting, which was held on 8-9 April 2013.

was no influence, disturbance, or interruption interjected into the scientific and technical judgments made by experts within an appropriate expert evaluation and elicitation framework.

The second type of activity – structured review interaction that occurred outside the instances of expert elicitations – made it possible to communicate questions and review issues with PRP leaders (TFIs, PRP PMT, and key SP4 participants) so that appropriate resolution of those questions and issues could be achieved to the greatest extent possible. In the case of workshop debriefing meetings, members of the NPP Monitoring Group [NPP-MG] (comprised of representatives from the Swiss NPPs) also participated in discussions.[4]

Together, the preceding principal participatory review activities provided a system for regularly monitoring the course of the Project so that if some aspect of the study was being conducted openly and in a manner that might preclude its acceptance by ENSI, then such aspect could be readily detected and communicated to the PRP leaders and sponsors. The feedback-interaction from such monitoring was designed to continuously clarify to PRP leaders what would constitute, from ENSI's point of view, appropriate process and treatment of technical topics (as related, for instance, to data quality and state-of-the-art alternative methods) and of quality assurance, and what would constitute an unbiased study (as related to effective, but neutral guidance and use of expert elicitation by PRP leaders). This interaction – which can only be effective if the Project operates in a transparent, consistent and compliant manner, without neglecting issues or introducing sudden surprises – was thus intended, to the extent reasonably possible, to avoid the potential that a review concern might be raised at the end of the study, which would threaten the study's potential regulatory approval or could result in a requirement of re-analysis and re-review. [5]

The approach and scope of the ENSI peer review were fulfilled considering Table 3-2 of the SSHAC guidelines, which summarizes the following recommendations for peer review of a TFI study (such as a SL4 analysis):

- Process peer review:
  - A participatory review is strongly recommended
  - A late-stage review is risky and unlikely to be successful
- Technical Peer review:
  - A participatory review is recommended
  - A late-stage review can be acceptable

For highest consistency with these recommendations, ENSI's review included both participatory process and participatory technical elements. This approach was also intended to help avoid an overly protracted

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[4] Although this interaction was also possible, and in some cases employed, by Swiss NPP representatives during PEGASOS workshop debriefing meetings, the PRP was specifically designed to achieve a greater level of technical knowledge transfer by the Swiss NPPs, through the NPP Monitoring Group. Accordingly, generally greater involvement of the Swiss NPP representatives in the workshop debriefings occurred during PRP as compared to PEGASOS.

[5] At the same time, ENSI recognized that, to be appropriately fulfilled as a SSHAC study (i.e., in accordance with SSHAC guidance concerning interaction between the peer review team and the Project [most specifically, the PMT and TFI]), the Project itself had the responsibility to ensure that the concerns of the review team were understood and timely resolved.

late-stage process review; thus, although for completeness ENSI activities were designed to include review of the PRP Summary Report, ENSI had intended its technical review to be mostly participatory.

An example of an ENSI-purposed variance to the SSHAC participatory (process and technical review) is the following: whereas the SSHAC guidance permits some appropriate interaction of peer reviewers with the PSHA project's experts (see footnote 4), ENSI sought to minimize, and in general completely avoid (to the extent feasible), any interaction between ENSI participants (when acting in a review capacity) and the experts of the PRP subprojects. ENSI's intended emphasis was, rather, to interact with the PMT, TFI, and SP4 team, and allow these key project members to decide if and how to address issues through their normal project activities with, and through elicitations involving, the experts. This approach was followed to insure that the TFI would be able to evaluate review observations and to make decisions that would still allow the TFI to take full ownership of the study, as intended by SSHAC guidelines. ENSI had employed this approach during PEGASOS, and found it to work well. Specifically, it served to minimize concern over the risk (noted in SSHAC guidance) that "peer reviewers might lose their objectivity as they interact with the project over time."

As ENSI fashioned its process and technical peer review according to SSHAC guidance {NRC, 1997}, in similar manner as fulfilled and documented for the PEGASOS review {HSK, 2004}, those reports can be consulted for further general details.

As PRP was intended to be an improvement / refinement of an existing SL4 study, ENSI's process peer review specifically considered that a suitably reasoned and justified narrowing of diversity in approaches and models (e.g., as compared to PEGASOS) – that still defines an informed community view concerning credible, or defensible, technical interpretations or viewpoints for post-PEGASOS study of seismic hazard – could possibly be realized.

Also, concerning technical aspects of review specific to PRP, ENSI followed closely the rather involved site-response modeling and geotechnical engineering elements (SP3) of PRP. As to technical review of PSHA calculations, similar to the case in PEGASOS, ENSI accepted an approach (in lieu of direct inspection of PSHA calculation algorithms and independent spot checks) that involved: (a) confirmation of the PRP's quality assurance (QA) guidelines (which were based on the PEGASOS QA Guidelines); (b) acknowledgement of the situation that a limited check of the software used for PRP calculations had been performed independently by the Pacific Earthquake Engineering Research Center (PEER, 2003), and that at least earlier versions of the base software used for PRP had seen extensive use in nuclear projects, had undergone prior validations, and had been approved by ENSI in the planning phase of the PRP project; and (c) an understanding with the PRP PMT that certain sensitivity results may be needed to provide insight into, and to test the impact of, some specific PSHA calculation methodologies and/or assumptions.

Although ENSI identified a number of technical review points concerning PRP, a comparatively greater number of process-related comments have been developed.

2.4.2 Specific review workshops, events and activities

ENSI participants observed all workshops, and as practical, a subset of elicitation meetings and a subset of SP4 meetings. Following each of these activities, the attending ENSI member(s) held discussions with the PMT and TFI to consider preliminary peer review observations. The peer review observations collectively included a number of comments significant to the PSHA process. Final review observations were then documented in ENSI review reports, with attached cover letters, and sent to the PRP project sponsor, swissnuclear. The following table summarizes the review reports prepared by ENSI during the course of implementation of the PRP project (see also Section 6, References):

PRP Activity	ENSI Review Reports of PRP	
	ENSI Report No.	Report Date
Introduction Workshop, Kick Off Meeting and Workshop WS-1	ENSI-AN-6705	9 October 2008
WS-2; Interface Workshops SP1/SP2/SP4, SP2/SP3/SP4 and SP3/SP4/SP5	ENSI-AN-6481	5 February 2009
Plenary Meeting 1: SP2 Preparatory Meeting, WS2/SP1 and SP1-SP2 Interface Workshop	ENSI-AN-6962	12 June 2009
Workshops WS2a/SP3, WS2b/SP3 and WS2c/SP3	ENSI-AN-7316	16 July 2010
Workshops WS3a/SP3 and WS3b/SP3	ENSI-AN-7519	10 March 2011
Workshop WS4/SP3	ENSI-AN-7528	30 March 2011
Workshops WS2 to WS7 / SP2; Interface WSs SP1-SP2; FFS WS; and Interface WS SP2-SP3	ENSI-AN-7557	27 April 2011
Workshops WS2/SP1 and WS3/SP1	ENSI-AN-7575	13 May 2011
Workshop WS8/SP2	ENSI-AN-7585	20 May 2011
Workshop WS5/SP3	ENSI-AN-7694	19 September 2011
Workshop WS6/SP3	ENSI-AN-8027	27 August 2012
Workshop WS9/SP2	ENSI-AN-8036	6 September 2012
Workshops WS10/SP2, SP2-SP3 Interface, WS1/SP5 and SP2-SP3-SP4-SP5 Interface	ENSI-AN-8319	18 April 2013
Workshop WS11/SP2 and Working Meeting on SP2-SP3-SP4 Interface	ENSI-AN-8341	14 May 2013
SP2-Experts-Meeting on Kappa (Workshop WS12 / SP2)	ENSI-AN-8663	17 December 2013

In addition to these activities, ENSI met on several occasions during the course of project implementation to conduct detailed internal RT discussions on review issues, review status and review project development and implementation.

2.4.2 Resolution of review issues

ENSI's participatory review generated several review comments, some of which were favorable to the Project, and some of which required further consideration, and were designated as individual open review points. These review points included process and technical issues, or a combination of such.

It was possible to clarify and/or resolve several review issues during the informal meetings held with the PMT and TFIs following each workshop, and where applicable, during ENSI-PMT meetings. The reports described in Section 2.4.4 were prepared to communicate the specific review issues resulting from each workshop/meeting. In general, the Project prepared a written response to each of those reports, and ENSI prepared a final review letter indicating its comments/reply on the Project's written response. In some cases, the Project's response was found to directly resolve the identified issues or to describe specified (or implicitly accept) actions that would be undertaken to resolve the issue.

Review points that were kept open were communicated to the Project by means of "open items" letters [ENSI 2014c, 2014b, 2013d, 2010b, 2010a, 2009b]. In these letters, review points were combined into a smaller number of consolidated open items that shared similarity in terms of nature of the overall concern. Among a total of 396 review comments developed by ENSI, the review points determined as not being closed were mapped to 18 different consolidated open items. (Further related details are discussed in Section 3.)

2.5 Late-Stage Review

The PRP late-stage review [6] commenced once the Project submitted its PRP Summary Report in December 2013, and concluded with the completion of the present review report. The main late-stage review activities are generally summarized / condensed as follows:

1. ENSI reviewed the PRP Summary Report (January-March, 2014), and developed a draft review report and requests for additional information (RAIs);
2. ENSI met multiple times with the PMT and TFI to clarify review comments and RAIs, as well as to receive responses and clarifications by swissnuclear;
3. ENSI convened a number of meetings involving ENSI-RT and ENSI Management, in order to communicate review status and findings;
4. ENSI convened several internal ENSI-RT meetings – both face-to-face meetings and an extensive number of web meetings – to communicate technical issues toward developing review consensus (including consideration of swissnuclear responses to RAIs), to collaborate on revisions to the review report, and to discuss resolution of the overall list of consolidated open items; and
5. ENSI completed its final review report as documented here.

ENSI's late-stage review focused on assessment of the PRP Summary Report, with one aspect being the development of an overall consolidation and resolution of open review points (including any new points that were raised during the late stage, as a result of ENSI's review of the PRP Summary Report).

A key product of the late-stage review is an overall assessment of the PRP study, including remaining review observations and areas of consideration for potential future improvement, as well as findings concerning validity and applicability (i.e., acceptability) of the PRP study results.

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[6] SSHAC describes a late-stage peer review as follows: "A review that occurs only after the project has been almost completed. Usually, such a review takes place when a draft of the final report has been prepared, or when the project's bottom-line results are close to being in final form. Sometimes, a late-stage peer review can examine an intermediate-stage result when it has been almost completed. The principal characteristic of a late-stage peer review is that, if major problems are discovered, the work may need to be substantially redone, without the mid-course correction benefits of a participatory peer review. The use of a late-stage review is, therefore, a 'gamble' – usually an informed gamble, of course – on the part of the sponsors that major problems will not be discovered. A late-stage review has the benefit of a perception of complete independence."

3 Closure of Participatory Review

Individual review points and consolidated open items resulting from the participatory review process described in Section 2.4 were evaluated for final disposition, following consideration of the PRP Summary Report, in order to develop closure on the participatory review. A closure letter developed by ENSI {ENSI, 2014c} provides a final table that summarizes the individual review points, their disposition status from the participatory review, their mapping to consolidated open items, and the participatory-stage closure status concerning each consolidated open item.

Review points that were raised during the participatory review and still remain open as documented in {ENSI, 2014c} are considered together with the review points that were raised during the late-stage review, as identified in Section 4 of this report. Section 5 of this report develops ENSI's final review position regarding both sets of open review items (i.e., those open review points raised during the participatory review, and those raised during the late-stage review).

4 Late-Stage Review Observations

In this section, late-stage review observations from ENSI's assessment of the PRP Summary Report and of RAI responses are provided, and are categorized according to the specific subproject and subproject interface. These late-stage observations include study strengths, as well as areas of potential improvement.

Although a number of late-stage review observations may pertain to consolidated items, as referenced in Section 3, they are generally intended as distinct observations based on independent observation and evaluation of the PRP Summary Report. Where a late-stage observation and a participatory-stage consolidated open item overlap in nature, the items referenced in Section 3 and the comments discussed in this section are considered to be relevant to the disposition of the review observations; ENSI's final disposition is ultimately developed in Section 5 of this report.

4.1 SP1

4.1.1 Strengths

Catalog update, ECOS-11

The PRP modified the SP1 component of the PEGASOS model. A major aspect of this modification occurred through update of the reference seismic catalog produced by the Schweizerischer Erdbebendienst (SED) [Swiss Seismological Service], as the ECOS-02 catalog used in PEGASOS was replaced by the new ECOS-11 catalog.

Occurrence of SP1 workshops

PRP involved dedicated SP1 workshops, WS2/SP1 and WS3/SP1, and a SP1-SP2 Interface Workshop (IWS).

4.1.2 Areas of Potential Improvements

ENSI identifies a number of areas of potential improvement in the SP1 elicitation, some of which associated with serious technical weaknesses that significantly degrade confidence in the PRP hazard results.

In the following subsections, observations concerning SP1 are organized according to: (a) the overall scope of elicitation; (b) the elicitation of parameter M_{Max}; (c) issues related to the application of the ECOS11 catalog; (d) the elicitation of activity rates; (e) the derivation and use of hypocentral depth; and (f) the assessment of epistemic uncertainty. Then, subsection 4.1.2(g) summarizes review observations which ENSI deems as critical relative to any potential acceptance of PRP SP1.

4.1.2(a) Overall scope of SP1 elicitation

The scope and extent of the SP1 elicitation were designed to produce only a limited refinement of the PEGASOS SP1, based on the replacement of the ECOS-02 catalog with the new EOCS-11 catalog. That is, the Project was not designed to include a comprehensive SP1 elicitation (e.g., see Section 2.4.2 of the PRP Plan {swissnuclear, 2008}), under the assumption that it would not be a source of significant change to the PEGASOS hazard. This assumption and the limited SP1 effort were accepted by ENSI in the initial PRP Plan, but ENSI cautioned the Project that sensitivity studies would have to validate the assumption of low impact of SP1 on PEGASOS refinement (e.g., see points no. 1 and 5 in HSK-AN-6705). [7]

Accordingly, ENSI provided many workshop debriefing comments to the PMT, and documented several associated review observations following each workshop. [See review points 94, 95, 96, 97, 98, 102, 103, 104, 105, 106, 107, 108, 109, 110, 111, 112, 113, 114, 115, 126, 128, 133, 136, 137, 164, 165, 170 and 171, and consolidated open items GEN-2, GEN-3, SP1-1 and SP1-2, referenced in {ENSI, 2014c}.]

ENSI also observed limitations in the actual implementation of the SP1 elicitation process, leading to questions concerning resulting features in the PRP SP1 model, which are further discussed in subsequent review observations.

As summary, the principal observed issues concerning the SP1 elicitation are described here:

- According to the Project Plan, the limited SP1 elicitation process was to be completed by 2011 (i.e., more than two years prior to overall project completion) using only two post-introductory dedicated workshops; during WS2/SP1, the PMT for the first time indicated that specific SP1 model parameters (e.g., seismicity parameters and M_{Max} values) and other choices developed in SP1 would indeed have a significant effect on the hazard results. To account for this finding and for complications in use of the new catalogue, the project expanded the individual elicitations of the EG1a-d teams by several months after WS3/SP1.
- ENSI-RT grew increasingly concerned about the state of the SP1 elicitation and argued repeatedly for a more comprehensive SP1 re-elicitation, whereas the PMT maintained that such an expansion of the SP1 effort was not justified and would not be conducted:
  - ➢ ENSI wrote (ENSI-AN-6962 [4.9]): "*... As the findings of the M_{Max} sensitivity were a surprise to the project, and the TFI indicated that the findings were not conveyed as part of PEGASOS, ENSI-RT believes that the issue of a potential requirement for re-elicitation of SP1 needs to be considered and now resolved, rather than left open...*" and the PMT replied (PMT-KS-1036): "*The PRP is a refinement and not a complete new reassessment. Based on the PEGASOS result, the focus of the PRP was put on the SP2 and SP3 models ...*"
  - ➢ ENSI wrote again (ENSI-AN-7575 [2.11]): "*ENSI recommends the project to ensure that a new elicitation of SP1 on M_{Max} values and distributions will be performed, and that a M_{Max} sensitivity study will also be included in the PRP and its documentation.*" and in [2.12]: "*ENSI advises the project to clarify how the new source seismicity parameters (activity*

[7] Furthermore, from early in the Project – despite review comments from ENSI favoring use of a full PRP SP1 model for Project sensitivity analyses -- the Project instead applied a Simplified SP1 Model (i.e., SP1 "TFI Model" from PEGASOS). Hence, an underlying basis of the Project's sensitivity analyses was that SP1 would not materially change (from PEGASOS to PRP), and that the PEGASOS TFI Model for SP1 would continue to be valid. Additionally, although ENSI indicated that the SP1 experts should be free to adjust their models (potentially requiring a more involved SP1 elicitation compared to that planned), and the Project agreed that such option to adjust models (and correspondingly, to undertake a more detailed SP1 elicitation) would be given to the SP1 experts, the Project indicated at the time of closure of the SP1 elicitation that the SP1 experts had not introduced material changes in their models.

rates, b-values, M_{Max}), assessment of other source characteristics, completeness analyses, etc., will be performed, as well as how SP1 will be re-elicited." The PMT replied (PMT-KS-1212): *"The SP1 experts will not be re-elicited for their full models as part of the PRP."*

- ENSI found that still the PMT did not appropriately complete or suitably adjust the SP1 elicitation (e.g., see points no. 4.1 to 4.3 in ENSI-AN-6962; and 2.1 to 2.4 and 3.2 to 3.4 in ENSI-AN-7575) and model building (e.g., see points no. 4.8 to 4.11 in ENSI-AN-6962; 2.11, 2.12 and 3.5, 3.8 to 3.10 in ENSI-AN-7575) to meaningfully reflect the then, newly noted (although originally unexpected) importance of changes in SP1. In particular, the subsequent addition to the PRP SP1 elicitation missed a number of crucial steps, as explained here:
    - ➢ Although extensive sensitivity tests showing associated relative changes in hazard were provided to the SP1 experts during the PRP elicitation, the changes in the cumulative activity rates – which are more indicative for understanding the effects of the SP1 choices – were shown for the first time only at the PRP Summary Meeting, two years after the SP1 elicitation had already been concluded. Yet, similar plots showing the resulting activity rates were indeed made and discussed during PEGASOS (e.g. TP1-TN-0334 to 0337or TP1-RF-0388; 2003) and were evaluated by the experts at the occasion of the PEGASOS workshop WS4/SP1 (2003). The PMT for PRP omitted this key element of feedback during the Project.
    - ➢ A third SP1 workshop would have enabled the EG1 teams to discuss their models and receive feedback from the other teams concerning defensibility of technical interpretations, following the additional SP1 elicitation conducted by the Project; however, such an additional workshop was not conducted.
    - ➢ The PMT did not provide any opportunity for feedback, and the SP1 experts were not given the opportunity to adjust their models after observing the change-in-hazard impacts of the SP1 inputs – including the cumulative activity rates – as presented during the PRP Summary Meeting.

4.1.2(b) SP1 elicitation of M_{Max}

Whereas the EG1a-d teams of SP1 were elicited as to values of the lowest, mean and largest M_{Max} values representing the community view, ENSI observed some related potential problem areas, including the following:

- The PRP results show that the lowest and the mean M_{Max} values are very relevant in determining the range of the applied M_{Max} prior distribution and in determining the proportions of events contributing the most to hazard (i.e., M5.5 to M6.5) in the cumulative activity rates. Such relevance can be seen, for example, in slide 63 of TP1-RF-1477 {AMEC, 2012} from the PRP Summary Meeting, as well as (concerning consequences on the final hazard results) in tornado plots presented in the PRP Summary Report {swissnuclear, 2013} (see for example Fig. 8.36-8.37, which shows inter-team variations of about 50%). The elicited M_{Max} distributions for the four teams, however, display significant inconsistencies; related observations include the following:
    - ➢ The EG1a-d choices for the lowest, mean and largest M_{Max} values are very different among the four teams, ranging between values of M5.5 and M8.0 (see response to RAI-21).
    - ➢ The lowest M_{Max} value (i.e., when considering results among all teams) is M5.5, which is much lower than the lowest M_{Max} value of M6.9 obtained through the community effort in

SHARE [Seismic Hazard Harmonization in Europe] (which was conducted in parallel with PRP and included some of the same experts), and also is significantly lower than the values obtained through paleo-seismic investigations {swissnuclear, 2009a}, which were provided to the SP1 experts (PMT-TN-1033 documents that the paleoseismic studies by Strasser (2006) and Ferry et al. (2005) indicate three to five occurrences of M6.5-7.0 events in 15'000 years (affecting the northern area of Switzerland where the plants are located).

- The M_{Max} distributions developed by the four teams cover surprisingly different magnitude ranges. The mean M_{Max} values for the host source of a given site differ by up to one unit of magnitude among the four teams (see Fig. 2.3, PRP Summary Report, Vol. 1). For the Leibstadt source, the M_{Max} distributions developed by EG1a-b show most of the weight (over 90%) for magnitudes smaller than M6.1, whereas the M_{Max} distribution of EG1d only begins at M6, and the EG1c distribution peaks at M7 {swissnuclear, 2014d}. While it is not expected that the CBR of each parameter assessment must match from expert-to-expert, it would nonetheless be expected that an exhaustive elicitation of the four SP1 teams would lead to a more converging and non-mutually-exclusive overlap in representing the community view (and as such, supposedly encompassing also the view of the other teams). The large variability of the M_{Max} estimations among the four EG1 teams points to insufficient feedback and interaction in the SP1 elicitation process, not in line with the requirements of a rigorous evaluation and integration phase of a SL4 study

- The elicitation of extreme limit parameters, such as the largest M_{Max} value, poses a special case as, essentially by definition, the highest proponent or defensible value proposed by any of the teams is retainable as a maximum value among the ITC; otherwise, a challenge to the credibility of the assessments of some individual team(s) is implied. The results of related assessments of the four SP1 teams, EG1a-d, show values of largest M_{Max} ranging from M6.4 to M8.0 for the Leibstadt host source {swissnuclear, 2014d}; this level of variation among the four teams in representing the extreme upper magnitude of the ITC is further evidence of an insufficient SP1 elicitation. [8]

4.1.2(c) Issues related to the application of the ECOS11 seismic catalog

A number of issues emerged in the application of the ECOS11 seismic catalog. Some were resolved in the elicitation, whereas some resulted in significant weaknesses of the cumulative activity rates, as discussed here:

- The PRP SP1 model is based on the ECOS-11 catalog, and therefore, on the choice of the non-linear regression adopted for magnitude scaling in ECOS-11; this relationship (Fig.1-2 in TFI-TN-1292 {swissnuclear, 2014c}) is characterized by a non-linear M_L-M_W relation for M_W smaller than M4, and by a linear relation for M_W larger than M4. A critical issue with the application of the non-linear M_L-M_W regression in PRP is that the cumulative magnitude-frequency distribution – if it were linear with the old magnitude scaling used in PEGASOS – becomes non-linear at

[8] The same issue of eliciting extreme limits of maximum or minimum parameter values holds also for other cases, such as the upper-limit maximum ground motion developed in SP2 and SP3, or the extreme limit of minimum Kappa developed in SP2. In the case of SP1, the unjustified variation in assessment of extreme upper M_{Max} for the ITC is considered to be both inappropriate and important to hazard.

low magnitudes after the correction. This difficulty was well noted by the experts, who demonstrated it to be a struggle to find a solution, and in the end opted for using only the linear portion of the distribution, so as to conserve the predictive character of the linear Gutenberg-Richter (G-R) relationship. All the expert teams expressed difficulty with the derivation of b-values with a non-linear M_L-M_W regression (see the Evaluation Summaries, PRP Summary Report Vol. 3):

- EG1a "*Based on these considerations the SP1a Experts decided to restrict their analysis of activity rate to M_W larger than 2.7, i.e. in an area where a constant shift of M_W from M_L can hold.*"
- EG1b "*The quadratic M_L-M_W relation requires to consider that the Gutenberg-Richter relation can be applied in its classical linear form only above a certain M_W ... therefore, it has been concluded for EG1b to limit the ECOS-11 M_W data to M_W 2.7 for the MLE (Maximum Likelihood Estimation) of the frequency-magnitude parameter.*"
- EG1c "*The recurrence rates are strongly influenced by the change in the catalogue. However it is mainly for magnitude range smaller than 3. We would like to limit the fit to M > 2.7 but have a evaluation of Gutenberg-Richter parameters for the different source zones.*"
- EG1d "*The possibility of a non-linear compression of the M_W scale relative to the M_L scale, and the lingering question in which scale a Gutenberg-Richter power law may in fact be valid, is unresolved right now ... we would like to see rate and hazard sensitivity calculations for a new model where the minimum completeness of the instrumental period is set to 3.0. At this Mc, the effect of the non-linear M_L-M_W conversion is minimal*".

In summary, all four EG1 teams expressed their preference to utilize only the linear portion of the conversion (with one exception where non-linear fitting forms were also attempted); however, in the end, events with magnitudes as low as M3.0 or M2.7 (depending on the teams) were used, owing to the need to maintain a sufficient number of events to perform the G-R regression, even though the M_L-M_W functional form remains nonlinear for magnitudes up to M_W of 4 (see TFI-TN-1292). The impact of using the nonlinear regression is an increase in the activity rates in the low-magnitude portion of the magnitude-frequency distribution (e.g., consider the differences in Figures 2.13, 2.30 and 2.128 in the PRP Report Vol. 3), which in turn results in higher b-values when using maximum-likelihood-based methodologies (as applied in PRP); higher b-values correspond to lower activity rates for higher-magnitude events of relevance for hazard assessment.

- The M_W scaling adopted in ECOS-11 has a constant shift of 0.1 magnitude unit for M_W larger than 4, such that the M_W values in ECOS-11 are lower than the corresponding values in ECOS-02. The PRP Summary Report (Vol.1, p. 56, last bullet) concluded that the noted difference in the SP1 contribution to hazard between PEGASOS and PRP "can be attributed entirely ... on the 0.1 magnitude shift downward between the M_L and M_W scaling". The impact of the 0.1 magnitude shift on the hazard results was made evident by the Project only in the PRP Summary Report and is not supported by adequate elicitation and sensitivity tests. In particular, ENSI makes the following observations:
  - The 0.1 magnitude shift in the linear portion of the ECOS-11 regression was obtained as part of a combined nonlinear regression of data ranging from M1 to M5.5; the data used to constrain the regression, however, are dominated by low-magnitude events,

and only few data obtained with different methodologies are available to constrain the linear portion of the regression above M_W 4, resulting in a very ill-constrained value for the shift (see Figure 1 in TFI-TN-1292).

- As previously observed, the experts selected to use only the higher magnitude M3 to M5.5 range for the derivation of G-R parameters; however, the 0.1 shift in the magnitude scale has not been validated through a linear regression in the applied magnitude range.

4.1.2(d) SP1 elicitation of activity rates

- The EG1a-d teams were elicited on the individual parameters contributing to the definition of the activity rates, such as b-value and M_{Max} distribution. However, the primary input in the hazard calculation is the cumulative activity rate obtained from the logic tree of each SP1 team. For the first time, the EG1 teams were shown such results – and then, only briefly and only partially – in the PRP Summary Meeting, two years after the conclusion of their elicitation, and were not given the chance to provide feedback on the effect of their choices of parameters on the cumulative activity rates.
- The range in resulting EG1 estimations of activity rates is broader, and the values are lower, than the corresponding PEGASOS distributions. ENSI's related observations include the following:
  - The comparison of the cumulative activity rates, for PRP versus PEGASOS, shows a systematic increase of about a factor of two in the spread of the four SP1a-d curves (see Slide 3 in the file "SupportingInformation_23-6-2014.pptx" provided in e-mail correspondence from the PMT to ENSI on 23 June 2014).
  - The variation in individual cumulative activity rates, among the four EG1 groups for the host source, as shown during the PRP Summary Meeting, is about a factor of 6 for events of M6.5 for different sites, and exceeds a factor of 20 in the case of recurrence rates for the Mühleberg site (e.g., rate values vary from about 1.7e-5/yr to 3.0e-4/yr in slide 63 of TP1-RF-1477).
  - In PRP, the four EG1a-d estimates of the repeat time for M6.5 earthquakes within a 50-km radius from Gösgen range between 4,500 and 25,000 years, with a combined mean of about 9,000 years (see additional material provided by the PMT on June 23, 2014); this area includes (among other sources) the Basel source (entirely or in-part, depending upon the specific team), and the EG1a-d repeat times for a M6.5 for the Basel source range between 8,000 (EG1c) and 25,000 years (EG1a,b,d) with a combined mean of 15,000 years (PMT-TN-1294). The PRP EG1a-d values for the repeat time of a M6.5 earthquake in the Basel area are much higher than the values constrained by historical seismology (with the 1356 Mw 6.6 event occurring in the past 1,000 years) and by paleoseismologic studies (e.g., trenching of the Rheinach fault has uncovered 5 events of M6.5 in the past 11,500 to 13,200 years, with a mean recurrence time of about 3,000 years). ENSI's conclusion from this comparison is, therefore, that the PRP activity rates significantly overestimate the repeat time of large earthquakes (i.e., significantly underestimate the rate of large earthquakes). For comparison, the same range of the four EG1a-d estimates for the repeat time for M6.5 earthquakes within a 50-km radius from Gösgen, in the PEGASOS study, was about 2,500 to 7,000 years, with a combined mean value of about 3,500 years, which is well within the data range.

4.1.2(e) SP1 derivation and use of hypocentral depths

Accounting properly for hypocentral depth is a key endeavor for PRP, since (i) several modern GMPEs (ground-motion prediction equations) employ a depth-dependent stress parameter, and (ii) the native distance metric used by most GMPEs is measured in terms of the top-of-rupture distance, thereby involving depth. PRP followed the same convention adopted by PEGASOS to derive the depth distributions of hypocenters for different magnitudes and focal mechanisms: for larger events, the distribution of hypocenters was modeled with a probability function in the lower half of extended sources. The depth treatment in the PRP hazard calculations is clarified in the PRP Summary Report, in the PMT answers to RAI-15 to RAI-18, and in TFI-TN-1292. In this information, however, the determination of the minimum depth of rupture is not satisfactorily addressed. As clarified in the answer to RAI-17 and in the PRP Summary Report, the depth distribution model approved by the EG1 teams does not allow significant seismic rupture to occur in the first 2 to 3 km below the surface; this feature is relevant for the overall treatment of top-of-rupture depth, but it does not appear to have been covered in the PRP elicitation, and contrasts with geological and historical evidence of surface rupturing of large earthquakes (M6.5 and higher) in a normal or strike-slip faulting environment. The potential impact of this limitation for near-fault hazard assessment has not been assessed by the Project.

4.1.2(f) Assessment of epistemic uncertainty

Epistemic uncertainty in some important elements of SP1 – such as the earthquake catalog, and the magnitude conversions applied – was not taken into account by introducing a proper logic-tree or equivalent mechanism. Whereas this approach could be considered as state-of-the-art practice at the time of the PEGASOS completion, it is no longer so (now ten years later). In this regard, the following points are significant:

- The change from ECOS-02 to ECOS-11 is identified in the PRP Summary Report as potentially being a major reason for the change in SP1 median hazard; however, no element of epistemic uncertainty is introduced relative to this important sensitivity. The ECOS-02 catalog used in PEGASOS has been replaced by ECOS-11 in PRP, whereas no evaluation was provided to indicate that the ECOS-02 catalog had any significant limitation. Although it can be argued that the ECOS-11 catalog is an improvement and as such it can be considered as a valid alternative of the EOCS-02 catalog, it has been noted that the SP1 experts had difficulties in accepting important new elements of ECOS-11 [see points under subsection 4.1.2(c) above]. Additionally, other international efforts resulted in published earthquake catalogs during the PRP period, covering also the area of ECOS; i.e., the SHARE project produced a new European reference catalog covering both historical and instrumental time periods; and the GEM (Global Earthquake Model) program of the International Seismological Centre (ISC) produced a new global reference catalog for larger instrumental and historical events. Elements of epistemic variation among these catalogs – such as the possible variability of the magnitudes for those regional historical earthquakes used to calibrate the magnitude scale for the entire catalog – were not addressed or discussed among the EG1 experts, and were not taken into account in PRP source modeling; neither were corresponding sensitivity studies performed in PRP.
- In consideration of the indicated importance of M_L-M_W scaling adjustment in ECOS-11, ENSI considers that the lack of explicit treatment of epistemic uncertainty in the functional form used for the M_L-M_W conversion represents a potentially important limitation of the PRP study [see subsection 4.1.2(c)].

- The PRP SP1 model was developed with few variations from PEGASOS and only considered area source zones and stationary Poissonian activity rates, whereas the definitions of seismic sources and activity rates, as developed in other projects of similar nature over the same time period, have considerably advanced in order to properly capture epistemic uncertainties, including also use of zoneless approaches, hybrid models constructed by fault-based source and background seismicity, and time-dependent statistics (e.g., see the SHARE, SED, GEM, EMME/SHARE and UCERF models).

4.1.2(g) Impacts on final hazard results

The PRP hazard results show, in general, a significant change with respect to PEGASOS. A comparison of PEGASOS and PRP 10,000-year S_a(100 Hz) values on rock, for NPP Beznau (see Fig. 8.48 of the PRP Summary Report), reveals relative reductions in ground-motion levels of 22%, 42%, 12% and 12% among the four SP1 teams.

From ENSI's evaluation presented here, this difference in PRP hazard appears to be due largely to parameters and choices adopted by SP1 that are not supported by a robust or sufficient elicitation.

ENSI considers at least the following features to be significant potential root causes for the noted change in hazard:

1. the 0.1 magnitude shift of the linear range of the magnitude scaling;
2. the regression of b-values using low magnitude values in the non-linear range of the magnitude scale; and
3. the variability, and in some cases the low values, of the M_{Max} models adopted by the different EG1 teams.

While extensive elicitation was conducted in PRP on these three identified factors, the overall elicitation strategy and schedule did not enable the experts to verify if their choices of individual parameters resulted in technically defensible estimates of the activity rates in the region, or to account in a more comprehensive fashion for epistemic uncertainties.

ENSI considers, in view of these most-significant SP1 weaknesses, that SP1 of PRP cannot be retained as a valid refinement of the PEGASOS SP1 and that, as direct consequence, the change in hazard (since PEGASOS) due to the SP1 contribution, is not suitably justified.

4.2 SP2

4.2.1 Strengths

New data and methods through research and development

The PRP has undertaken a particularly extensive effort in the refinement of the existing SP2 model of PEGASOS. In particular, ENSI acknowledges the valuable R&D efforts of the project, which have both extended the knowledge of ground-motion characteristics pertaining to Switzerland (including regional subsurface mechanical characteristics influencing ground motions, and development of improved characterizations of the Swiss seismic stations), and are currently adding to the body of knowledge of modern methods in engineering seismology for ground-motion prediction.

Significant specific related factors in SP2 include the following:

- A systematic approach was applied for the selection of candidate existing ground-motion prediction equations (GMPEs).
- Multiple, new synthetic-based ground-motion relationships were developed in PRP using a Swiss point-source stochastic model (PSSM). A principal seismological parameter influencing the nature (e.g., median level) of the PSSM is stress drop; i.e., by expert weighting of alternative, physically possible interpretations of stress drop, a meaningful degree of variation in PSSM-based ground-motion relationships can be obtained, lending confidence that the models are reasonably realistic and have relevance for uncertainty assessment.
- The Project championed a correction paradigm, termed V_S-κ_0 (shortened here as Vs-Kappa, or phrased "V sub S, Kappa") correction, which is tied to a long-established seismological model of ground motion and use of the parameter κ_0 as basis for damping / filtering of high-frequency (HF) ground motion. The Project undertook development of a number of novel (and potentially alternative) approaches for conducting the Vs-Kappa correction (Kappa scaling of ground-motion relationships), with perhaps the most prominent being the recently published Inverse Random Vibration Theory (IRVT) approach. The project developed Vs-Kappa corrections primarily for adjusting GMPEs from host environment to target (Swiss case), but also applied the approach to the adjustment of the PSSM-based ground-motion relations.
- The Project correspondingly developed models of κ_0 for the Swiss NPP sites, and a rational approach/framework for partitioning κ_0 among the site-specific reference rock condition underlying each plant site, and the subsurface materials (soil deposits) above the reference rock condition.
- Through the preceding process, the Project was able to substantially harmonize – i.e., establish consistency between – the PSSM-based and corrected-GMPE-based ground-motion relationships, as to the center, body and range (CBR) of interpretations, to a degree not realizable during PEGASOS.
- The Project furthermore developed a new, systematic treatment for partitioning the overall ground-motion aleatory variability into components, and successfully achieving the goal of deriving a single-station sigma (σ) model that avoids over-counting variability (i.e., removing those components of aleatory variation that do not apply to PSHA of individual sites). Aside from providing the support for development and publication of the approach, the Project implemented the sigma-modeling framework so as to specifically avert any double counting of aleatory variability between SP2 and SP3.
- The Project also undertook new approaches, elicitations and logic-tree models for a relatively comprehensive set of interpretations including (in addition to those factors already mentioned) the following:
  - V/H ground-motion modeling
  - Vertical sigma model (σ_{Add}) relative to sigma for horizontal motion
  - Upper-bound ground motions for horizontal and vertical cases
- As basis for centering the experts' ground-motion models with respect to available Swiss historical data, the Project developed a so-called "Mixture Model" derived from the motion Intensity database.

- The Project undertook studies that considered the potential relevance of advanced numerical models and techniques that hold emergent promise for use in future development of ground-motion models (e.g., finite-fault simulation [FFS]).
- The Project undertook a large number of workshops involving SP2; i.e., 12 dedicated workshops and a significant number of SP interface workshops, SP2 working meetings and webinars.

4.2.2 Areas of Potential Improvement

SP2 evaluation and integration phases

Owing to the extended R&D phase/aspect of PRP, the Project somewhat compromised the evaluation and integration phases and the associated aims of a SL4 study. The Project was apparently faced with some difficult choices and circumstances requiring the development of important trade-offs, as well as agility in project implementation. Although ENSI believes that the Project achieved a reasonable – and in many cases commendable – balance in its resolution of these challenges, ENSI notes a number of concerns, as follows:

- The Project lost two key SP2 experts at a critical point during the middle of PRP fulfillment. ENSI considers that this event could have been better anticipated and managed so as to reduce subsequent risks to the Project.
- The PMT decided to replace the two experts by a single SP2 expert, rather than two experts. This approach was incongruent with the PRP Plan, and ENSI interprets the reason for such approach being that the number of suitably qualified experts who were available and stood reasonable chance to catch-up with Project developments was quite limited. In fact, ENSI considers the Project to have been very fortunate to find a new SP2 expert with the required background, qualifications and availability.
- The R&D phase of the Project occurred from 2008 through mid-2011, well over half of the duration of the Project. Additionally, some of the aspects of the initial phases of SP2 (e.g., development of selection criteria and implementation for candidate GMPE identification) did not follow SL4, and the Project seemed to not be fully intent on performing a SL4 study for about the first 12 to 16 months of PRP implementation. More importantly, ENSI did not observe a reasonable evaluation phase of the Project until about 2011, despite commenting on this concern (and the related issues of problematic scheduling) several times. Once the Project did start a recognizable evaluation phase, ENSI noted that the SP2 experts still had various struggles to decouple themselves from a proponent role, and to behave as evaluators to an acceptable degree for a SL4 study. Accordingly, although ENSI judges that a satisfactory evaluation phase was eventually realized, ENSI considers the evaluation process of PRP to be comparatively weak (e.g., relative to PEGASOS).

Scope in representing a community view

ENSI has concerns that the approaches conceived and employed for SP2 may not be sufficiently broad to well-encompass applicable methods and perspectives of the relevant informed community, and (owing to the recent and comparatively isolated nature of their development) are not yet sufficiently incorporated into the community view and state of the art. Some specific related points include the following:

- Although ENSI assigns accolades to the Project for its developments around the Vs-Kappa quantitative correction paradigm, ENSI does not believe this paradigm encompasses the spectrum of available approaches among the informed community who are capable of developing relevant technically defensible interpretations. ENSI does accept that the Vs-Kappa correction framework incorporates sufficient parameter variation flexibility such that the CBR of technically defensible interpretations of the (broader-than-PRP) informed technical community can likely still be meaningfully captured. Still, ENSI does not consider the approaches developed and followed in PRP to invalidate other, alternative approaches, new or existing. For instance, ENSI does not find that an approach of expert weighting of available ground-motion relationships according to more-qualitative correction factors (e.g., degree-of-belief weighting of models based on relative similarity of tectonic province, perceived quality of model development and representativeness to given reference rock conditions) – more similar to what was done in PEGASOS – has become inapplicable. Similarly, ENSI notes that there are suitable, established alternatives to reliance on Kappa for treatment of damping/filtering of high-frequency motion. At the same time, ENSI encourages future development of ground-motion relationships around emergent, advanced and flexible modeling approaches, such as finite-fault simulations.
- ENSI notes that the Vs-Kappa correction approaches do not address the relevant parameters of anelastic attenuation (Q) and stress drop as additional factors applicable to correction of ground-motion relationships (e.g., host-to-target GMPE corrections can generally be expected to relate to Q and stress drop also, and not only to Kappa, and Vs).

Epistemic variation in deaggregation results from SP2

ENSI observed significant differences in the deaggregation results of PRP versus those (for similar cases) derived from PEGASOS. For PRP, dominant modal contributions for different return periods, and for frequencies of a few Hertz and higher, are centered on values of magnitude around 5.5 (e.g., see Figure 8.6, pg. 217, Vol. 1 of the PRP Summary Report, and similar plots) and decrease rather sharply in the contribution for events below M5.5. This effect appears to be consistent with the low contribution to PGA hazard observed from PRP results for events with magnitudes in the M4.5-M5 range (e.g., see Figure 8.30 of the PRP Summary Report). In response to RAI-19 {ENSI, 2014a}, the TFI produced the technical note TFI-TN-1287 {swissnuclear, 2014a}, suggesting that the noted differences are due primarily to systematic differences in ground-motion models (PRP versus PEGASOS), as well as the determination of relevant distance metrics for scenarios simulated in the PSHA code. In consideration of this information, ENSI notes the following:

- For the results of the three teams shown in TFI-TN-1287, there is a substantial difference in the dominant magnitude contribution between the models published in 2014 and models published a decade ago by the same team (e.g., AS14 vs. AS97; BSSA14 vs. BJF97; CB14 vs. CB03), with the contributions appearing to be at times in antithesis (e.g., see the dominant contribution of M5.5 in BSSA14 versus the lack of contribution at the same magnitude in BJF97).
- The comparison of the three models published in 2014 shows substantially and surprisingly different magnitude contributions (e.g., see Figures 7, 11 and 15 of TFI-TN-1287).
- The low-magnitude cut-off appears to be very different among the 2014 models (e.g., in TFI-TN-1287, compare the peak at M5 for AS14 in Fig. 5, with that at M5.5 for BSSA14 in Fig. 9); this difference and the rapid decay of the hazard contribution for lower-magnitude values can

be explained by the different magnitude motion scaling corrections applied by the different models at low magnitudes, which are very different among the different models (see Figure 17 of TFI-TN-1287).

ENSI considers these differences to be significant and unexpected, and the TFI's explanation suggests that this aspect of the PRP requires careful explanation, as well as communication to those using PRP results. In particular:

- ENSI notes that the PRP report has not conveyed the important element of epistemic variation in deaggregation results due to impacts of alternative SP2 models.
- ENSI considers it doubtful that the SP2 experts were sufficiently aware of the pronounced magnitude sensitivity of the different GMPEs as shown in TFI-TN-1287.
- ENSI notes also that the large differences in the magnitude contributions of the more modern models (published in 2014, as conveyed in TFI-TN-1287), and in the low-magnitude ground-motion scaling models adopted by the different authors, raise questions that the overall PRP model will be retainable as a stable model for a reasonable future time frame. Thus, it may be the case that a revision of the SP2 model could be indicated as more stable GMPE models become available.

4.3 SP3

4.3.1 Strengths

PRP planning of a dedicated subproject SP3 for addressing site response

ENSI considers the systematic evaluations of the impact of site response on the ground motions in the near-surface soil layers to be general strengths of both PRP and the earlier study PEGASOS. For example, these projects devoted a comprehensive sub-project (SP3) to this issue, through formal elicitation according to the SSHAC L4 procedure, whereas such a rigorous and systematic treatment of site response, with aim to suitably represent the „community view", has not yet been implemented in any other seismic hazard study.

PRP planning of site investigations and response analyses

The PRP Plan includes two appendices which specify the course of complete and state-of-the-art geotechnical and geophysical investigations, as well as site response calculations, to be conducted at all of the Swiss NPP sites. These specifications were reviewed and approved by the SP3-experts. The NPPs implemented their site investigations and response calculation studies, and the Project followed the plan for using the findings of the specified investigations.

Expanded site-specific soils database

For use in PRP, the NPPs extended the available soils database by undertaking a large number of borehole investigations, including site measurements and laboratory tests of soil samples. The new data support the refined interpretations of the soil models in PRP, and they represent a significantly improved basis for the PRP and for future projects. For each NPP site, a significant number (three to five) of new soil profiles has been developed, based on the existing and new boreholes and on in-situ measurements. This comprehensive site data have helped to reduce (as compared to PEGASOS) the epistemic uncertainties in shear-wave and compression-wave velocity profiles. Additionally, material models for the soil layers have been refined (with associated reduction in epistemic uncertainty), supported by laboratory testing of strain-dependent stiffness and damping, as well as by using the improved basis of available published material laws.

Multiple approaches to site-response analysis

The site response analyses for PRP were conducted using diverse appropriate methods and software, including: equivalent-linear response for wave propagation, random vibration theory, and some nonlinear analyses. The specification of NPP-specific reference bedrock condition (e.g., as characterized by V_{S_30} and κ_{0_Rock}) and associated rock input motion spectra used for site response analyses were coordinated with other sub-projects of PRP (principally, SP2) in a consistent manner, to ensure an accurate interface with negligible double counting of uncertainties.

Plausibility of probabilistic site-amplification functions

The probabilistic site amplification functions produced in PRP – which usefully convey the site response as an intermediate result, from which soil hazard is computed from input rock hazard – show plausible shapes, and appear to reasonably reflect the fundamental frequencies (and their possible variations) for the soil deposits at the NPP sites. The resulting soil Uniform Hazard Spectra (UHS) results from PRP correspondingly depict (and enable one to ascertain) the fundamental frequencies of the soil deposits. This result helps confirm that the soil hazard results – compared to the rock hazard results – convey information consistent with the amplification functions.

SP3 workshops

The Project undertook a significant number of workshops involving SP3 (i.e., six dedicated workshops, plus SP3-related interface workshops and SP3 working meetings).

4.3.2 Areas of Potential Improvement

Reliance on 1D analyses

The refinement of the SP3 site-response evaluation in PRP is supported exclusively by use of one-dimensional (1D) soil column analyses (and depends on existing considerations in PEGASOS for more advanced modeling). This approach is specified in the PRP Plan and was accepted by the SP3-experts. The cases of two-dimensional (2D) and three-dimensional (3D) effects are discussed only in reference to the former investigations in PEGASOS. The experts evaluated the impact of this simplification and documented their assessments in the evaluation summaries. Considering the degree and nature of spatial variation of the collected soils data, however, ENSI notes that 2D and 3D modeling of site response is considered to be an area of valid and useful future refinement. [This comment refers to open review points 56, 292 and 333, and to consolidated open item SP3-1 (see {ENSI, 2014c}).]

Open (partial) elicitation of one SP3 expert

In the specific case of one SP3 expert who is now deceased, the elicitation could not be concluded in all aspects. ENSI indicated that the Project could, on reasonable basis, consider eliminating the ground-motion truncation portion of this expert's model (see Fig. 6.27 of the PRP Summary Report, Vol. 1) from the SP3 logic tree, and regenerating hazard results based on this adjustment. [This comment refers to open review point 328, and to consolidated open item SP3-1 (see {ENSI, 2014c}); see also RAI-44 {ENSI, 2014a}.]

As a response to ENSI's indication, the Project provided additional comparisons of resulting hazard curves for the Beznau and Mühleberg sites. The comparisons demonstrated a small sensitivity of the hazard to inclusion of this expert's truncation model into the overall logic tree. The Project further reiterated the reasoning provided by the expert for the Mühleberg site: i.e., he judged that for higher motions the soft layer will liquefy and thus, will not be able to transmit higher ground motions to the surface.

ENSI finds the Project's reasoning to be overly idealized in that potential liquefaction at the Mühleberg site has been described not as widespread and uniform, but rather, as likely occurring in separated pockets, or lenses, of susceptible soils. It is optimistic, therefore, to assume that comparatively higher levels of motion would not result from wave propagation through relatively more-competent soils at the site. Also, response models for assessing soil strains under given ground motions are themselves idealized and simplified approximations, and cannot be taken as precise predictors as to the highest ground-motion levels that a site can transmit, particularly where such idealizations appear to be contradicted by available empirical data. Even though the specific issue of motion truncation has apparent negligible impact on hazard, ENSI still judges that this aspect of the SP3-model does not represent a community assessment of maximum ground motion.

Reporting of rock input motions

The PRP Summary Report provides no information on the rock input motions which were applied to the site-response analyses. The PRP Plan specification indicated that 10 pairs of input time histories (horizontal and vertical) were to be developed for magnitudes M5, M6 and M7 events, based on hazard deaggregation results from the former PEGASOS project. The Project has also not commented as to whether or not (and why) the range of magnitudes is still representative in view of the PRP deaggregation results and their differences relative to PEGASOS.

Strain-dependent model curves for KKG

For KKG, the model curves for the strain-dependent material properties (G/G_{Max} and damping) do not in all cases adequately fit the measured data. For the KKG site, the damping ratios show some physical inconsistencies, and the curve fits appear to be optimistic (e.g., see Vol. 5, Figures I-4.22 and I-4.23 of the PRP Summary Report). ENSI indicated to the Project that it would be potentially useful to conduct a sensitivity analysis which demonstrates the impact of the implemented damping values on the site amplification functions, and to determine whether or not an adjustment to reported hazard results is justified. [This comment refers to open review point. 281, and to consolidated open item SP3-1 (see {ENSI, 2014c}); see also RAI-40 {ENSI, 2014a}.]

In addition to its response to RAI 40, the Project referred to the already completed sensitivity analyses which are documented with SP3-specific tornado plots in the PRP Summary Report (Volume 2, Figures 3.18.1 to 3.18.6), demonstrating the impact of the assigned variations in the soil material model on the resulting hazard.

Interpretations and reporting regarding liquefaction for KKM

For the case of KKM, ENSI considers that the PRP Summary Report does reflect the essential interpretations of strong ground shaking provided by the SP3-experts, who candidly reported a potential for liquefaction of a silty-sand layer, generally in the upper (near surface) soil deposits at the site, below the ground water table. [This comment refers to open review points 278, 291 and 308, and to consolidated open item SP3-2 (see {ENSI, 2014c}); see also RAI-39 {ENSI, 2014a}.]

Sampling of gravel layers at KKM

For KKM, in contrast to the other three Swiss NPP sites, the Project has indicated that it was not possible to obtain soil samples for the gravel layers. The specified laboratory testing as a tool to determine strain-dependent stiffness and damping parameters, therefore, was abandoned for KKM, and the material curves were developed exclusively based on published data. In ENSI's view, the PRP Summary Report (Volumes 1 and 5) does not provide a clear or convincing explanation for this variance to the soil investigation procedure, or a discussion of its corresponding implications. Additionally, this variance may lead to somewhat greater epistemic variation in soil modeling for KKM as compared to the other Swiss NPPs.

Site-investigations procedures for existing and planned plants at the locations of KKM and KKG

EKKB, EKKM and KKN were planned as future plants at the sites of, respectively, the existing KKB, KKM and KKG plants. Owing to considerations made for the future plants in PRP, the procedures for conducting soil investigations and analyzing site response at the formerly planned-future plant sites were different for KKM and KKG, as compared to KKB. For Beznau, it was decided to analyze the existing site and the new-plant site separately; for Mühleberg and Gösgen, however, no distinction was made between the sites of the existing and the new plant. As the new plants are no longer expected to be realized, ENSI considers that the included variation of the soil properties for KKM and KKG might be somewhat greater than necessary when applied for only the existing plants.

4.4 SP4

4.4.1 Strengths

SP4 presence at workshops

To a significant extent, the Project was able to follow ENSI's guidance to have a SP4 participant on hand at PRP workshops, in order to help ensure that SP4 would be aware of any special or challenging issues affecting the development of suitable inputs and performance of suitable PSHA calculations.

Alertness to problems

PRP was able to detect and correct a problem in the calculation effort prior to development of results for the PRP Summary Meeting. This incident provides evidence that the Project took care for procedural quality assurance during a period of intensive calculation work, and that the PMT demonstrated the appropriate action and courage to openly draw attention to, and rectify, this incident.

4.4.2 Areas of Potential Improvement

Formal procedures of software QA and maintenance

ENSI notes that, near the close of PRP fulfillment, new guidelines applicable for recommended quality assurance of nuclear engineering analysis software {EPRI, 2013b} have increased the desired rigor in software development and testing, with methods of software engineering applied in commercial-grade software being specified. These requirements go beyond the development approaches employed for the PSHA software applied in PRP. In addition to this development, the version of PSHA software employed in PRP is no longer maintained by the original licenser of the software, and is accordingly outside of a suitable software maintenance program.

Provision for independent checking of hazard results

Independent checking of PSHA results has been consistently employed in the US (e.g., NRC independent checking of PSHA results developed by EPRI) since the 1980's, and continues to the time of development (late-2014) of the present review report. For the case in Switzerland, ENSI considers that – as the PMT and TFI have ownership over the asset and technical aspects of the PRP model – the Project is in the best position, if not the only practical position, to direct independent checks of hazard based on the PRP model. In RAI-8 {ENSI, 2014a}, ENSI indicated to the Project the expected value of performing PSHA checks using independent software codes and experts to implement the PRP model. The Project's response to this RAI stated that independent checking is not state of the art for PSHA studies, and that the Project does not plan to perform such checking.

4.5 SP1, SP2 Interface

4.5.1 Strength

Dedicated SP1-SP2 interface workshops

The Project arranged two dedicated SP1-SP2 Interface workshops.

4.5.2 Areas of Potential Improvement

Consistency in treatment of earthquake size

The M_W measure of earthquake size is used in SP1 to estimate activity rates and the probability of occurrence of future earthquakes, and in SP2 for the application of the GMPEs; as such, it is an important SP1-SP2 interface parameter. As noted by ENSI, SP2 introduced a small-magnitude correction reducing the wave amplitudes (PGA) expected for events of magnitude M_W<5.5-6 (Fig. 17, TFI-TN-1287), while SP1 introduced a non-linear, positive M_W - M_L correction, implying again lower wave amplitudes for events with magnitudes M_W< 4 (see Figure 1 of TFI-TN-1292).

ENSI requested confirmation and explanation during the project, and in RAI-14 {ENSI, 2014a}, of the consistent application of magnitude calibration across the whole PRP modeling and computation chain; however, the Project did not provide a check that ensures that the earthquake size has been consistently treated. Such a check would be expected to confirm at least the following:

- that the different techniques, attenuation models and rock definition used for M_L, M_0 and M_W calculations by SED are compatible among themselves and with the GMPE logic-tree model adopted by SP2;
- that the M_W definition used for the different GMPEs included in the SP2 logic tree has been derived using consistent low-magnitude scaling adjustments, so as to ensure a coherent assessment of the controlling events;
- that the ground-motion scaling adopted in the most recent GMPE relationships for events of magnitude M_W<5.5-6 (see Fig. 17 of TFI-TN-1287) is compatible with the ground motion scaling implied by the nonlinear M_W - M_L relationship used in ECOS-11 for events of magnitude M_W<4 (Fig. 1 of TFI-TN-1292);
- that rock and soil definitions and site corrections are harmonized in the SED and PRP procedures for magnitude calibration and GMPE selection; and

- that possible scaling effects, which may inadvertently influence the assessment of the activity rates, are ruled out.

Quality and level of SP1-SP2 interaction

As suggested by the observation in Section 4.1.2, the Project included a generally weak treatment, and elicitation, as regards SP1. ENSI developed a number of review comments indicating that the SP1 experts were not highly engaged in workshops, and this observation also generally applied to the SP1-SP2 interface sessions. Thus, in ENSI's view, the needed level of interaction between SP1-SP2 at the interface workshops, for ensuring a consistent treatment, was lacking.

4.6 SP2, SP3 Interface

4.6.1 Strengths

Dedicated SP2-SP3 interface workshops

The Project arranged for several dedicated SP2-SP3 interface workshops, and these were generally conducted in reasonably effective manner.

Common expert among SP2 and SP3

The Project organization provided for a common SP expert participant among SP2 and SP3. This arrangement helped ensure that SP2-SP3 interface issues were not addressed in isolation, owing to the expected situation that the common SP2 expert would identify and comment on relevant interface concerns.

SP2-SP3 integrated single-station sigma model

A new single-station "sigma (σ)" model was derived as part of PRP, to more accurately address the treatment of aleatory variability of ground motion, and was developed as a coordinated effort between sub-projects SP2 and SP3 (with implementation in SP4). This model was designed to remove the site-to-site component of aleatory variation in motion predictions, and was also developed in such a way as to avoiding double counting of uncertainties among SP2 and SP3.

SP2-SP3 interface on Kappa and Kappa correction

Similar to, and in conjunction with, the SP2-SP3 integrated treatment of the sigma model, the Project developed and implemented Kappa scaling in a manner that appeared to be generally well coordinated between SP2 and SP3.

4.6.2 Areas of Potential Improvement

Schedule impact on SP2-SP3 interface

The final SP2 workshop (WS12/SP2) occurred too late for enabling a final interaction between SP2 and SP3.

Representation of community view

As was the case during dedicated SP workshops, for interface workshops also, SP2 and SP3 experts, held most frequently to proponent viewpoints, and appeared tentative in being able to represent a community view; correspondingly, interface issues raised by these experts may not systematically represent community viewpoints.

5 Overall Review Assessment and Conclusions

By means of several ENSI meetings that focused on development of the present review report, ENSI synthesized and jointly resolved the residual findings (including consolidated open items) from the participatory review (Section 3) and the review observations from the late-stage review (Section 4). As a result of this aspect of the review process, ENSI developed a final overall review position and a set of key final review observations, which are summarized in this section.

Some principal considerations in ENSI's development of a final review position include the following factors:

- The manner and degree to which PRP serves to refine PEGASOS;
- The extent and quality of SL4 conformance by PRP; and
- The net impact of review points on validity of PRP results.

ENSI's judgments concerning these factors and their relevance to final review conclusions are further explained below, as is also a concise commentary on applicability of PRP results.

5.1 PRP as Refinement of PEGASOS

5.1.1 HSK Review Observations on PEGASOS

Scope and nature of HSK review observations

The final review report (HSK-AN-5364 {HSK, 2004}) from HSK's review of PEGASOS listed nine specific review observations and areas for potential refinement. Of these, four were related solely to SP1, whereas an additional two were related to SP1 interfaces with other subprojects (i.e., SP1/SP2 and SP1/SP2/SP3 interfaces). Of the remaining three observations: one was related to the SP2/SP3 interface; one pertained specifically to SP3; and the remaining one pertained specifically to SP4.

Thus, most (six of the nine) review observations pertained to refining SP1 and related interfaces. Generally speaking, the HSK observations directly on SP1 pertained to the undertaking of improvements to the SP1 modeling and its exposition, whereas the observations concerning all SP interfaces were focused on potential refinements in uncertainty assessments.

The HSK observation on SP3 indicated the potential to develop enhanced understanding and compatibility of soil ground-motion modeling and related soil failures, and hence, was not specifically aimed at enhancing understanding of uncertainties.

The HSK observation on SP4 pertained to the importance of suitable PSHA software validation (e.g., through a PEER study being conducted), which was accepted by HSK as a pragmatic alternative to performing independent spot check of PSHA results.

From this summary, ENSI notes that PRP addressed some, but not all, of the HSK comments on PEGASOS. Furthermore, HSK's review observations on PEGASOS were heavily weighted toward improving robustness of SP1, whereas the Project focused largely on uncertainty reductions in SP2 and SP3, with comparatively minor attention devoted to SP1.

5.1.2 Project Planning and Implementation

Several iterations of the PRP Plan occurred over the Project duration. The first version of an ENSI-approved PRP Plan was set in August 2008. The last ENSI-approved version of the Plan was established in December of 2011, but itself was not well followed by the Project during the concluding stage of the PRP. In general, throughout the original development and subsequent revisions of the PRP Plan, the Project consistently focused its effort on providing for more significant refinement of SP2 and SP3 relative to PEGASOS.

Owing to the changing nature of the plan, a defining characteristic of PRP (compared to PEGASOS) was its focus on non-systematic, ad hoc project agility, in contrast to holding hard-and-fast to an original plan. Some factors compelling the need for an agile approach included:

- The unexpectedly long initial R&D phase of the Project;
- Provision for hazard calculations at prospective new Swiss plant sites;
- The situation that two SP2 experts resigned from the Project;
- Elimination of the prospective new plant sites from the scope of work following occurrence of the Fukushima event; and
- The Project's endeavor to obtain ENSI approval on specific items (e.g., SP5, which was ultimately removed from the scope of ENSI's review).

An impact of these developments on ENSI's review of PRP is that many review points (e.g., many more than during PEGASOS) were generated concerning schedule and related process issues.

5.1.3 General Results for Mean and Median (Central Measures)

ENSI examined comparisons between PEGASOS and PRP results produced by the Project, and noted that PRP mean results are generally lower than corresponding PEGASOS results, whereas median results of the two studies can be comparable in some cases. Also, the Project performed a limited comparison of PRP and SHARE, with a general finding that central measures of hazard for PRP are lower than those for SHARE.

5.1.4 Results for Uncertainties (Body and Range Measures)

A principal conclusion from the HSK review of PEGASOS (HSK-AN-5364) was that the overall epistemic variation in PSHA results may be somewhat too diffuse, due primarily to separate elicitation of ground motions for rock and soil, as well as other areas where potential refinements in integrated assessments are possible.

The PRP took significant steps in SP2 and SP3 to refine data and methods toward potentially reducing uncertainties, and relative-based comparisons of PRP uncertainty ranges with corresponding results from PEGASOS do reveal a general reduction for PRP. Although, in ENSI's view, the PRP has likely been successful at uncertainty reduction, it is difficult to conclude that the reported PRP uncertainties are themselves valid, given the critical review findings on SP1. Thus, the degree and robustness of uncertainty reduction cannot be confidently assessed based on current information.

5.1.5 New Data and Methods

In ENSI's view, the PRP was very successful at developing new data and methods relevant to achieving refinements – in modeling of ground motions on rock, as well as soil amplification factors – that are applicable to seismic hazard studies of the Swiss NPPs. PRP has added new elements of state-of-the-art in PSHA. As elaborated in Section 4, some particularly noteworthy aspects of PRP include:

- Its collection and use of site-specific dynamic soil properties for use in site-response evaluation, and its evaluation of this information within the scope of SL4 expert elicitation of SP3;
- Development and use of a new "sigma" (σ) model for separating elements that contribute to overall ground-motion aleatory variability; and
- Development of Swiss-specific ground-motion relationships based on the following two alternative approaches:
  - new Swiss point source stochastic modeling (PSSM); and
  - adjustments to existing ground-motion prediction equations (GMPEs) based on new V_S-κ (V_S-Kappa) correction approaches.

5.2 PRP Implementation of SSHAC Guidance

During the early phases of PRP, there were some questions as to whether the study would be fulfilled as SL3 or SL4. It eventually became clear that the Project was seeking to satisfy the essential requirements of a SL4 study. The Project's aim thus became more aligned with the ENSI-A05 guidance specifying that a SL4 PSHA study should be performed for seismic hazard assessment of the Swiss NPPs.

Nonetheless, as elaborated below, there were variances in the PRP SL4 implementation versus what had been observed during the review of PEGASOS. Consequently, ENSI consulted applicable guidance {NRC, 2012b and 1997}, in order to assessing the quality of SL4 implementation in PRP. Key quality criteria related primarily to suitability of evaluation and integration of technical viewpoints, as well as repeatability in capturing the center, body and range (CBR) of the community view.

5.2.1 Comments concerning SP1

Concerning SP1 of PRP, a significant variance (versus PEGASOS) as to SL4 implementation was that the elicitation of SP1 was not planned and implemented in a manner commensurate with the other SPs. SP1 elicitation and involvement were ended two years prior to the Project Summary Meeting, not allowing the experts sufficient opportunity to understand the Project's use of their interpretations or their implications, and not permitting some important components of epistemic variation to be recognized and addressed. ENSI provided several review comments pertaining to SP1 – both on process issues as well as on a number of technical issues that appeared to be only superficially addressed – during the participatory phase of the Project. ENSI evaluated the PRP Summary Report as to potential resolution of these issues, and held two meetings with the Project as part of late-stage review activities, in order to discuss related review concerns. During these late-stage activities, ENSI identified the inconsistency that much of the supposed refinement (i.e., change) in hazard (PRP relative to PEGASOS) appeared to be attributable to SP1 – i.e., the aspect of the study where the elicitation was weakest, the refinement was expected to be only minor, and the effort in refinement was the lowest (among SPs). Owing to this late-stage finding, ENSI undertook a more careful technical examination of SP1, consistent with SSHAC guidance concerning the potential benefits of late-stage technical review. From this more-detailed, late-stage review of technical elements, ENSI identified a number of weaknesses and problems in technical aspects of SP1 (as documented in Section 4). ENSI found a high dependency between these technical weaknesses and the low effort and corresponding weaknesses observed during the SP1 elicitation (as explained in participatory review comments and consolidated open items). ENSI thus concludes that, although SP1 was planned and executed as a SL4 study, in the end the implementation of SP1 of the PRP is found to be too weak to accept, on both process and technical grounds.

The relevant key SP1-related weaknesses, as evident from consolidated open items from the participatory review, include the following (see {ENSI, 2014c}):

GEN-2 PRP Process and Procedures. The elicitation of SP1 experts did not include a high level of interaction.

GEN-3 PRP Schedule. Schedule issues persisted from beginning through the end of the Project; SP1 was given inadequate elicitation opportunity; and schedule did not permit any re-elicitation after the Project Summary Meeting, when the implications of SP1 assessments were first fully encountered.

SP1-1 SP1 Sensitivities and Review Advice. A number of ENSI's review points concerned areas of further study that were not sufficiently addressed or elucidated within SP1, such as development of alternative methods for the magnitude-dependent depth distribution and for the M_{Max} distribution.

SP1-2 SP1 Expert Requests for Evaluations. The SP1 experts asked for some evaluations, which the Project decided not to address.

Concise summary of the key SP1-related weaknesses from the late-stage review is provided as follows (see Sections 4.1 and 4.5):

- The SP1 elicitation was insufficient, and was closed too early by the Project:
  - The original concept of a "limited" SP1-elicitation within PRP was based on the expectation that potential SP1 refinements would have no substantial impact on the hazard results. That expectation turned out to be disproved: the applied changes in the original (PEGASOS) SP1-models were found to have a significant impact on the hazard results. They cause a significant change (reduction) in hazard, and a correspondingly significant change in ground accelerations.
  - This unexpected finding became obvious only late in the project (May 2013), whereas the elicitation of SP1 has been closed two years earlier (2011). At this time there was no feedback to the SP1 experts foreseen (e.g., as contingency) in the PRP Plan.
  - The Project did not adequately react on this inconsistency. Although this was not a formal violation of the PRP Plan, it was a missed action to revise the PRP Plan based on the experienced impact.
- Based on the interpretations and the documented sensitivity analyses the ENSI-RT identified and communicated the need for a more comprehensive elicitation of the following model features and parameters:
  - M_{Max}: maximum magnitude in relevant seismic sources (e.g., see point no. 3.5 in ENSI-AN-6705, no. 4.8 in ENSI-AN-6962, and no. 2.11 in ENSI-AN-7575);
  - M_L-M_W: conversion of magnitude scales (e.g., see point no. 4.6 in ENSI-AN-6962, and no. 4.1 in ENSI-AN-7575);
  - Activity rates in relevant seismic sources (e.g., see point no. 3.6 in ENSI-AN-6705, no. 4.10 in ENSI-AN-6962, and no. 3.7 in ENSI-AN-7575);

- Hypocentral depth distribution (e.g., see points no. 4.7 in ENSI-AN-6962, and nos. 2.9, 3.6 and 3.10 in ENSI-AN-7575); and

- Epistemic uncertainties of earthquake catalog data and magnitude conversion (e.g., see points no. 4.6 and 4.11 in ENSI-AN-6962, and nos. 2.8, 2.10, 3.5 and 3.8 in ENSI-AN-7575).

5.2.2 Comments concerning SP2 and SP3

Concerning SP2 and SP3 of PRP, variances (versus PEGASOS) as to SL4 implementation were also encountered. The extended initial R&D phase of the Project significantly delayed, and compressed, the SL4 evaluation and integration phases of SP2 and SP3. About mid-way through Project implementation, two SP2 experts resigned from the Project, and were replaced by a single expert. Also, in SP2, rather new and unique approaches (e.g., Vs-Kappa correction) were pursued, making it unclear if other qualified experts, going through a similar SL4 process, would follow a similar approach for representing the CBR (community view) or would obtain similar results. Such factors have led to several review observations, suggesting that the SL4 implementations of SP2 and SP3 were not at the same level of quality as in PEGASOS. Similar to the case for SP1, ENSI evaluated the PRP Summary Report as to potential resolution of these SP2 and SP3 issues, and the two meetings held with the Project during the late-stage review also devoted discussion to potential resolution of issues pertaining to SP2 and SP3. ENSI did not find the degree of refinement attributable to SP2 and SP3 to be non-commensurate with the level of effort undertaken in implementation. Owing to the noted number of comments and issues observed during the participatory review, however, ENSI investigated specific technical issues also for SP2 and SP3 during the late stage. From this late-stage review of technical elements, ENSI identified strengths and potential improvements pertaining to technical aspects of SP2 and SP3 (as documented in Section 4). ENSI found high consistency between areas of technical weakness encountered in the late stage and corresponding weaknesses observed during the elicitation phases of SP2 and SP3 (as explained in participatory review comments and consolidated open items). ENSI views the weaknesses as areas for further consideration (e.g., potentially leading to additional caveats that may need attention in application of results, to help ensure that use of results is consistent with the development of the hazard) and for potential future improvements. Still, without the benefit of further insights from successful resolution to the problems noted with SP1, ENSI considers at this time that the weaknesses in SP2 and SP3 are likely not sufficiently severe to preclude acceptance of SP2 and SP3. Furthermore, sensitivity results produced by the Project suggested that the PRP results are not strongly dependent on any single expert team of SP2 or SP3. This indication lends confidence that a principal aim of SL4 guidance was still achieved in the Project for SP2 and SP3.[9]

5.3 Review Findings on Validity of PRP

Considering the findings described above, ENSI provides the following as key conclusions concerning the validity of PRP:

- PRP produced valuable new data and methods, added new elements of state-of-the-art in probabilistic seismic hazard assessment (PSHA), and was successful in its principal intent of refining SP2 and SP3.

[9] In contrast, the Project was unable to support a similar indication for SP1 (i.e., there appears a more significant expert-to-expert variation in the SP1 contribution to PRP results, as evidenced by the figures presented in {swissnuclear, 2014a,c}).

- PRP suitably implemented SP4.
- PRP included valuable initial research and development; this aspect of PRP prolonged the project beyond plan.
- Software use in PRP was valid as planned; continuing validity of PSHA calculations for Swiss nuclear plants requires post-PRP improvements in the software platform.
- SP1 of PRP was found to be deficient and not acceptable, and as a consequence the reported PRP hazard results are also not acceptable.
- SP2 and SP3 models of PRP are suitable for developing hazard results to be further verified using a compatible and accepted SP1.

5.4 Applicability of PRP

Based on the preceding summary of review findings, and concerning the applicability of PRP to studies involving Swiss NPPs, ENSI notes that:

- The PRP model provides the most suitable SP2 and SP3 inputs for use in computing seismic hazard results, subject to verification of the resulting hazard.
- The existing PRP model for SP1 is not suitable for use in computing hazard results.
- The existing PRP hazard results (including dependent SP5 products) are not suitable for use in safety-relevant applications because they rely on SP1 from PRP.

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