QUARTERLY REPORT
Project WP#339: Structural Significance of Mechanical Damage

Date of Report November 30, 2010

Contract No: DTPH56-08-T-000011

Prepared For: United States Department of Transportation
Pipeline and Hazardous Materials Safety Administration
Office of Pipeline Safety

Project Title Project WP#339: Structural Significance of Mechanical Damage

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For Period Ending: November 30, 2010

Invoice for this quarterly period **$16,941**

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Funds and Work Completed During this Quarterly Period

		Federal Funding			Cost Share Funding			
Task # per MS	**Task Description**	**Budget**	**Expended (Actuals) This Quarter**	**Expended (Actuals) to Date**	**Budget**	**Expended (Actuals) This Quarter**	**Expended (Actuals) to Date**	**% Task Work Completed**
1	Project Kick Off Meeting and Subcontracting	$9,335	$0	$9,335	$831	$0	$831	100%
2	Purchase & Characterize Pipe Material	$134,674	$15,107	$34,674	$146,108	$44,454	$140,562	80%
3	Literature Review	$11,549	$0	$11,549	$8,669	$0	$8,669	100%
4	Testing of Dents on Welds & Corrosion Features	$188,507	$0	$157,363	$599,632	$25,934	$525,520	75%
5	Testing of Dents with Gouges	$150,020	$0	$150,020	$254,404	$62,476	$222,093	60%
6	Demonstration of Mechanical Damage Model Performance	$22,008	$0	$0	$10,930	$0	$0	30%
7	Industry Workshop	$12,030	$0	$0	$4,325	$0	$0	0%
8	Project Management and Reporting	$88,366	$1,834	$58,910	$43,959	$0	$1,692	On-going
	GRAND TOTAL	**$616,490**	**$16,941**	**$421,851**	**$1,068,858**	**$132,864**	**$899,367**	

Technical Status

Technical activities undertaken through the Tenth quarter focused on the following tasks:

- Task 2—Purchase & Characterize Pipe Material
- Task 4—Testing of Dents on Welds and Corrosion Features
- Task 5—Testing of Dents with Gouges
- Task 8 – Project Management and Reporting

A summary of the technical status and results to date are presented below for each tasks.

The technical group for this program has maintained close communication with other related research projects being conducted by PRCI and DOT to ensure program coordination. The team has forwarded any issues of concern to PRCI and DOT for their consideration.

Task 2: Purchase & Characterize Pipe Material
There are three currently different pipe steels in this program:

- Pipe 1 and 2 are modern IPSCO pipes manufactured between 2005 and 2006

- Pipe 3 is intended to be of older steel which was initially intended to be a manufactured pipe that replicates vintage pipe properties. Due to challenges identified with this initial approach, the project is now using vintage pipe from former in-service pipelines provided by PRCI member companies. This has resulted in use of several different pipes, one vintage material for dents and a separate material for dent+gouge.

GDF SUEZ has received three samples of Pipe 1 and two samples of Pipe 2 all with a length of 11.8 m. Pipe 1 is API X52 grade and has a 24 in diameter and 7.9 mm wall thickness. Pipe 2 is API X70 grade. It also has the same diameter but has a wall thickness of 9.0 mm. IPSCO manufactured the pipe using the electric resistance welding (ERW) process. GDF SUEZ material characterization for Pipes 1 and 2 is fully complete and results presented in previous reports.

The team removed a sample of vintage Pipe 3 from the field and delivered it to Stress Engineering Services (SES) facility near Houston, TX for inspection by the research team. Based on the inspection of the pipe conditions, they selected five pipe joints for preliminary material characterization to confirm that the material properties are consistent with standard vintage pipe materials. SES cut ring samples from each of the five pipe joints and sent them to BMT Fleet Technology's (BMT) facilities in Kanata, ON (Canada) in June 2010. BMT completed the preliminary characterization, and forwarded the results to the team in early September 2010. The material characterization has confirmed the suitability of the vintage pipe for the full-scale testing program and they have begun a detailed material characterization including, tensile testing, chemistry, Charpy, microstructure, hardness measurements and cyclic material properties.

PRCI finalized arrangements and secured a second set of vintage pipes for the dent+gouge test samples. The pipe is 24 in. diameter and made of X50 steel that was manufactured in the early 1940 by A.O. Smith. The sections of pipe have been transported to SES, where the team will perform a preliminary visual inspection and catalogue this vintage pipe with respect to the locations of known anomalies such as existing girth welds, sleeves, metal loss, and other features that could have an impact on the full-scale test results. SES cut ring samples from the three longest sections of pipe (i.e., the 24 ft. section and two 40 ft. sections) and sent it to BMT for immediate preliminary material characterization which includes the same test parameters as the Pipe 3. Preliminary material characterization was carried out and results forwarded to the team.

The other vintage pipes recovered from service and provided by Williams Companies were previously shipped to SES and will also undergo preliminary testing of material properties to confirm their use as vintage pipes. SES will then cut ring samples from each of two 40 ft. sections of the 24 in. pipe for preliminary characterization of basic materials properties. The team will designate the most appropriate vintage pipe as Pipe 4 and GDF SUEZ will use it to perform tests on the dent+gouge defects.

BMT characterized a vintage Pipe 4 (24 in. diameter and 0.25 in. nominal thickness) to complement the dent + gouge test program. The results reflect relatively good characteristics for a vintage pipe, especially its Charpy toughness. BMT or SES will quickly characterize another vintage pipe with the hope of a lower Charpy V thickness and a thicker wall. If this is not the case, team may evaluate other vintage pipes for use in further experiments.

Task 3: Literature Review

The literature review regarding cyclic fatigue dent assessment techniques is complete. A report summarizing the findings and demonstrating the performance of the identified assessment techniques will be available following the completion of the testing.

Task 4: Testing of Dents on Welds and Corrosion Features

BMT has commenced the full scale dent testing of vintage pipe specimens. The initial phase of the program includes testing of eight plain dent specimens, as summarized in the table below. The team has identified the specimens and has developed a cutting and identification plan to ensure a specimen's original pipe segment is fully traceable.

Table 1: Full Scale Vintage Pipe Plain Dent Testing – Initial Phase

Specimen #	Pipe Segment from which to take the specimens	Specimen ID to be recorded on each pipe	Pipe Material	Nominal Indenter Diameter	Indenter Travel/Dent Depth	Dent Restraint	Interacting With	Indentation Pressure	Initial Pressure Cycle	Cyclic Pressure Range	Weld Seam/Indenter Location
				(in)	(%)				(%SMYS)	(%SMYS)	
41	EEE-3	EEE-3-41	C	2	5	R	Plain	0%	100%	10%-80%	NA
42	EEE-10	EEE-10-42	C	4	10	R	Plain	0%	100%	10%-80%	NA
46	EEE-3	EEE-3-46	C	12	5	R	Plain	0%	100%	10%-80%	NA
48	EEE-12	EEE-12-48	C	2	15	U	Plain	0%	100%	10%-80%	NA
52	EEE-10	EEE-10-52	C	4	15	U	Plain	0%	80%	10%-80%	NA
54	EEE-5	EEE-5-54	C	12	15	U	Plain	0%	100%	10%-80%	NA
56	EEE-10	EEE-10-56	C	4	20	U	Plain	0%	100%	10%-80%	NA
57	EEE-5	EEE-5-57	C	12	20	U	Plain	0%	80%	10%-80%	NA

Task 5: Testing of Dents with Gouges

GDF SUEZ is in charge of the creation, characterization, burst test, and fatigue test of realistic combined defects, i.e., "dents with gouges", and their program is described in the next table:

The defects are identified by three characters **X.Y.Z.** which are numbers:

- **X.**Y.Z.—**X** identifies the **Pipe X** material which is noted by 1, 2, or 3 in this program;

- X.**Y.**Z.—**Y** defines the **type of dent and gouge defect** characterized by its geometry notably in terms of dent depth and length, and gouge depth and length. This program is considering a maximum of three different kinds of defects per pipe material, and therefore, the value of Y can range from 1 to 3; two extreme aggression conditions are considered in this study: highly dynamic and slower aggression. The former corresponds to defect Types 1 and 2 for Pipe 1 (two different excavator teeth used) and Type 1 for Pipe 2, while the latter corresponds to Type 3 for Pipe 1 and Type 2 for Pipe 2.

- X.Y.**Z.**—**Z** is the **number of defect in the defined type of defect**. There are three similar defects per type of defect. The number 1 is for a detailed geometrical, mechanical and metallurgical in-depth defect characterization after its creation. Number 2 is a similar defect

for the burst test to evaluate the defect behavior of under monotonic pressure load and number 3 is a similar defect for the fatigue test to evaluate the defect behavior under cyclic variation of the internal pressure.

In the previous quarterly reports, the following results were presented:

- Creation conditions and results for 17 defects (15 + 2 repeated ones): 1.1.1, 1.1.1b, 1.1.2, 1.1.3, 1.2.1, 1.2.1b, 1.2.2, 1.3.1, 1.3.2, 1.3.3, 1.2.3, 2.1.1, 2.1.2, 2.1.3 , 2.2.1, 2.2.2 and 2.2.3;
- Burst test conditions and results for 3 defects in Pipe 1: "1.1.2, 1.2.2 and 1.3.2" and two in Pipe 2: "2.1.2 and 2.2.2".
- Fatigue test conditions and results for 2 defects in each Pipe :
    - Pipe 1: "1.1.3 and 1.2.3" Pipe 2: "2.1.3 and 2.2.3".
- Metallurgical Failure Investigation for 3 defects "1.1.2, 1.1.3, 1.2.2 and 2.1.3".

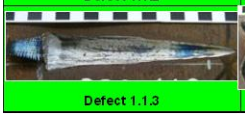
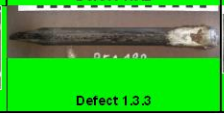
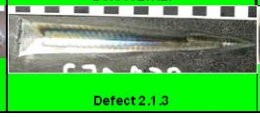
This report presents:

- Fatigue test condition of defect 1.3.3;
- Additional investigation of the hardened layer at the gouge bottom.

Table 2 below summarizes the progress of the task on "Dent and Gouge" defects for the MD4-1 part of the program. The background color in the table represents:

- White: Defects not yet created
- Yellow: Defects already created but not yet characterized/investigated or submitted to either burst or fatigue tests
- Green: Defects created and tests completed

Table 2: Status of "Dent and Gouge" defects for the MD4-1part of the program

MD 4-1					DOT	
Pipe 1 (current steel X52)			**Pipe 2** (current steel X70)		**Pipe 4** (older	
Type 1	Type 2	Type 3	Type 1 or 2	Type 2 or 3	Type 1 or 2	Type 2 or 3
Defect 1.1.1b	Defect 1.2.1b	Defect 1.3.1	Defect 2.1.1	Defect 2.2.1	*Defect 4.1.1*	*Defect 4.2.1*
Defect 1.1.2	Defect 1.2.2	Defect 1.3.2	Defect 2.1.2.	Defect 2.2.2	*Defect 4.1.2*	*Defect 4.2.2*
 Defect 1.1.3	Defect 1.2.3	 Defect 1.3.3	 Defect 2.1.3	Defect 2.2.3	*Defect 4.1.3*	*Defect 4.2.3*

<u>Task 5: Testing dents with gouges: Fatigue test condition of defect 1.3.3</u>

Defect 1.3.3 is a severe dent with shallow gouge (about 5.8% dent without pressure and gouge of 20% depth). The burst test of similar defect 1.3.2, showed, during the pressure increase, a significant bulging effect starting at around 30 bar (defect creation pressure) up to around 50 bar, which are low compared to the burst pressure of 130.9 bar (see Figure 1).

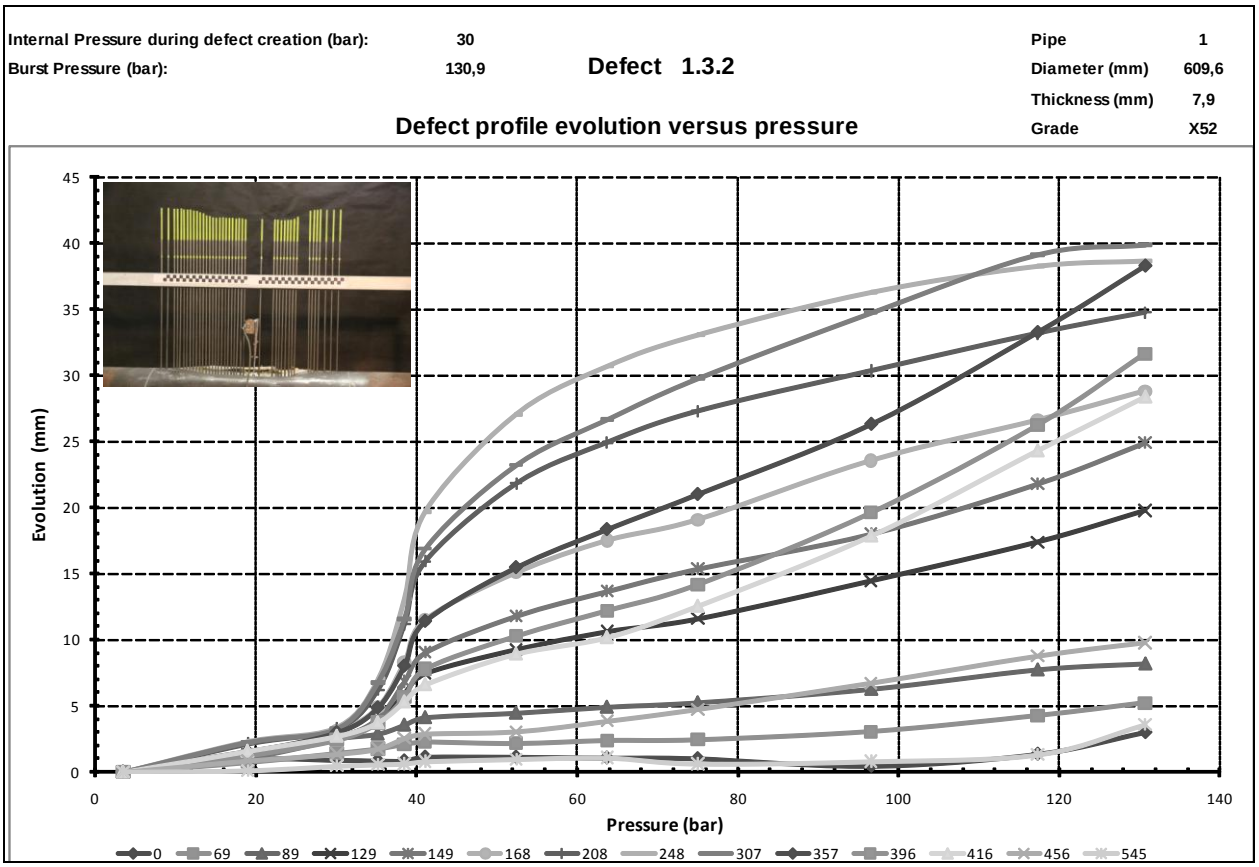


Figure 1: Bulging effect of defect 1.3.2 during the pressure increase.

The researchers noted the same bulging effect in a similar defect in Pipe 2, (2.2.2). So, they performed a fatigue test on defect 2.2.3 in Pipe 2 with a pressure amplitude in the range of bulging pressures (20-60 bar) which are low compared to the burst pressure (193.5 bar). Although no initial crack was detected by Magnetic Particles Inspection (MPI) and the fatigue pressure levels were low, the defect failed quickly in 2,000 cycles.

In order to confirm that fatigue cycling in the pressure range of bulging has very significant effects on the defect fatigue lifetime, the researchers at GdF SUEZ decided, for fatigue test of defect 1.3.3, to proceed with high pressure levels above the bulging pressure range. They confirmed the decision with the PRCI project team and Battelle who is in charge of fatigue modeling. Using results shown in Figure 1, the team chose a pressure range with a minimum pressure of 53 bar and a maximum pressure of 93 bar (80% SMYS) which are above bulging pressure range.

Defect 1.3.3 is well instrumented with the following equipment:

- Opening clip gauge;
- Four strain gauge rosettes around the gouge;
- One strain gauge at the bottom of gouge;
- Two vertical displacement sensors in the gouge;
- Potential drop;

- Acoustic emission sensors;
- A camera was used to photograph the targets positions on each side of the gouge and was synchronized with the maximum and minimum pressures to trace the defect width evolution versus time and detect the crack and leak initiation.
- Reference strain gauges and vertical displacement sensors on pipe body outside the defect.

The fatigue test of defect 1.3.3 is ongoing and at the time of writing this report, exceeds 18,000 cycles. Although the test is not complete, it is confirms that the choice of the fatigue cycling pressure range, as compared to the bulging pressure range, has a dominant effect on cycle life. In comparison, the similar defect 2.2.3, tested in the bulging pressure range, failed in 2,000 cycles only.

Task 5: Testing dents with gouges: Additional investigation of hardened layer observed on defect 2.1.3

The researchers systematically observed that, after dynamic impact, a hardened layer is created at the gouge surface as shown in Figure 2.

Figure 2: Hardened layer on gouge surface of defect 2.1.3

This layer most often has a thickness between 50-100µm and its hardness is very high, around 600 HV0.5. Until now, it was assumed that the pipe steel turned into a martensitic phase due to the thermal effect from the tooth impact. However, the researchers did not expect such high hardness values, so to check this basic assumption, the team carried out several unplanned investigations: several thermal tests were performed with a Gleeble machine or furnace to reproduce this martensitic microstructure of the pipe steel. They were unable to reproduce same hardness levels; the highest hardness achieved was around 275 HV, far below 600 HV. Alternatively, the researchers used the Blondeau formula giving the martensitic hardness versus the chemical content of steel and cooling speed (tr) between 800°C and 500°C:

$$HV=127+949*\%C+27*\%Si+11*\%Mn+8*\%Ni+16*\%Cr+21*\log(tr)$$

Using the chemical content of pipe steel and estimating cooling rates between 1°C/s and 5°C/s, the scientists calculated hardness between 200HV and 220HV. The low hardness levels exist because the carbon content is too low to produce a hard martensitic microstructure. This calculation confirms the brief experimental study that the hardened layer is not only made of pipe steel.

So, in second step, researchers analyzed a tooth used for impact tests (Figure 3)

Figure 3: Samples taken from a tooth for chemical and hardness analysis

The researchers at GdF SUEZ performed chemical and hardness analysis on the tooth samples and compared the results to the hardened layer characteristics. The hardness values are close (535 HV for the tooth and around 600 HV for the hardened layer). The chemical contents in Table 3 were the tooth and the hardened layer were similar, but the pipe steel contained different levels of silicon, chromium, and magnesium.

Table 3: Comparison of chemical contents between hardened layer, tooth and pipe steel

	%Si	%Cr	%Mn
Hardened layer	0.63	0.63	1.54
Tooth	0.64	0.63	1.49
Pipe steel	0.25	0.09	2.2

These results open the way to the interpretation of the creation of the hardened layer from the tooth material. But it is still an interpretation to be confirmed by a relevant detailed description of the diffusion mechanism due to thermal effects and friction between the tooth and pipe steel during the impact duration.

Business Status

The project remains well coordinated with the pipeline industry through PRCI.

Funds Expended

The financial condition of the project is shown in the table below.

		Federal Funding			Cost Share Funding			
Task # per MS	**Task Description**	**Budget**	**Expended (Actuals) This Quarter**	**Expended (Actuals) to Date**	**Budget**	**Expended (Actuals) This Quarter**	**Expended (Actuals) to Date**	**% Task Work Completed**
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	GRAND TOTAL	**$616,490**	**$16,941**	**$421,851**	**$1,068,858**	**$132,864**	**$899,367**	

Schedule

The project is generally on schedule, but as discussed in prior reports, Task 5 is impacted by the decision to add neutron diffraction testing of selected dent+gouge samples to the program. The facility initially selected to perform the neutron diffraction testing, the Canadian Neutron Beam Centre (CNBC) at Chalk River, ON, experienced a shutdown for an extended period and this has delayed the proposed additional testing. To help address the delay, the Program Team has coordinated with National Institute of Standards and Technology (NIST) Center for Neutron Research at Gaithersburg, MD to perform the testing. In April, NIST received defects 1.1.1b and 1.3.1, and NIST is finishing the experimental work and interpretation of the data this month. The reader should note that the analysis of the defect samples using neutron diffraction was not included in the original scope of work and was added to the program to capitalize on the availability of the neutron diffraction testing equipment and laboratories at no cost to the project. The data generated will be very beneficial to improving the understanding the behavior of dent+gouge defects and providing further input for improving the mechanical damage modeling projects.

Task No.	Task	Scheduled Completion Date	Completed Date	Status (if delayed)
1	Project Kick Off Meeting and Subcontracting	8/31/2008	8/31/2008	
2	Purchase & Characterize Pipe Material	8/31/2010	Ongoing	Pipe 1 and 2 complete, work on Vintage Pipe 3 is on-going.
3	Literature Review	11/30/2009	11/30/2009	
4	Testing of Dents on Welds and Corrosion Features	2/28/2012	Ongoing	
5	Testing of Dents with Gouges	2/28/2012	Ongoing	
6	Demonstration of Mechanical Damage Model Performance	11/30/2011	Ongoing	
7	Industry Workshop	5/31/2012	Not Yet Started	
8	Project Management and Reporting	5/31/2012	Ongoing	

Payable Milestones

Payable milestones for this period are shown in the table below.

Task No.	Task	Status % Complete	Scheduled Completion Date	Payable Milestone (Item No)
1	Project Kick Off Meeting and Subcontracting	100%	8/31/2008	
2	Purchase & Characterize Pipe Material	67%	8/31/2010	16
3	Literature Review – effect of pre-strain and dent-gouge defect from field feed-back	100%	11/30/2009	22, 26, 29, 33
4	Testing of Dents on Welds and Corrosion Features	75%	2/28/2012	35
5	Testing of Dents with Gouges	60%	2/28/2012	
6	Demonstration of Mech. Damage Model Performance	30%	11/30/2011	
7	Industry Workshop	0%	5/31/2012	
8	Project Management and Reporting	On-Going	5/31/2012	37

Results and Conclusions
A summary of the results are:

- Task 2—Material characterization are complete for Pipe 1 and Pipe 2;
- Task 3—The literature review of cyclic fatigue dent assessment techniques is complete;
- Task 4—The testing of dents interacting with girth welds is complete;
- Task 5—The fatigue test on defect 1.3.3 is ongoing and its lifetime has exceeded 18,000 cycles. Additional investigation of the hardened layer showed that this layer could be created from tooth material deposited during aggression.

Issues, Problems or Challenges
As discussed above, the team plans to complete preliminary material characterization of the vintage pipe in early September for Pipe 3 and later for other vintage pipes (i.e., Pipe 4 and other pipe materials used for dent+gouge test samples). However, the full characterization will continue through at least March 2011. The team believes that this delay will not affect the overall project schedule, since the other testing will continue in parallel during this time. The team is in the process of evaluation options to expedite the characterization process.

Plans for Future Activity
Planned activities for the project are presented below.

Task 2: Purchase & Characterize Pipe Material

The detailed material characterization on the vintage Pipe 3 is currently being carried out by BMT. The full scale dent gouge test activities will begin on the vintage material once the materials are delivered to the test facility (GDF SUEZ in Saint Denis, France). Prior to delivering the materials to the testing facilities, BMT and SES will perform preliminary material characterization to verify that the selected materials are representatives of vintage pipe properties. If the material is considered representative of vintage pipe properties, the team will carry out a detailed characterization.

BMT or SES will quickly characterize another vintage Pipe 4 pipe with the hope of a lower Charpy V thickness and a thicker wall. If this is not the case, team may evaluate other vintage pipes for use in further experiments.

Task 4: Testing of Dents on Welds and Corrosion Features

BMT will provide updates of the full scale dent testing of Pipe 3 through the monthly and quarterly reports, as they become available.

Task 5: Testing of Dents with Gouges

GDF SUEZ will interpret the full results of fatigue test on defect 1.3.3 and will continue the metallurgical investigation on several already created defects.