Refined Crack Growth Calculations Supporting Industry Response to Wolf Creek Pressurizer Dissimilar Metal Weld Indications

Issue Statement

A main concern following the detection of NDE indications consistent with circumferential PWSCC at Wolf Creek station in October 2006 is whether hypothetical future growth of such indications without mitigation would lead to rupture without being preceded by through-wall penetration and leakage. NRC staff has presented fracture mechanics calculations that indicate growth to rupture without being preceded by leakage in some cases. However, these calculations make some conservative assumptions that can be addressed with refined modeling efforts.

The purpose of this project is to perform additional refined crack growth calculations removing the unnecessarily conservative assumption that the crack shape remains a semi-ellipse as it grows through the weld thickness. Based on detailed evaluation of past calculations for the stress intensity factor at each point along the crack front assuming a semi-elliptical flaw shape, it is expected that consideration of the changing crack shape will result in calculation of a significant time period between through-wall penetration and rupture for the limiting case reported by the NRC (Wolf Creek relief nozzle). The work scope also supports sensitivity studies and peer review efforts with the goal of reaching consensus within the industry and with the regulator regarding the appropriateness of the refined crack growth calculations.

a. Responsible MRP Group:

Assessment ITG, A600 Focus Group

b. Project Scope:

Task 1: *Custom Extensions to FEACrack Software*

In the first task as a subcontracting effort to DEI, Quest Reliability LLC will perform customized extension to the FEACrack software that will permit DEI to explicitly consider a changing crack shape in the crack growth calculations, for the case of growth of part-depth flaws as well as of through-wall flaws. Additional customized extension of the software will also be performed to permit a significantly greater level of automation in the crack growth calculation process. This is desirable because of the iterative nature of a crack growth calculation considering a changing arbitrary crack shape based on incremental growth from the previously calculated crack size and shape. The customized software extension will permit DEI to efficiently consider various cases of weld geometry and loading and initial crack size and shape.

Task 2: *Phase I Calculations.*

The Phase I calculation will revise the crack growth calculation reported in Section 5 of the MRP white paper (transmitted to the NRC under MRP-2007-003) to explicitly consider the effect of a changing crack shape on the crack area at the

time of through-wall penetration. This crack area will be compared to the area that is calculated to result in rupture for normal operating and faulted conditions. Because of the time sensitive nature of the proposed work, the Phase I results are separated from the Phase II work and will be reported as soon as available.

Task 3: *Phase II Calculations*.

In Phase II, additional calculations using the customized software will be performed to investigate a wide range of input assumptions, including those for weld diameter, weld thickness, piping loads, welding residual stress, initial crack size, and initial crack shape. In addition, the time from through-wall penetration to rupture will be explicitly calculated based on the crack profile at the time of through-wall penetration with growth of the through-wall crack accounting for the change in the shape of the through-wall profile based on the stress intensity factor calculated at each node on the crack front. Phase II will explicitly include peer review by fracture mechanics, materials, and corrosion experts within the industry and the regulator.

c. Schedule

The following schedule for the above work scope reflects movement of labor resources away from currently scheduled projects in order to make a "dedicated" staff available for the subject project:

- Task 1: Modify FEACrack Software–January 22 - March 1, 2007
- Task 2: Phase I Calculations–Wolf Creek Relief Nozzle – March 1–19, 2007
- Task 3: Phase II Calculations–Sensitivity Studies and Benchmarking – March 19 – July 30, 2007 (preparation begins in February)

Attachments 1 and 2 provide additional task and schedule detail.

d. Deliverables

The deliverable for Phase I will be a formal DEI calculation note presenting the results and methodology of the Phase I calculations. The deliverable for Phase II will be an EPRI report presenting and discussing the methodology and results of the Phase I and II calculations, including model analytical validation.

e. Project Risk

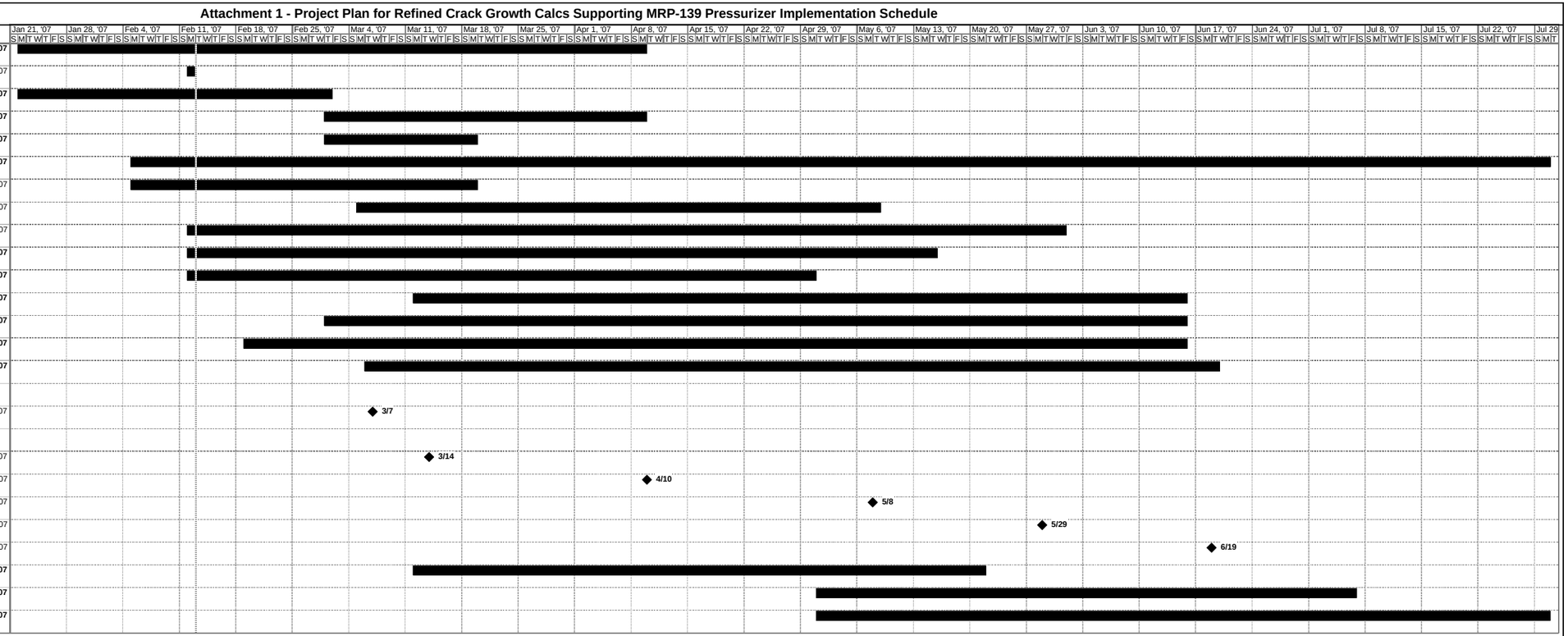
Quest Reliability is developing the software changes required in Task 1 above, and has confirmed that these changes can be implemented within the schedule cited above. There is high confidence in the technical success of Task 1 based on Quest Reliability's proven expertise in this area and past performance.

Once the software modification are complete, there is high confidence that the Phase I calculation can be efficiently completed. This calculation will be highly automated, enabling DEI to quickly concentrate on model checking and validation. Based on previous detailed assessments of the results of past FEA calculations for the semi-elliptical flaw shape, there is reasonable confidence that the Phase I calculation will show significant margin in crack area at the time of through-wall penetration versus the critical area for rupture for the case of the relief nozzle.

The Phase II work is intended to gain industry and regulator concurrence with the technical validity of the refined crack growth calculations. The Phase II work supports this goal through (1) investigation of a wide set of conditions addressing the various uncertainties associated with growth of flaws in the Wolf Creek welds (assuming no mitigation) and in pressurizer welds of concern in other plants, (2) analytical validation efforts, and (3) critical review of the methodology and validation efforts with respected industry and regulator experts. It is recognized that application of fracture mechanics techniques to stress corrosion cracking has some limitations due to the role of detailed chemistry and materials (microstructure) parameters. The situation is also complicated by the possibility of multiple crack initiation effects, such as growth of two relatively large and separated flaws. In response to these types of challenges, Phase II is designed to maximize the likelihood of success through application of state-of-the-art analytical tools and participation of the highly respected experts of Quest Reliability LLC.

Attachment 1 - Project Plan for Refined Crack Growth Calcs Supporting MRP-139 Pressurizer Implementation Schedule

ID	Task Name	Duration	Start	Finish
1	**Software Development**	**56 days**	**Mon 1/22/07**	**Mon 4/9/07**
2	Meeting in Boulder	1 day	Mon 2/12/07	Mon 2/12/07
3	**Part-Depth**	**29 days**	**Mon 1/22/07**	**Thu 3/1/07**
8	**Thru-Wall**	**28 days**	**Thu 3/1/07**	**Mon 4/9/07**
11	**Phase I**	**13 days**	**Thu 3/1/07**	**Mon 3/19/07**
17	**Phase II**	**126 days**	**Mon 2/5/07**	**Mon 7/30/07**
18	Gather geom, load params for 9 plants	31 days	Mon 2/5/07	Mon 3/19/07
19	Verification	47 days	Mon 3/5/07	Tue 5/8/07
20	FM Position Paper	79 days	Mon 2/12/07	Thu 5/31/07
21	**Residual Stress**	**67 days**	**Mon 2/12/07**	**Tue 5/15/07**
27	**Critical Size**	**56 days**	**Mon 2/12/07**	**Mon 4/30/07**
33	**Case Matrix**	**70 days**	**Mon 3/12/07**	**Fri 6/15/07**
38	**Multiple Cracks**	**77 days**	**Thu 3/1/07**	**Fri 6/15/07**
42	**Validation**	**85 days**	**Mon 2/19/07**	**Fri 6/15/07**
48	**Consensus (Industry & NRC)**	**76 days**	**Tue 3/6/07**	**Tue 6/19/07**
49				
50	Status & Phase II review mtg (tentative)	1 day	Wed 3/7/07	Wed 3/7/07
51				
52	Conf call Phase I results (tentative)	1 day	Wed 3/14/07	Wed 3/14/07
53	Conf call #1 on Phase II progress	0 days	Tue 4/10/07	Tue 4/10/07
54	Phase II independent review meeting	1 day	Tue 5/8/07	Tue 5/8/07
55	Conf call #2 on Phase II progress	0 days	Tue 5/29/07	Tue 5/29/07
56	Present Phase II results	1 day	Tue 6/19/07	Tue 6/19/07
57	**DEI OPTIONAL SUBTASKS**	**51 days**	**Mon 3/12/07**	**Mon 5/21/07**
60	**Report**	**49 days**	**Tue 5/1/07**	**Fri 7/6/07**
65	**Deliverable - EPRI report**	**65 days**	**Tue 5/1/07**	**Mon 7/30/07**



Project: Refined Crack Growth Calcs
Date: Tue 2/13/07

Task | Progress | Milestone | Summary | Rolled Up Task | Rolled Up Milestone | Rolled Up Progress | Split | External Tasks | Project Summary | Group By Summary | Deadline

Attachment 2 - Project Plan for Refined Crack Growth Calcs Supporting MRP-139 Pressurizer Implementation Schedule

Task			SubTask	SubTask Item	
#	ID	Description	Description	Description	Item Description
1	1	Software			Custom extensions to FEACrack software
1	2	Software	Meeting		Meeting in Boulder to discuss Task 1 and Quest Involvement in Task 3
1	3	Software	Part-Depth		Software modules for part-depth circ cracks
1	4	Software	Part-Depth	Shape	Permit arbitrary part-depth shape and link to automatic crack growth
1	5	Software	Part-Depth	Temps	Permit input tables for setting temperatures to simulate residual stress loading
1	6	Software	Part-Depth	Contact	Allow rigid contact surface as nonlinear boundary condition to simulate effect of crack
1	7	Software	Part-Depth	Deliverable	Release of part-depth FEACrack software modules
1	8	Software	Thru-Wall		Software modules for thru-wall circ cracks
1	9	Software	Thru-Wall	Shape	Permit arbitrary part-depth shape and link to automatic crack growth
1	10	Software	Thru-Wall	Deliverable	Release of thru-wall FEACrack software modules
2	11	Phase I			Repeat white paper Section 5 calculation for WC relief nozzle weld
2	12	Phase I	Verification		Verify that software including new modules is producing mathematically correct answers, including running of test cases versus other published solutions
2	13	Phase I	Calc		Run automated software to produce base case results for WC relief nozzle
2	14	Phase I	Write-up		Write up DEI calc note, separate write-up, and presentation slides
2	15	Phase I	Review		Quick outside review cycle for releasing DEI calc note and separate write-up
2	16	Phase I	Deliverable		DEI calc note, separate write-up, and presentation slides
3	17	Phase II			Calculate time to leakage and rupture bounding 9 spring 2008 plants
3	18	Phase II	9 Plants		Gather and evaluate geometry, loading, fabrication, and weld repair data for the pressurizer nozzle Alloy 82/182 welds in the set of 9 spring 2008 plants
3	19	Phase II	Verification		Verify that software including new modules is producing mathematically correct answers, including running of test cases versus other published solutions. This task will build upon the Phase I verification task, and include more extensive QA dedication of the FEACrack software including its new modules. Test cases for the thru-wall crack geometry must be considered in addition to those for the part-depth geometry. Results are also expected to be produced by EMC2 for an arbitrary crack geometry for comparison to MRP results.
3	20	Phase II	FracMech		Produce a position paper on technical basis for the fracture mechanics calculation methods being used, including the treatment of boundary conditions such as the simulation of residual stresses. The purpose of this Subtask is to gain acceptance of the calculation approach being applied for the crack growth calculation.
3	21	Phase II	Res Stress		Develop welding residual stress assumptions for the matrix of crack growth calculation runs
3	22	Phase II	Res Stress	Organize for 9	Organize and compare available weld repair data for 9 spring 2008 plants.
3	23	Phase II	Res Stress	Collect FEA	Sort and organize existing welding residual stress FEA calculation results produced by DEI and other available/published results
3	24	Phase II	Res Stress	New FEA	Perform a limited number of additional FEA welding residual stress calculations.
3	25	Phase II	Res Stress	Literature	Collect and evaluate welding residual stress data in the open literature including BWR (ASME) mockup data.
3	26	Phase II	Res Stress	Assumptions	Produce write-up with welding residual stress cases to be considered in the crack growth calculations, including justification.
3	27	Phase II	Critical Size		Resolve issues regarding appropriate calculation for critical crack size for rupture. The critical crack size defines the end point for the crack growth calculations. It would be desirable to determine the stability of part-depth and through-wall cracks of arbitrary shape.
3	28	Phase II	Critical Size	Misc Loads	Reach a consensus concerning how residual stress, seismic, stratification (surge nozzle), thermal startup (surge nozzle), and cold spring loads should be treated in the critical crack size calculation. Treatment of deadweight and pressure loads is clear, and pipe thermal expansion loads are addressed above.
3	29	Phase II	Critical Size	Sec Approach	Develop technical approach to treatment of secondary (i.e., pipe thermal expansion) loads on crack size for rupture. The result of this item could be a technical basis for concluding that secondary stresses do not need to be considered, or it could be a calculation methodology for determining the extent to which secondary stresses affect the size for unstable rupture.
3	30	Phase II	Critical Size	Sec Calcs	If necessary, perform calculations determining the extent to which secondary stresses affect the crack size for rupture

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Task			SubTask	SubTask Item	
#	ID	Description	Description	Description	Item Description
3	31	Phase II	Critical Size	EPFM Approach	Develop technical approach to consideration of EPFM failure mode in addition to limit load failure mode
3	32	Phase II	Critical Size	EPFM Calcs	If necessary, perform EPFM calculations of critical crack size.
3	33	Phase II	Case Matrix		Run matrix of weld diameter and thickness, crack initial size and shape, pipe loads, and simulated welding residual stress to cover/bound group of 9 plants and address modeling uncertainties
3	34	Phase II	Case Matrix	Set Matrix	Design the matrix of sensitivity cases to be considered
3	35	Phase II	Case Matrix	Part-depth	Run the software for growth of part-depth surface circ cracks
3	36	Phase II	Case Matrix	Thru-wall	Run the software for growth of thru-depth surface circ cracks (with initial shape based on final shape of part-depth flaw)
3	37	Phase II	Case Matrix	Document	Document the results of the case matrix and summarize and interpret the results
3	38	Phase II	Multiple		Consider effect of multiple cracks on the calculation results, by enveloping the cracks by a single crack and/or explicitly modeling 2 or 3 cracks in the FEA model itself.
3	39	Phase II	Multiple	Approach	Decide on approach
3	40	Phase II	Multiple	Software	OPTIONAL ITEM: Add capability to software to explicitly model multiple flaws in the automated crack growth model
3	41	Phase II	Multiple	Calcs	Run cases and document results for multiple flaw cases
3	42	Phase II	Validation		Benchmarking/validation of modeling approach versus data
3	43	Phase II	Validation	Approach	Develop best feasible approach or approaches to validation. Possible sources of data for validation include PWR and BWR plant experience, laboratory data, and published data for other industries.
3	44	Phase II	Validation	Gather data	Gather and organize data for validation
3	45	Phase II	Validation	Runs	Perform additional software runs with inputs specific to validation cases
3	46	Phase II	Validation	Compare	Produce plots comparing the validation data with the model results
3	47	Phase II	Validation	Write-up	Document the validation approach, results, and conclusions
3	48	Phase II	Consensus (Industry & NRC)		Hold meetings and answer questions to build consensus on methodology, inputs, and assumptions
3	50	Phase II	Consensus		Status & Phase II review meeting (tentative)
3	52	Phase II	Consensus		Conference call discussing Phase I results (tentative)
3	53	Phase II	Consensus		Conference call #1 on Phase II progress
3	54	Phase II	Consensus		Phase II independent review meeting
3	55	Phase II	Consensus		Conference call #2 on Phase II progress
3	56	Phase II	Consensus		Washington, DC meeting to present Phase II results and solicit input for final EPRI
3	57	Phase II	Optional		Optional Probabilistic & Weld Residual Stress modeling subtasks
3	58	Phase II	Probabilistic		OPTIONAL SUBTASK: Perform relatively simple probabilistic calculation examining likelihood of WC indications being detected with narrow range of reported depths and still growing as rapidly as calculated by NRC. This calculation can be accommodated within the current schedule and budget.
3	59	Phase II	WRS FM		OPTIONAL SUBTASK: Insert fracture mechanics submodel with crack tip mesh into DEI welding residual stress model to calculate crack growth with residual stresses calculated in the same FEA model. It is suggested that the feasibility and benefit of this approach be discussed in early March after the planned software modifications are in use.
3	59	Phase II	WRS FM	Software	Implement additional refinements to FEACrack
3	59	Phase II	WRS FM	Pick Cases	Select cases for investigation
3	59	Phase II	WRS FM	Run Cases	Run and document selected cases
3	60	Phase II	Report		Produce draft EPRI report presenting and discussing the methodology and results of the Phase I and II calculations, including model analytical validation
3	61	Phase II	Report	Methodology	Write up of analysis techniques used and approach
3	62	Phase II	Report	Inputs	Documentation and justification of inputs
3	63	Phase II	Report	Results	Presentation of matrix of cases
3	64	Phase II	Report	Discussion	Application of results to 9 spring 2008 plants plus general discussion of wider applicability
3	66	Phase II	Deliverable		Draft EPRI report
3	67	Phase II	Comments		Address comments received from EPRI, industry, and NRC on draft report
3	68	Phase II	Deliverable		EPRI report submit to EPRI publishing