Transactions, **SMiRT-26**
Berlin/Potsdam, Germany, July 10-15, 2022
Division II

Overview of International Probabilistic Fracture Mechanics Code Models and Capabilities for Piping Applications

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Introduction

Probabilistic fracture mechanics (PFM) for piping applications addresses questions such as the likelihood that a crack in a pipe will be present, whether it is detected during a given inspection, and if it grows to a critical size before the next inspection, causing a leak or a break. Therefore, PFM is a key analytical tool for understanding and modeling leak-before-break (LBB) behavior. A variety of PFM codes have been developed in the Organisation for Economic Co-operation and Development (OECD) member states during the last four decades to support the continued safe operation of ageing components. However, these codes have been designed using different models and assumptions because there are no internationally accepted PFM guidance and acceptance criteria, and it is not trivial to understand the effect of these differences. Additionally, comparisons and reconciliations between probabilistic and deterministic LBB approaches are scarce.

To address these challenges, the metals sub-group of the Working Group of Integrity and Ageing of Structures (WGIAGE) of the Committee on the Safety of Nuclear Installations (CSNI) of the Nuclear Energy Agency (OECD/NEA) has launched an activity to benchmark

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PFM approaches for piping applications. The PFM benchmark is intended to address the following five objectives:

1) Understand differences in PFM software design to prepare more effective benchmark cases
2) Benchmark deterministic fracture mechanics (DFM) models
3) Evaluate the effectiveness of leak detection in reducing piping component failure probabilities
4) Reconcile deterministic and probabilistic LBB approaches
5) Evaluate the importance of several risk-significant parameters in affecting piping failure probabilities (e.g., in-service inspection and weld residual stresses (WRS))

The present paper summarizes participants' responses to a questionnaire on PFM code design to fulfill the first objective of the project. An analysis of the participants' responses is presented to include the following: (1) a compilation of short- and long-term acceptance criteria for PFM applications; and (2) a comprehensive list of references for the various fracture mechanics models related to the simulation of a circumferential crack and primary stress corrosion cracking (PWSCC), including WRS, stress intensity factor (SIF) solutions, J-integral solutions, net-section collapse stability, crack opening displacement (COD), leak rate, and crack growth.

Questionnaire Design

Appendix B shows the questionnaire issued to the participants. To guide the participants in preparing their responses, the questionnaire included sample answers. Also, the content of the questionnaire was carefully designed to ensure that all participants could complete it in about 2 hours.

Participants and Computer Codes

Participants from 15 organizations and 12 different countries contributed to this benchmarking activity. The 14 computer codes are summarized in Table 1. Multiple participants have access to two PFM codes. To avoid duplication in the comparison of codes which were accessible to multiple organizations, PROMETHEUS is associated with Emc^2, and PROLOCA is associated with KINS. Because GRS and PSI use different analysis options of the same code (PROST), both organizations were presented in the comparison tables below.

Table 1: List of Participants and PFM Codes

Organization	Code	Version	Organization	Code	Version
CRIEPI, Japan	PEDESTRIAN	1.1	KIWA, Sweden	NURBIT	6
Emc^2, USA	PROMETHEUS	2.0	LEI, Lithuania	SACC	
Emc^2, USA	PROLOCA	7.02	MPA, Germany	Xpipe	3.3-R0a-p1
KINS, South Korea	PROLOCA	7.02	NRG, Netherlands	DeMoT	2.1
PSI, Switzerland	PROLOCA	7.02	SIA, USA	Beyond-PRAISE	2.1
PSI, Switzerland	PROST	4.7.3	SNC, Canada	PRAISE-CANDU	2.1
GRS, Germany	PROST	4.7.3 Beta	USNRC, USA	xLPR	2.2 Beta
IPP-Centre, Ukraine	SIF-Master	2.0	VTT	VTTBESIM	0.8
JAEA, Japan	PASCAL-SP	2			

The adopted coding languages, quality assurance (QA) standards, and parallel processing capabilities are summarized in Table 2. The primary coding languages include C++, C#, Java, Fortran, Matlab, and visual basic (VB). Most codes were developed and are maintained under nationally or internationally recognized QA standards and requirements, such as Title 10 of the *Code of Federal Regulations*, Part 50, Appendix B [1], ASME NQA-1-2008 [2], CSA N286.7-16 [3], IAEA SSG-2 [4], and ISO/IEC/IEEE 90003 [5].

Table 2: Coding Language, QA Standard, and Parallel Processing

	LEI	KIWA	EMC^2	CRIEPI	VTT	KINS	JAEA	IPP	MPA	NRG	PSI	GRS	USNRC	SNC	SIA
Coding Language	Fortran VB	Fortran C#	Fortran	Fortran	Matlab	Fortran	C++	C++	C++ VB	Matlab	Java	Java	Fortran C#	C#	C#
QA Standard	No	Yes	No	No	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Parallel Processing	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No

Summary of PFM Code Capabilities

Table 3 presents some of the PFM codes' core modeling capabilities. The items identified as the focus areas for the benchmark problems are highlighted and include circumferential cracks, PWSCC, leak detection, inspection with tabular probability of detection (POD), and WRS uncertainty. These items were selected to accommodate the most participants and to reflect current issues of interest in the nuclear power industry. The shaded cells indicate that the response was either not received or was not applicable. It is worth noting that there are considerable differences among the codes in the treatment of crack face pressure (CFP) in the calculation of SIFs for both part-through-wall (PTW) and through-wall (TW) cracks and in the calculation of the COD. Their effects on the LBB quantities of interest (QoIs), such as the margin between leak and break and the probability of failure, should be considered case-by-case.

Table 3: Comparison of PFM Code Core Modeling Capabilities

`	Participant Coverage	LEI	KIWA	Emc2	CRIEPI	VTT	KINS	JAEA	IPP	MPA	NRG	PSI	GRS	USNRC	SNCL	SIA
Axial Crack	67%		√	√				√	√	√		√	√	√	√	√
Circ. Crack	100%	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Low Cycle Fatigue	93%		√	√	√	√	√	√	√	√	√	√	√	√	√	√
IGSCC	93%	√	√	√	√	√	√	√	√	√		√	√	√	√	√
PWSCC	100%	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Non-idealized through-wall crack	67%	√	√	√		√	√				√	√		√	√	√
Leakage Detection	100%	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Mid-life Mitigation	53%			√			√	√				√	√	√	√	√
Parallel Computing	13%												√	√		
Transition Depth	100%	90%tw	90%tw	95%tw	95%tw	95%tw	95%tw	95%tw	95%tw	80%tw	95%tw	95%tw	95%tw	95%tw	95%tw	95%tw
Fatigue Initiation	73%		√	√		√	√		√		√	√	√	√	√	√
SCC Initiation	87%	√	√	√		√	√	√	√		√	√	√	√	√	√
Spatial Discretization	60%			√			√		√	√	√	√		√	√	√
Inspection-Tabular POD	100%	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
CFP on SIF for PTW Crack	100%	0%	100%	100%	100%	100%	100%	100%	100%	100%	0%	0%	0%	100%	100%	100%
CFP on SIF for TW Crack	100%	0%	0%	100%	100%	100%	100%	100%	100%	100%	0%	0%	0%	100%	100%	100%
CFP on COD	87%		0%	50%		50%	50%	0%	100%	100%	0%	0%	0%	50%	50%	50%
WRS Uncertainty	87%		√	√		√	√	√	√	√	√	√	√	√	√	√
Compliance with QA Standard	67%		√			√			√	√	√	√	√	√	√	√

Design of Benchmark Problems

The benchmark study includes deterministic [6] and probabilistic benchmark problems. A pre-existing circumferential crack is postulated in a fictitious butt-weld fabricated from Alloy 182 in a pressurized-water reactor coolant system. The degradation mechanism is PWSCC. The crack in the weld grows from the prescribed normal operating loads (i.e., pressure, deadweight, and thermal expansion) and WRS. A total operating life of 60 years is assumed.

Since the objective of the benchmark problems is designed to provide a meaningful quantitative comparison among the various codes involved in the benchmark study, the crack initiation and subsequent crack coalescence are ignored to ensure broad participation in the benchmark activities. Most of the PFM codes cannot model the coalescence of multiple cracks.

WRS Models

WRS is a key driving force for the initiation and growth of PWSCC in Alloy 82/182 dissimilar metal welds. For circumferential cracks, the through-thickness axial WRS profile is required. In a PFM code, the axial WRS is typically defined in one of the following approaches: tabular form, polynomial equations, and linear axisymmetric. These different modeling approaches could have a pronounced effect when a complex WRS profile, such as a 3rd order polynomial, is considered. In addition, finite element analysis and lab measurements have shown a large scatter in the WRS profile. The capability to consider WRS uncertainties is essential in the PFM benchmark.

Table 4 summarizes the responses received from all participants on their WRS models. The response from Emc^2 is for the PROMETHEUS code, the responses from PSI and GRS are for the PROST code, and the response from KINS is for the PROLOCA code.

Table 4: Definition of Axial WRS Profile for Circumferential Crack

Definition of WRS Profile	LEI	KIWA	EMC^2	CRIEPI	VTT	KINS	JAEA	IPP	MPA	NRG	PSI	GRS	USNRC	SNC	SIA
Tabular form	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes
Polynomial	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
Linear	No	No	No	No	No	No	No	Yes	Yes	Yes	No	No	No	Yes	Yes
Uncertainty Treatment	No	No	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

SIF Solutions

To evaluate a time-dependent problem, the accuracy of the calculated SIFs along the crack profile has a fundamental impact on the calculated time to leakage or time to rupture. The SIF solution models [7]-[27] are summarized in Table 5. Comparisons of these solutions are beyond the scope of the present paper. References [28] and [29] present some recent comparisons of various SIF solutions.

Table 5: SIF Solutions

Crack Type	LEI	KIWA	EMC^2	CRIEPI	VTT	KINS	JAEA	IPP	MPA	NRG	PSI	GRS	USNRC	SNC	SIA
PTW Crack	[7]	[8]	[10]	[12]	[17]	[10]	[13] [14]	[17] [18] [19] [20]	[8]	[9]	[23]	[23] [24] [25] [26]	[10]	[17]	[17]
TW Crack	[7]	[8][9]	[11]	N/A	[17]	[11]	[15] [16]	[17] [21]	[8]	[22]	[11]	[11] [21]	[11]	[27]	[27]

J-Integral Solutions

The J-integral is an important parameter in evaluating crack growth and crack stability based on elastic-plastic fracture mechanics, which assumes that the crack grows by ductile tearing caused by remotely applied tension and bending loads. The J-integral solution models [8],[9],[21],[23],[30]-[36] are summarized in Table 6. However, comparing these models was not a focus of the benchmark study.

Table 6: J-Integral Solutions

Crack Type	LEI	KIWA	EMC^2	CRIEPI	VTT	KINS	JAEA	IPP	MPA	NRG	PSI	GRS	USNRC	SNC	SIA
PTW Crack	[23]	[8][9]	N/A	N/A	[8]	N/A	[31]	[21]	[8] [32]	N/A	[33] [34] [35]	[23] [34]	N/A	[36]	[36]
TW Crack	[23]	[8][9]	[30]	N/A	[8]	[30]	[21]	[21]	[8] [32]	N/A	[33] [34] [35]	[23] [34]	[30]	[36]	[36]

Net-Section Collapse Models

For circumferential cracks, the net-section collapse model is commonly used to determine whether a component with a crack of a specific size will remain stable under specified loading conditions. The list of net-section collapse solutions [8],[13],[21],[23],[30],[37]-[47] is summarized in Table 7.

Table 7: Net-Section Collapse Models

Crack Type	LEI	KIWA	EMC^2	CRIEPI	VTT	KINS	JAEA	IPP	MPA	NRG	PSI	GRS	USNRC	SNC	SIA
PTW Crack	[37]	[8]	[38]	N/A	[17]	[38]	[13] [41]	[42]	N/A	[44]	[23]	[45]	[38]	[38] [47]	[38] [47]
TW Crack	[37]	[8]	[39] [40]	N/A	[17]	[39]	[13] [41]	[21] [43]	N/A	[44]	[23]	[45] [46]	[39] [40]	[38] [47]	[38] [47]

COD Models

A COD model is required to calculate the leakage from a TW crack. For a circumferential TW crack, Table 8 summarizes the COD models [22],[46],[48]-[59] used by all the participants.

Table 8: COD Models

Crack Type	LEI	KIWA	EMC^2	CRIEPI	VTT	KINS	JAEA	IPP	MPA	NRG	PSI	GRS	USNRC	SNC	SIA
TW Crack	[48] [49]	[50] [51]	[52]	N/A	[52] [53] [54]	[53] [54] [55]	[56]	[57]	[46] [58]	[22]	[59]	[46] [58]	[55]	[52] [53] [54]	[52] [53] [54]

Leak Rate Models

The ability to predict leak rates from potential TW cracks is central to the LBB concept. The most prominent leak rate codes used by the participants were SQUIRT [60] and LEAPOR [61], which both treat crack morphology similarly. A comprehensive description of the latest development in leak rate models can be found in Section 2.2.9 of Reference [62]. A four-regime leak rate model was developed and briefly described as follows:

1) The model for Regime 1 is based on the empirically adjusted, homogeneous equilibrium model originally developed by Henry and Fauske in References [63]-[66] for choked, two-phase flow through tight cracks. Further extensions to the Henry-Fauske are documented in References [67]-[69].

2) Regimes 2 and 3 make the transition from Regime 1 to 4 and employ the Henry-Fauske approach with some additional constraints [70]. In Regime 2, the mass flux (leak mass per area per second) is assumed to be constant and calculated at the ratio of the effective flow path length to the hydraulic diameter equal to 30, the value that defines the boundary between Regimes 1 and 2.

3) Regime 3 is a linear interpolation of the square of the mass flux between Regime 2 and Regime 4 using the ratio of the effective flow path length to the hydraulic diameter as the interpolant variable.

4) Regime 4 is based on Bernoulli’s equation for an inviscid fluid along a streamline with inclusion of a discharge coefficient to add an empirical correction for viscous losses.

An extensive review of other leak rate models and their comparisons to a set of benchmark problems can be found in References [71] and [73].

There are two methods in implementing the leak rate code into the PFM code:

1) Direct call (DC) – The leak rate code is called by the PFM code at every time step.
2) Look-up table (LUT) – A pre-processor generates leak rate LUTs for each supported degradation mechanism for ranges of COD, crack length, weld thickness, pressure, and temperature values. The leak rates are then interpolated from the LUTs by the PFM code each time step.

The participants’ responses for leak rate models are summarized in Table 9.

Table 9: Leak Rate Models

Crack Type	LEI	KIWA	EMC^2	CRIEPI	VTT	KINS	JAEA	IPP	MPA	NRG	PSI	GRS	USNRC	SNC	SIA
Models	[68] [69]	[60] [68] [74]	[61]	N/A	N/A	[60] [61]	[66] [75]	N/A	[46]	[63] | [66]	N/A	N/A	[63] | [70]	[60] [61]	[60] [61]
Implementation Method	DC	DC	DC	N/A	DC	DC	LUT	N/A	DC	DC	LUT	DC	LUT	LUT	LUT

SCC Growth Models

For the interests of the present benchmark project, time-dependent growth models for stress-corrosion cracking (SCC) are presented. Table 10 presents the information received from the participants [76]-[95]. Most of the PFM codes have multiple crack growth model implementations: tabular form, Paris Law type of relationship, PWSCC-specific model, intergranular stress corrosion cracking (IGSCC)-specific model, and other types.

Table 10: SCC Growth Models

	LEI	KIWA	EMC2	CRIEPI	VTT	KINS	JAEA	IPP	MPA	NRG	PSI	GRS	USNRC	SNC	SIA
Tabular Form (K vs. da/dt)	√	√	-	-	-	-	-	-	-	-	-	-	-	√	√
Paris Law (K vs. da/dt)	√	√	√	-	√	√	-	-	-	-	√	√	-	-	-
PWSCC	√	√	[76]	-	[77]	[76]	[82] [83]	-	-	-	[89] [90]	[89] [90]	[91] [92] [93] [94]	[76]	[76]
IGSCC	-	√	[78] [79]	-	-	[78] [79]	[12] [81	-	-	-	-	-	-	[95]	[95]
Other SCC	-	-	-	[12]	-	[80]	[84] [85]	[86]	[8]	-	[87] [88]	[87] [88]	-	-	-

Acceptance Criteria for PFM Applications

The acceptance criteria vary significantly with the intended applications. For example, use of PFM results to optimize inspection scope and frequency would require a different acceptance criterion than the use of PFM results to disposition detected flaws for fitness-for-service purposes. When the questionnaire was prepared, only limited PFM piping applications had been accepted by the regulatory bodies. The acceptance criteria will likely evolve with time through more applications by both industry and the regulatory bodies. Hence, both short- and long-term acceptance criteria data were solicited.

Organizations from 11 countries provided their short-term acceptance criteria. These responses fell into four categories:

1) PFM must be performed for the nuclear power plant to provide as comprehensive a picture of safety as possible. This is the approach in Sweden, according to KIWA.
2) PFM is used to support or supplement DFM. This response was received from SNC in Canada, VTT in Finland, GRS in Germany, NRG in Netherlands, and CRIEPI in Japan.
3) PFM is used in general structural integrity assessments. This response was received from LEI in Lithuania, PSI in Switzerland, and IPP in Ukraine.
4) For reactor coolant loop piping, a representative value for the probability of fluid system pipe rupture which would qualify as "extremely low" would be of the order of 10^{-6} per reactor year when all rupture locations are considered in the fluid system piping or portions thereof [96]. This response was received from the USNRC in the USA.

Organizations from three countries provided responses to the long-term acceptance criteria as follows:

1) According to SNC, although acceptance criteria are under development in Canada, they will heavily depend on the intended applications. If the objective is to demonstrate pressure boundary integrity of American Society of Mechanical Engineers (ASME) Class 1 piping (e.g., flaw disposition), then the concept of extremely low probability (e.g., 10^{-6} annual failure frequency) might be acceptable. For applications to support Level 3 defence-in-depth (safety analysis focused on prevention of core damage or large release), the acceptance criteria could be back-calculated from the core damage frequency or large release frequency.
2) According to PSI, although acceptance criteria are under development in Switzerland, they will heavily depend on the intended applications. To ensure the structural integrity of SA 508 Grade 1 piping and nozzle (e.g., flaw disposition), the concept of extremely low probability (e.g., 10^{-9} failure frequency) could be acceptable to the regulator.
3) According to the USNRC, in the USA, Regulatory Guide 1.174 Revision 3 [97] provides approaches for developing risk-informed applications for licensing basis changes that consider engineering issues and apply risk insights. As part of the supporting engineering analysis, the licensee should evaluate the proposed licensing basis change with regard to the principles of maintaining consistency with the defence-in-depth philosophy, maintaining sufficient safety margins, and ensuring that proposed increases in core damage frequency and large early release frequency are small and consistent with the intent of the NRC's Safety Goal Policy Statement. In addition, Regulatory Guide 1.245 [98] describes a framework to develop the contents of a licensing submittal when performing PFM analyses in support of regulatory applications.

Summary

This paper provides a high-level overview of the responses to the questionnaire on PFM code capabilities as they related to modeling PWSCC for circumferential cracks. The extensive list of references for the various fracture mechanics models provided in this paper would be useful to developers for future PFM code design and benchmarking. The information has been used for developing more effective benchmark problems and for interpreting code-to-code differences in the benchmark problem results. Both DFM and PFM benchmark results will be presented in upcoming international conferences or seminars.

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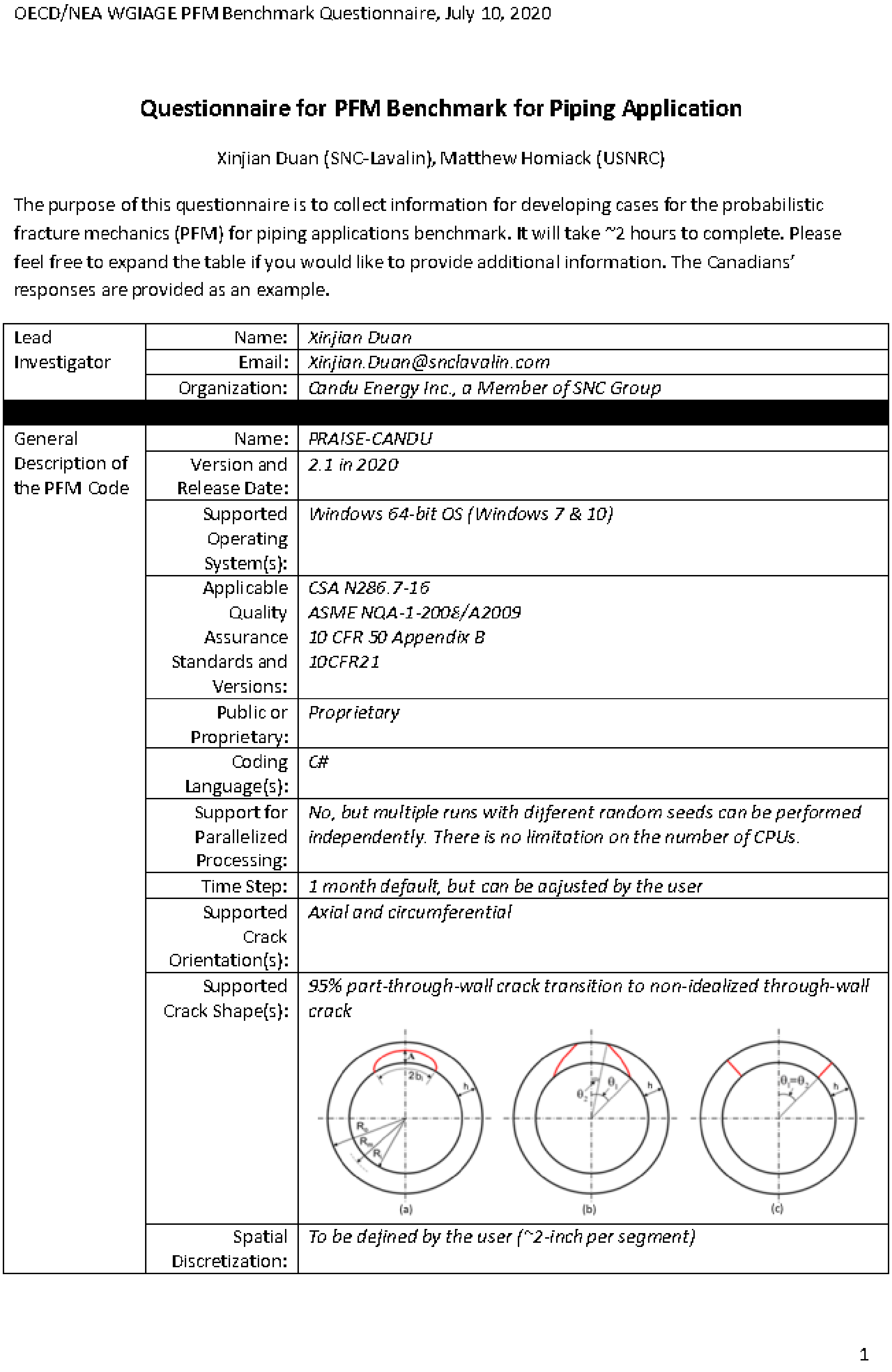
Appendix A: Acronyms

AFCEN	Association française pour les règles de conception et de construction des matériels des chaudières électro-nucléaires
ASME	American Society of Mechanical Engineers
BPVC	Boiler and Pressure Vessel Code
CDF	core damage frequency
CFP	crack face pressure
COD	crack opening displacement
CRIEPI	Central Research Institute of Electric Power Industry
CSA	Canadian Standards Association
DFM	deterministic fracture mechanics
Emc^2	Engineering Mechanics Corporation of Columbus
EPFM	elastic plastic fracture mechanics
EPRI	Electrical Power Research Institute
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit
IEC	International Electrotechnical Commission
IEEE	The Institute of Electrical and Electronics Engineers
IGSCC	intergranular stress-corrosion cracking
ISO	International Orginazation for Standardization
JAEA	Japan Atomic Energy Agency
JSME	Japan Society of Mechanical Engineers
KINS	Korea Institute of Nuclear Safety
KIWA	Kiwa Technical Consulting AB
LEI	Lithuanian Energy Institute
LRF	large release frequency
MPA	Materialprüfungsanstalt, University of Stuttgart
NRC	Nuclear Regulatory Commission
NRG	Nuclear Research and Consultancy Group
PFM	probabilistic fracture mechanics
PSI	Paul Scherrer Institut
PTW	part-through-wall circumferential crack
TW	through-wall circumferential crack
PWSCC	primary water stress-corrosion cracking
QoI	quantity of interest
SCC	stress corrosion crakcing
SIA	Structural Integrity Associates
SIF	stress intensity factor
SQA	software quality assurance standards such as American Society of Mechanical Engineers NQA-1, “Quality Assurance Requirements for Nuclear Facility Applications”
SNC	SNC-Lavalin Inc.
USNRC	United States Nuclear Regulatory Commission
VTT	VTT Technical Research Centre of Finland

Appendix B: Questionnaire Issued to Participants



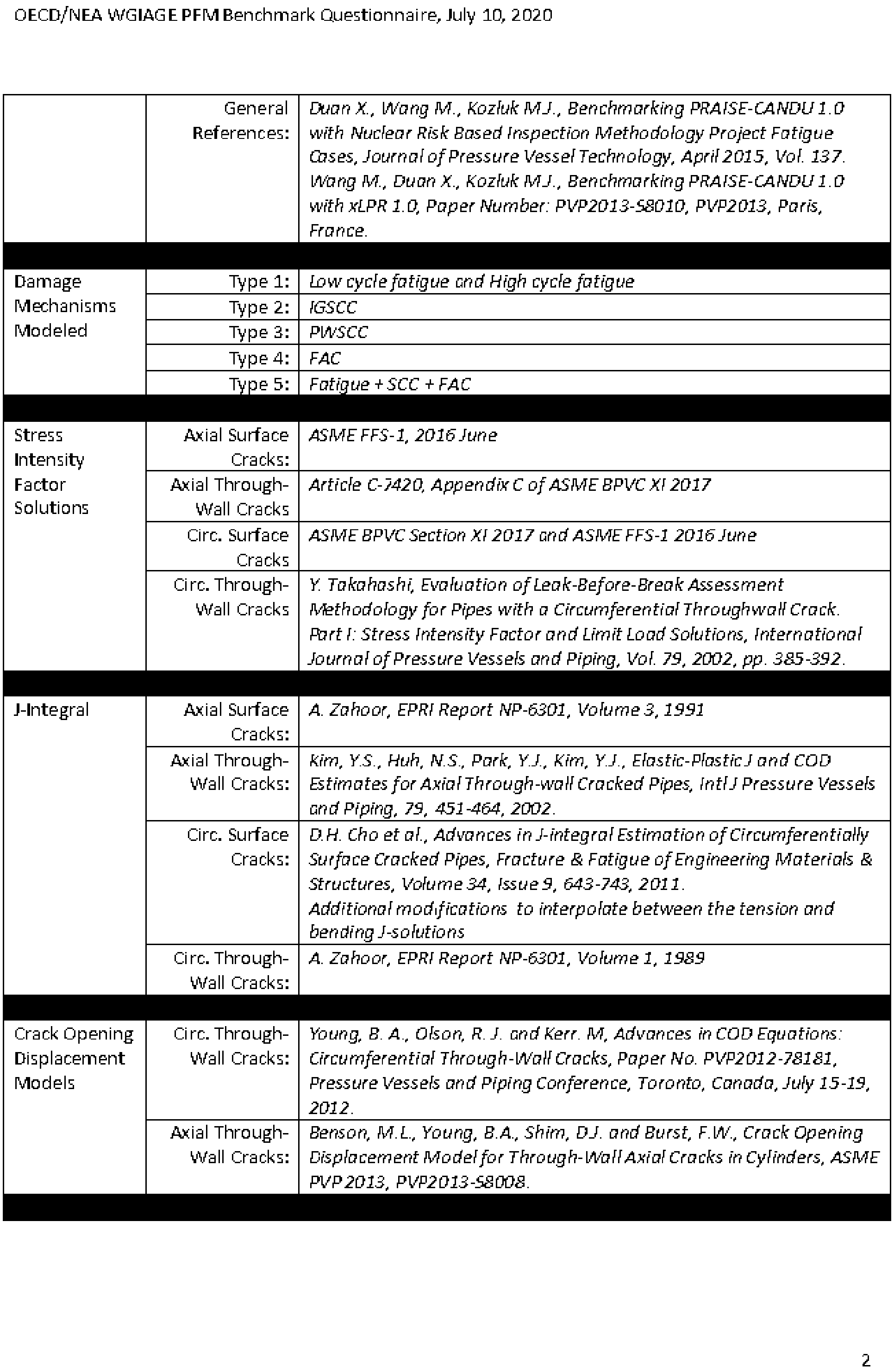
OECD/NEA WGIAGE PFM Benchmark Questionnaire, July 10, 2020

Questionnaire for PFM Benchmark for Piping Application

Xinjian Duan (SNC-Lavalin), Matthew Homiack (USNRC)

The purpose of this questionnaire is to collect information for developing cases for the probabilistic fracture mechanics (PFM) for piping applications benchmark. It will take ~2 hours to complete. Please feel free to expand the table if you would like to provide additional information. The Canadians' responses are provided as an example.

Lead Investigator	Name:	*Xinjian Duan*
	Email:	*Xinjian.Duan@snclavalin.com*
	Organization:	*Candu Energy Inc., a Member of SNC Group*
General Description of the PFM Code	Name:	*PRAISE-CANDU*
	Version and Release Date:	*2.1 in 2020*
	Supported Operating System(s):	*Windows 64-bit OS (Windows 7 & 10)*
	Applicable Quality Assurance Standards and Versions:	*CSA N286.7-16* *ASME NQA-1-2008/A2009* *10 CFR 50 Appendix B* *10CFR21*
	Public or Proprietary:	*Proprietary*
	Coding Language(s):	*C#*
	Support for Parallelized Processing:	*No, but multiple runs with different random seeds can be performed independently. There is no limitation on the number of CPUs.*
	Time Step:	*1 month default, but can be aajusted by the user*
	Supported Crack Orientation(s):	*Axial and circumferential*
	Supported Crack Shape(s):	*95% part-through-wall crack transition to non-idealized through-wall crack*
	Spatial Discretization:	*To be defined by the user (~2-inch per segment)*



OECD/NEA WGIAGE PFM Benchmark Questionnaire, July 10, 2020

	General References:	*Duan X., Wang M., Kozluk M.J., Benchmarking PRAISE-CANDU 1.0 with Nuclear Risk Based Inspection Methodology Project Fatigue Cases, Journal of Pressure Vessel Technology, April 2015, Vol. 137.* *Wang M., Duan X., Kozluk M.J., Benchmarking PRAISE-CANDU 1.0 with xLPR 1.0, Paper Number: PVP2013-58010, PVP2013, Paris, France.*
Damage Mechanisms Modeled	Type 1:	*Low cycle fatigue and High cycle fatigue*
	Type 2:	*IGSCC*
	Type 3:	*PWSCC*
	Type 4:	*FAC*
	Type 5:	*Fatigue + SCC + FAC*
Stress Intensity Factor Solutions	Axial Surface Cracks:	*ASME FFS-1, 2016 June*
	Axial Through-Wall Cracks	*Article C-7420, Appendix C of ASME BPVC XI 2017*
	Circ. Surface Cracks	*ASME BPVC Section XI 2017 and ASME FFS-1 2016 June*
	Circ. Through-Wall Cracks	*Y. Takahashi, Evaluation of Leak-Before-Break Assessment Methodology for Pipes with a Circumferential Throughwall Crack. Part I: Stress Intensity Factor and Limit Load Solutions, International Journal of Pressure Vessels and Piping, Vol. 79, 2002, pp. 385-392.*
J-Integral	Axial Surface Cracks:	*A. Zahoor, EPRI Report NP-6301, Volume 3, 1991*
	Axial Through-Wall Cracks:	*Kim, Y.S., Huh, N.S., Park, Y.J., Kim, Y.J., Elastic-Plastic J and COD Estimates for Axial Through-wall Cracked Pipes, Intl J Pressure Vessels and Piping, 79, 451-464, 2002.*
	Circ. Surface Cracks:	*D.H. Cho et al., Advances in J-integral Estimation of Circumferentially Surface Cracked Pipes, Fracture & Fatigue of Engineering Materials & Structures, Volume 34, Issue 9, 643-743, 2011.* *Additional modifications to interpolate between the tension and bending J-solutions*
	Circ. Through-Wall Cracks:	*A. Zahoor, EPRI Report NP-6301, Volume 1, 1989*
Crack Opening Displacement Models	Circ. Through-Wall Cracks:	*Young, B. A., Olson, R. J. and Kerr. M, Advances in COD Equations: Circumferential Through-Wall Cracks, Paper No. PVP2012-78181, Pressure Vessels and Piping Conference, Toronto, Canada, July 15-19, 2012.*
	Axial Through-Wall Cracks:	*Benson, M.L., Young, B.A., Shim, D.J. and Burst, F.W., Crack Opening Displacement Model for Through-Wall Axial Cracks in Cylinders, ASME PVP 2013, PVP2013-58008.*

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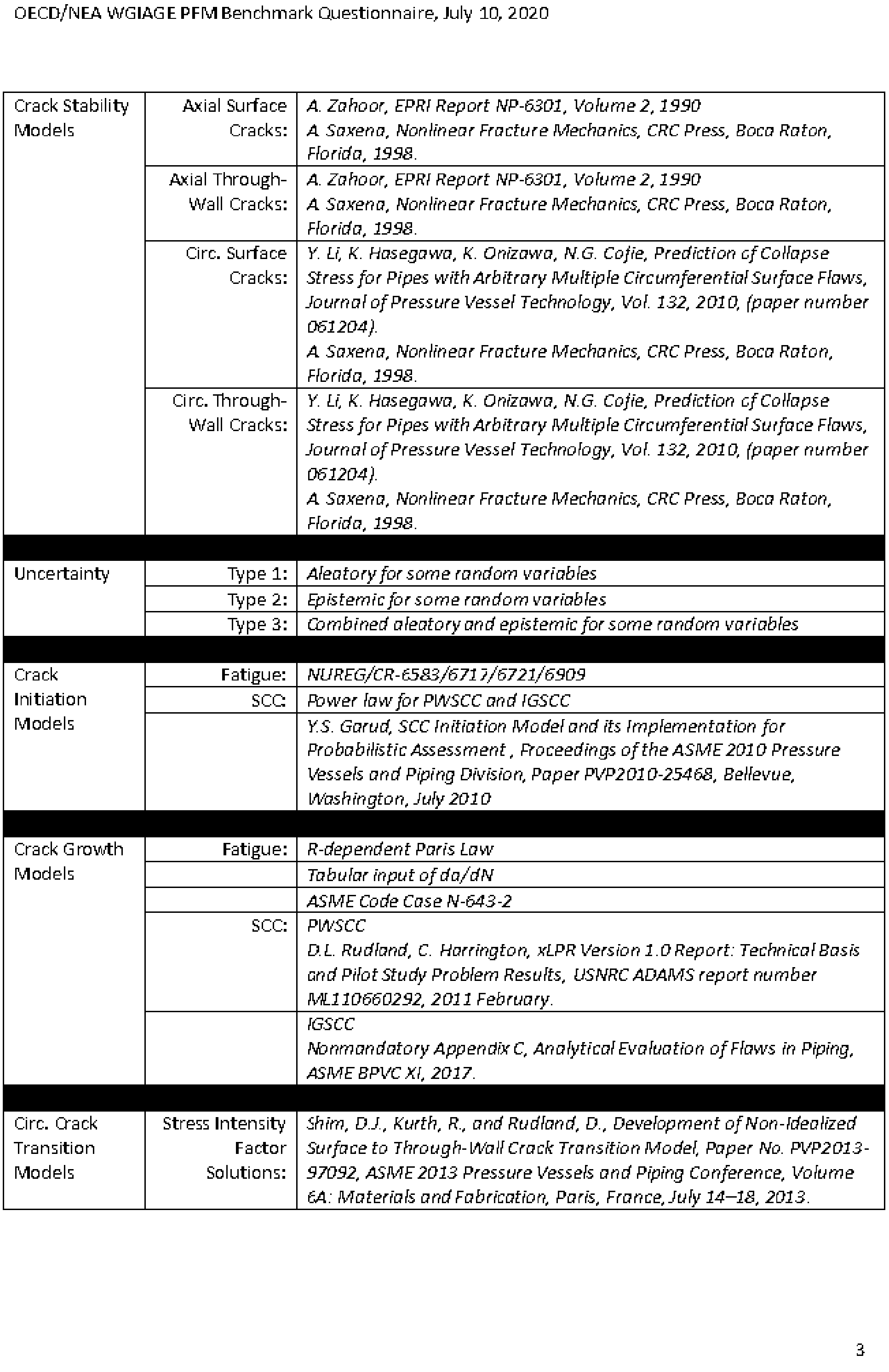

OECD/NEA WGIAGE PFM Benchmark Questionnaire, July 10, 2020

Crack Stability Models	Axial Surface Cracks:	*A. Zahoor, EPRI Report NP-6301, Volume 2, 1990* *A. Saxena, Nonlinear Fracture Mechanics, CRC Press, Boca Raton, Florida, 1998.*
	Axial Through-Wall Cracks:	*A. Zahoor, EPRI Report NP-6301, Volume 2, 1990* *A. Saxena, Nonlinear Fracture Mechanics, CRC Press, Boca Raton, Florida, 1998.*
	Circ. Surface Cracks:	*Y. Li, K. Hasegawa, K. Onizawa, N.G. Cofie, Prediction of Collapse Stress for Pipes with Arbitrary Multiple Circumferential Surface Flaws, Journal of Pressure Vessel Technology, Vol. 132, 2010, (paper number 061204).* *A. Saxena, Nonlinear Fracture Mechanics, CRC Press, Boca Raton, Florida, 1998.*
	Circ. Through-Wall Cracks:	*Y. Li, K. Hasegawa, K. Onizawa, N.G. Cofie, Prediction of Collapse Stress for Pipes with Arbitrary Multiple Circumferential Surface Flaws, Journal of Pressure Vessel Technology, Vol. 132, 2010, (paper number 061204).* *A. Saxena, Nonlinear Fracture Mechanics, CRC Press, Boca Raton, Florida, 1998.*
Uncertainty	Type 1:	*Aleatory for some random variables*
	Type 2:	*Epistemic for some random variables*
	Type 3:	*Combined aleatory and epistemic for some random variables*
Crack Initiation Models	Fatigue:	*NUREG/CR-6583/6717/6721/6909*
	SCC:	*Power law for PWSCC and IGSCC*
		Y.S. Garud, SCC Initiation Model and its Implementation for Probabilistic Assessment , Proceedings of the ASME 2010 Pressure Vessels and Piping Division, Paper PVP2010-25468, Bellevue, Washington, July 2010
Crack Growth Models	Fatigue:	*R-dependent Paris Law*
		Tabular input of da/dN
		ASME Code Case N-643-2
	SCC:	*PWSCC* *D.L. Rudland, C. Harrington, xLPR Version 1.0 Report: Technical Basis and Pilot Study Problem Results, USNRC ADAMS report number ML110660292, 2011 February.*
		IGSCC *Nonmandatory Appendix C, Analytical Evaluation of Flaws in Piping, ASME BPVC XI, 2017.*
Circ. Crack Transition Models	Stress Intensity Factor Solutions:	*Shim, D.J., Kurth, R., and Rudland, D., Development of Non-Idealized Surface to Through-Wall Crack Transition Model, Paper No. PVP2013-97092, ASME 2013 Pressure Vessels and Piping Conference, Volume 6A: Materials and Fabrication, Paris, France, July 14–18, 2013.*

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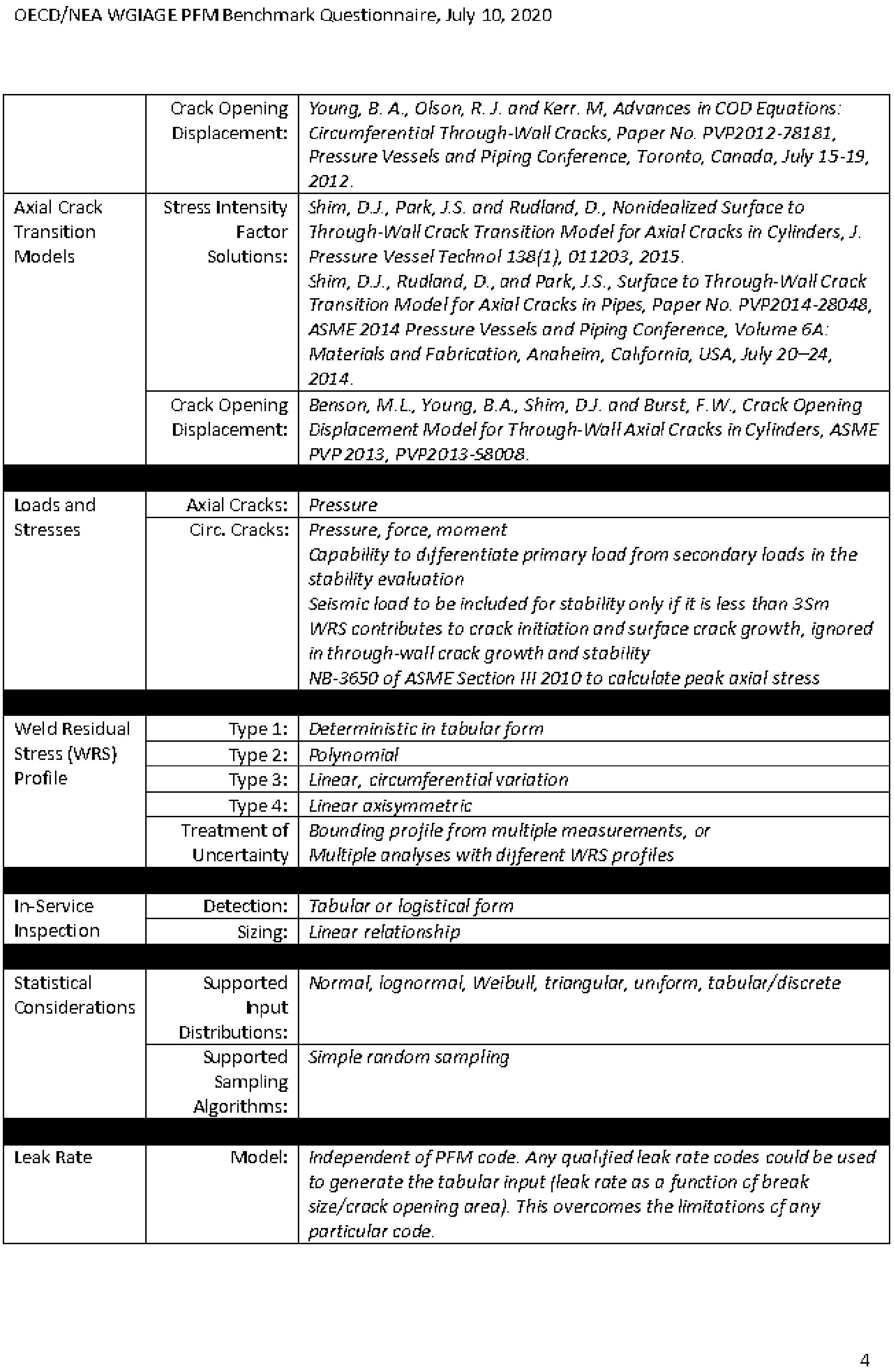
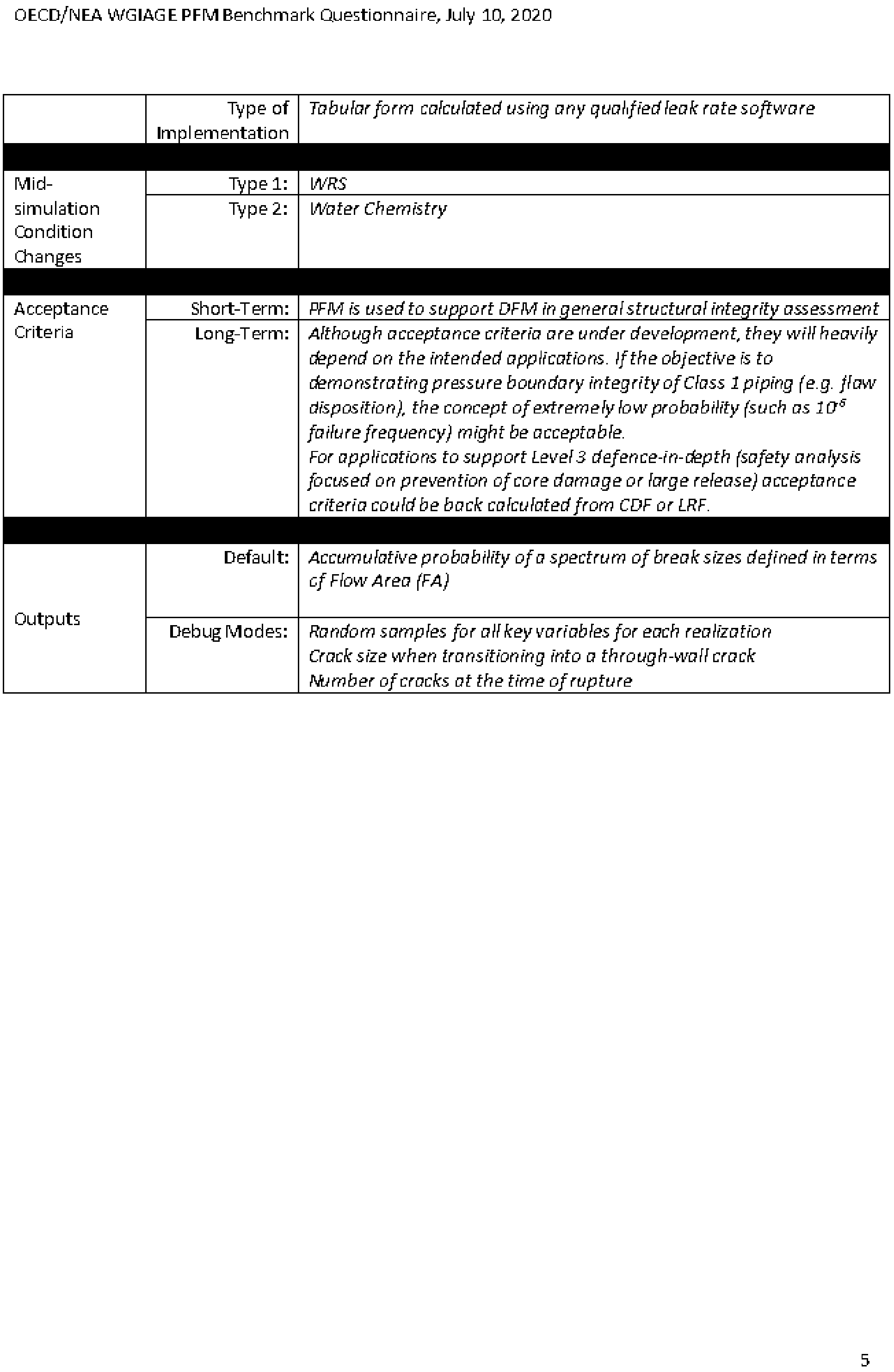


OECD/NEA WGIAGE PFM Benchmark Questionnaire, July 10, 2020

	Crack Opening Displacement:	*Young, B. A., Olson, R. J. and Kerr. M, Advances in COD Equations: Circumferential Through-Wall Cracks, Paper No. PVP2012-78181, Pressure Vessels and Piping Conference, Toronto, Canada, July 15-19, 2012.*
Axial Crack Transition Models	Stress Intensity Factor Solutions:	*Shim, D.J., Park, J.S. and Rudland, D., Nonidealized Surface to Through-Wall Crack Transition Model for Axial Cracks in Cylinders, J. Pressure Vessel Technol 138(1), 011203, 2015.* *Shim, D.J., Rudland, D., and Park, J.S., Surface to Through-Wall Crack Transition Model for Axial Cracks in Pipes, Paper No. PVP2014-28048, ASME 2014 Pressure Vessels and Piping Conference, Volume 6A: Materials and Fabrication, Anaheim, California, USA, July 20–24, 2014.*
	Crack Opening Displacement:	*Benson, M.L., Young, B.A., Shim, D.J. and Burst, F.W., Crack Opening Displacement Model for Through-Wall Axial Cracks in Cylinders, ASME PVP 2013, PVP2013-98008.*
Loads and Stresses	Axial Cracks:	*Pressure*
	Circ. Cracks:	*Pressure, force, moment* *Capability to differentiate primary load from secondary loads in the stability evaluation* *Seismic load to be included for stability only if it is less than 3Sm* *WRS contributes to crack initiation and surface crack growth, ignored in through-wall crack growth and stability* *NB-3650 of ASME Section III 2010 to calculate peak axial stress*
Weld Residual Stress (WRS) Profile	Type 1:	*Deterministic in tabular form*
	Type 2:	*Polynomial*
	Type 3:	*Linear, circumferential variation*
	Type 4:	*Linear axisymmetric*
	Treatment of Uncertainty	*Bounding profile from multiple measurements, or* *Multiple analyses with different WRS profiles*
In-Service Inspection	Detection:	*Tabular or logistical form*
	Sizing:	*Linear relationship*
Statistical Considerations	Supported Input Distributions:	*Normal, lognormal, Weibull, triangular, uniform, tabular/discrete*
	Supported Sampling Algorithms:	*Simple random sampling*
Leak Rate	Model:	*Independent of PFM code. Any qualified leak rate codes could be used to generate the tabular input (leak rate as a function of break size/crack opening area). This overcomes the limitations of any particular code.*

4



OECD/NEA WGIAGE PFM Benchmark Questionnaire, July 10, 2020

	Type of Implementation	*Tabular form calculated using any qualified leak rate software*
Mid-simulation Condition Changes	Type 1:	*WRS*
	Type 2:	*Water Chemistry*
Acceptance Criteria	Short-Term:	*PFM is used to support DFM in general structural integrity assessment*
	Long-Term:	*Although acceptance criteria are under development, they will heavily depend on the intended applications. If the objective is to demonstrating pressure boundary integrity of Class 1 piping (e.g. flaw disposition), the concept of extremely low probability (such as* 10^{6} *failure frequency) might be acceptable.* *For applications to support Level 3 defence-in-depth (safety analysis focused on prevention of core damage or large release) acceptance criteria could be back calculated from CDF or LRF.*
Outputs	Default:	*Accumulative probability of a spectrum of break sizes defined in terms of Flow Area (FA)*
	Debug Modes:	*Random samples for all key variables for each realization* *Crack size when transitioning into a through-wall crack* *Number of cracks at the time of rupture*

5