Development of Permanent Mechanical Repair Sleeve for Plastic Pipe

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ABSTRACT

The report presents a comprehensive summary of the project status related to the development of a permanent mechanical repair fitting intended to be installed on damaged PE mains under blowing gas conditions. Specifically, the product definition has been developed taking into account relevant codes and standards and industry input. A conceptual design for the mechanical repair sleeve has been developed which meets the product definition.

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Executive Summary

The objective of this program is to develop a plastic pipe repair sleeve; a simple, mechanical device that can be installed on damaged 4” polyethylene (PE) pipe under system operating pressure. Once developed, a comprehensive testing and evaluation program must be performed in order to ensure that the newly developed fitting meets current standards and codes.

To date, the program has made significant progress. With input and guidance from the utility sponsors, a product definition was established at the onset of the program. The product definition established the minimum requirements that the mechanical repair fitting must satisfy and served as the foundation throughout the design process. Key criterion included:

- Design and development efforts should focus on 4-inch pipe size
- Fitting should conform to existing ASTM standards and specifications (ASTM D2513 and F1924 requirements, as applicable)
- Fitting should be able to be installed under blowing gas conditions at typical line pressures (60 psig)
- Fitting should have a target pressure rating of 100 psig (60 psig at a minimum)
- Once installed, the fitting design should effectively mitigate the continued propagation of the damage via the slow crack growth (SCG) failure mechanism

Based on the aforementioned product definition, GTI and its manufacturing partners undertook an iterative design process, which has led to promising design concepts for the mechanical repair fitting. While numerous design alternatives were considered and modeled, a promising design concept has been developed that meets the established product definition. In addition, a hybrid approach (analytical and experimental) was undertaken to ensure that the proposed fitting design effectively mitigates the SCG failure mechanism and the fitting to serve as a permanent repair option.

This report presents a summary of the conceptual design process and methodology to ensure the fitting does not adversely affect the overall pipe system integrity and can effectively mitigate the propensity for Slow Crack Growth (SCG).

Experimental

Based on the product definition developed by the project team, a conceptual design process was initiated. The design of the mechanical repair fitting was contingent on its ability to withstand internal pressures up to 100 psig and to effectively mitigate the propensity for continued slow crack growth around the damage opening. In addition, the product definition provided for the fitting to be installed under blowing gas conditions without having to reduce the line pressure through some flow control device upstream of the damage opening.

With this in mind, GTI and R.W.Lyall reviewed several possible design alternatives. In order to meet all of the aforementioned requirements, several observations were made:

1. Based on a review of the steel band clamp, it was hypothesized that the design for the proposed mechanical fitting must have an annular space to ensure that the strain energy is sufficiently removed to prevent continued growth of the damage via the SCG mechanism.
2. The overall fitting geometry and the clamping system must be sufficiently sized in order to ensure a leak tight seal while operating at 100 psig.
3. The fitting design must ensure adequate means for the gas to blow away from the trench in order to be installed under blowing gas conditions

Slow Crack Growth (SCG) Considerations

In addition to ensuring leak tightness and the ability to be installed under blowing gas conditions, another important design consideration was the fittings ability to amply mitigate the propensity for slow crack growth in the axial direction beyond the end seals. Based on previous experience with steel band clamp fittings, it was hypothesized that an annular space was required in the fitting design that would equalize the pressure between the pipe and the annular space within the fitting. This would then remove the strain energy necessary to drive the crack. In order to test the efficacy of this argument, a comprehensive analytical model was developed.

Analytical Modeling – SCG Consideration

It is well known that thermoplastic gas pipe materials behave in a nonlinear elastic manner which makes the conventional approach known as linear elastic fracture mechanics (LEFM) only valid for “older” PE gas pipe such as that extruded prior to the mid 1980’s, and only approximate for more modern pipe materials. However, because this study would take a “worst case” bounding approach (e.g., all damage will be considered to be crack-like), and the results will be used only in a relative sense to help determine which scenarios are to be used in a subsequent experimental program, an LEFM based approach was utilized.

The primary parameter in an LEFM based analysis is the stress intensity factor, commonly denoted by K, which characterizes the stress and deformation states at the tip of a sharp crack. The parameter K is a function of the applied stress, the crack size and shape, and the dimensions of the component in which the crack is embedded. It is important to recognize that K is not dependent upon the material, so long as that material behaves predominantly in an elastic manner. Accordingly, there is a multiplicity of sources for K that should include a good approximation to the case of primary interest here: a finite width and depth (e.g., semi-elliptical), part through wall crack that is subjected to a biaxial stress field in a thick walled tube.

Once the most appropriate relationship for the K factor is ascertained, a determination can be made of the combination of parameters (including initial crack depth, aspect ratio, and the angle of the crack surface from the axial direction) that has the most potential for SCG propagation to take place in the axial direction. Because of the number and ranges of these variables, an analytical model was developed to draw preliminary conclusions, and provide guidance for a subsequent experimental effort.

To simplify the analysis effort enough, it was focused on a single representative PE gas pipe size and two PE materials. The pipe size that was considered for the bulk of the calculations was a 2 inch diameter, SDR11, PE2306I-A-482 gas pipe operating at 100 psi. One of the two materials is one for which extensive SCG data has been developed by Battelle[1], the other an earlier vintage PE2306 material has been studied in work by the Southwest Research Institute. While the bi-directional shifting functions can be conveniently used to consider any operating temperature, for simplicity, the present work considered only a fixed temperature of 70^{o} F. In this preliminary stage, no consideration was given to seasonal temperature and pressure changes, or to residual stresses induced by the extrusion process. A “bounding” approach was taken in which conservative assumptions and simplifications were used to the extent possible that would give a lower (pessimistic) bound on the potential for axial direction growth.

The first step in developing an analysis model suitable for the purposes outlined above was to conduct a brief literature search for stress intensity factor relations. Based on the model, the modified versions of the finite element solutions generated by I. S. Raju and J. C. Newman for surface cracks in plates under tension were utilized [2].

The modified Raju-Newman solutions gives the mode I stress intensity factor, K, at all points along the periphery of a semi-elliptical crack as a function of the crack depth, a; one-half of the surface length of the crack, c; the wall thickness, h; and the remote tensile stress, σ. For present purposes, a simplified form of these equations that results from assuming that c » a was used. This simplification is appropriate both because the focus of this work was on long axial cracks (i.e., large values of c), and the SCG failure surfaces that have been examined generally show that this was a typical initial condition. The modified version of the Raju-Newman equations are then:

$$K = K_D \{1 + [0.1 + 0.35 \ (a/h)^2](1- \sin^2\varphi) \ \sin \varphi\} \quad \text{.... Eqn. (1)}$$

and

$$K_D = \sigma(\pi a)^{1/2} \sec^{-1/2}(\pi a/2h) \quad \text{.. Eqn. (2)}$$

It can be seen that the K values at the point of deepest penetration (i.e., at $\varphi = 90^o$) is the highest value, and that the K value on the surface (i.e., at $\varphi = 0^o$) is zero. However, this does not imply that axial direction crack growth is not possible. Whatever the propensity for axial direction SCG, it will likely always be terminated before any significant extent of growth takes place by the pressure loss resulting from depth direction (through wall) SCG that breaches the wall of the pipe. To quantify this effect, the LEFM based technology that was shown to be appropriate for characterizing in-service SCG failures in PE pipe can be introduced [3]. In essence, this involves two equations that prescribe the SCG behavior of a given PE gas pipe material. These are:

$$t_i = B \times K^{-m} \quad \text{Eqn. (3)}$$

and,

$$da/dt = A \times K^{m} \quad \text{Eqn. (4)}$$

where t_i is the time required for SCG to be initiated, da/dt is the time rate at which SCG occurs, and A, B, and m are material (temperature-independent) constants. It should be understood that, strictly speaking, these relations are valid only for "older" PE gas pipe materials; i.e., materials in pipe extruded prior to the mid 1980's.

Unfortunately, the use of Eqns. (3) and (4) are frequently constrained by insufficient SCG data by which the material constants A, B, and m can be evaluated. There is a similar general lack of specific information on the extrusion related residual stresses that exist in a particular PE gas pipe. However, there was some data available that was useful for the purposes of this study. One set of data are for a 2 inch diameter, SD11, PE2306I-A-482 gas pipe which was extruded in the 1980"s (exact date unknown). A second set of data is for a similar pipe, but one that was extruded in the early 1970's. From these data, the values shown in Table 1 have been derived:

Table 1: SCG Material Constants for Two PE 2306 Materials

	1970 Vintage PE Material	**1980 Vintage PE Material**
A	2.5877×10^{-6}	1.0306×10^{-9}
B	4.1195×10^{4}	1.6950×10^{7}
m	3.0	2.1

In Table 1 the constants A and B have dimensions involving stress in psi, length in inch, and time in years, while m is dimensionless[1]. Note that all of the above values were derived directly from the experimental data, except for constant B for the 1980 vintage material for which SCG data were not available.

Preliminary calculations using Eqns, (1), (2), (3) and (4), along with the data for the 1980's vintage of PE2306, were performed in an attempt to predict the failure times and other aspects of the field failure that is shown in Figure 1. These calculations provided results that were generally good approximations of the observed results. However, they also suggested that the K

[1] In the calculations that are presented in this report, unless otherwise indicated, a remote tensile stress of 500 psi has been used. This stress corresponds to the hoop stress from a pressure of 100 psi in an SDR11 PE gas pipe.

value for axial growth based on Eqn (1) was too low. Two expedients were introduced to force the model to better approximate both the failure times and the length of axial SCG growth.

First, the axial stress was arbitrarily forced to be a multiple of the depth direction stress by the constant 1.132. Second, the value of the material constant B for the 1980's vintage material, for which data were not available to determine in the same manner as the other constants in Table 1, was selected arbitrarily. The result was that the time to wall breakthrough calculated with the model was 15.1 years, with the maximum extent of axial crack growth calculated as 0.035 inch.

Tables 2 and 3, respectively, provide calculated predictions for the times to failure in from initial crack-like damage in 2 inch diameter, DR11, PE2306 gas pipes extruded, respectively, in the 1980's and the 1970's. It can be seen that the predicted failure times are entirely consistent with the initial damage depths that have been used as input to the model. In particular, for the same damage depth, the time at which the 1980 material was predicted to fail is an order of magnitude greater than for the 1970 material; see eighth column. As many failures have been found in 1970's material within a few years after their installation, while relatively few have ever been found in 1980's material, these predictions are well in accord with experience.

But, of most importance to the goals of this work, the predictions of axial direction growth (see tenth column) are found to be benign for all initial damage depths. For example, for the 1970 material, the maximum axial growth is 0.350 inch, while it is only 0.060 inch for the 1980 material. Considering that an MRS device would surely be designed to have its ends be least one inch from the ends of the damage, it can be concluded that the risk of axial SCG is surely minimal.

Table 2: Calculated Results for 1980 Vintage PE2306 Material

Initial Crack Depth (m)		Hoop	Initial K Values			Depth Direction SCG		Axial Direction	
	a/h	Stress (MPa)	Radial	Axial	Int (yrs)	Prop (yrs)	Fail (yrs)	Int (yrs)	Length (m)
1.27*10^-4	0.025	2.76	60.16	68.1	77.85	35.31	113.16	53.67	4.83*10^-4
2.54*10^-4	0.05	2.76	85.08	96.31	27.53	22.27	49.79	18.98	7.11*10^-4
5.08*10^-4	0.1	2.76	120.32	136.2	9.73	13.08	22.82	6.71	1.07*10^-3
1.27*10^-3	0.25	2.76	190.24	215.35	2.46	5.1	7.56	1.7	1.52*10^-3
2.54*10^-3	0.5	2.76	269.03	304.55	0.87	1.46	2.33	0.6	1.27*10^-3
3.81*10^-3	0.75	2.76	329.49	372.98	0.47	0.27	0.74	0.33	5.59*10^-4

Table 3: Calculated Results for 1970 Vintage PE2306 Material

Initial Crack Depth (m)		Hoop	Initial K Values			Depth Direction SCG		Axial Direction	
	d/h	Stress (MPa)	Radial	Axial	Int (yrs)	Prop (yrs)	Fail (yrs)	Int (yrs)	Length (m)
1.27*10^-4	0.025	2.76	60.16	68.1	7.56	1.22	8.78	5.82	7.6*10^-3
2.54*10^-4	0.05	2.76	85.08	96.31	3.65	0.95	4.6	2.81	7.95*10^-3
5.08*10^-4	0.1	2.76	120.32	136.2	1.76	0.69	2.45	1.36	8.3*10^-3
1.27*10^-3	0.25	2.76	190.24	215.35	0.67	0.36	1.03	0.52	8.9*10^-3
2.54*10^-3	0.5	2.76	269.03	304.55	0.33	0.13	0.46	0.25	8.46*10^-3
3.81*10^-3	0.75	2.76	329.49	372.98	0.21	0.03	0.24	0.16	7.5*10^-3

Experimental Validation – SCG Considerations

While the results of the analytical modeling strongly indicate that the risk of significant axial direction SCG is virtually nonexistent, modified experiments were performed to validate the observations and assure the veracity of the analysis.

It is important to emphasize that there are a large number of variables that can impact the potential for axial direction crack growth that were not be included in the analysis model for simplification purposes, and were not considered experimentally either. For example, while the main driving force for SCG of a part through wall crack in a pipe wall is the hoop stress, the possibility exists for seismic events, fatigue loading sequences due to freeze/thaw cycles or road traffic, and/or extreme bending due to construction that could propagate a crack axially out of the repair.

GTI developed a modified SCG test set-up to validate the analytical model. The modified test set-up was developed specifically to test the assumption that equalization of strain energy would retard the growth of the crack. This is conservative in that the compressive forces applied at the fitting end seals was not taken into account.

Controlled sharp notches (95% of the pipe wall thickness) were placed on three pipe specimens from both 2-inch medium density and high density PE materials. The 2-inch pipes were then inserted into 4-inch PE pipes and pressurized, as shown in Figure 1. The 2-inch pipes were allowed to fail on their own accord at room temperatures. The pipe specimen assemblies have been on test to date with only one failure. The failed pipe specimen was removed and the crack length was recorded. The assembly was then re-pressurized and is still on test. The testing on all of the pipe specimens is presently on going and will continue through January 2005. Once complete, the crack will then be measured once again to determine the amount of crack growth, if any.

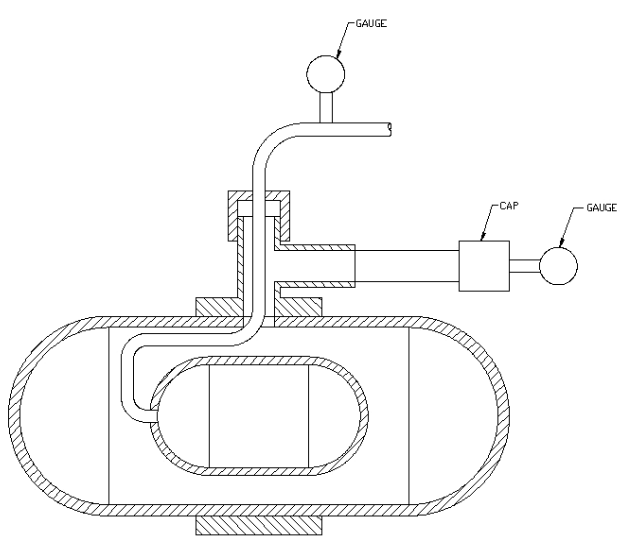

Figure 1: Schematic Illustration of the modified SCG test set-up

Conceptual Design

The design of the mechanical repair fitting was contingent on its ability to withstand internal pressures up to 100 psig and to effectively mitigate the propensity for continued slow crack growth around the damage opening. In addition, the product definition provided for the fitting to be installed under blowing gas conditions without having to reduce the line pressure through some flow control measure upstream of the damage opening.

With this in mind, GTI and its partners reviewed several possible design alternatives. In order to meet all of the aforementioned requirements, several observations were made:

4. The fitting design must ensure a means for the gas to blow away from the trench in order to be installed under blowing gas conditions
5. Based on a review of the steel band clamp, it was evident that the design for the proposed mechanical fitting must have an annular space to ensure that the strain energy is sufficiently removed to prevent continued growth of the damage via the SCG mechanism.
6. The overall fitting geometry and the clamping system must be sufficiently sized in order to ensure a leak tight seal while operating at 100 psig.

Utilizing 3D computer modeling software (SolidWorks), a first generation design was developed as shown in Figures 2 and 3 below.

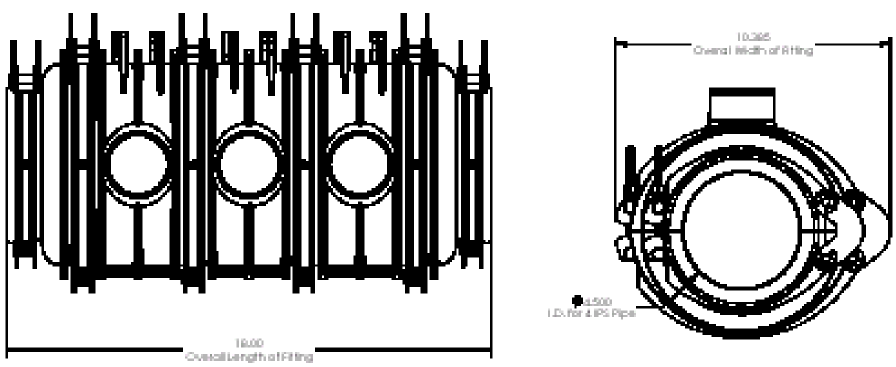

Figure 2: Schematic Illustration of the 1st Generation Mechanical Repair Fitting – Top View and Side View

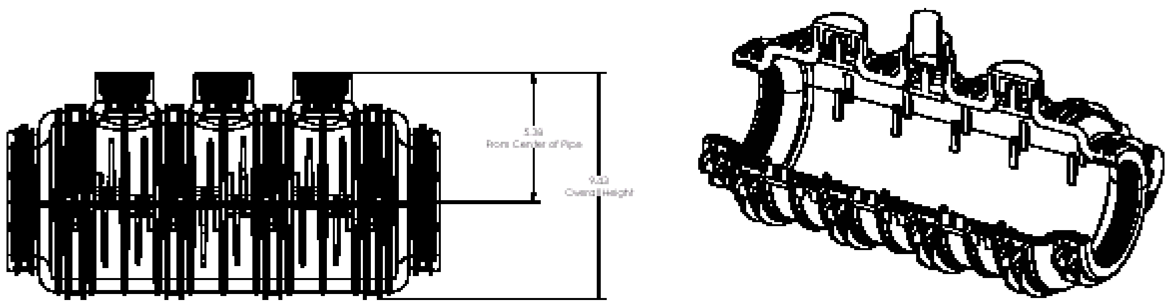

Figure 3: Schematic Illustration of the 1st Generation Mechanical Repair Fitting – Front View and Cut-out

A finite element model was created to ascertain the overall system stress between the pipe and installed fitting. The model was created in SolidWorks and the static analysis was perfomed with CosmosWorks utilizing a solid mesh and the FEEPLUS solver.

As a first approximation, the clamps were omitted and the outside circumferential surface in the clamping area was restrained as fixed. Figure 3 illustrates the mode of flexing at the area between the clamps subjected to an internal pressure of 125 psig. The stress plot is shown at a greatly exaggerated deformation to clearly demonstrate the mode of flexing in the fitting. The stresses were within a 3.125 safety factor in all areas except at the point of the greatest bulging which is centered between the two clamp areas at the interface of the two halves. The deformation between the two halves is approximately 35 mils. The deformation notwithstanding, by this time the seals would have failed first. As a result, small scale modifications were required to the clamping structure to provide additional rigidity.

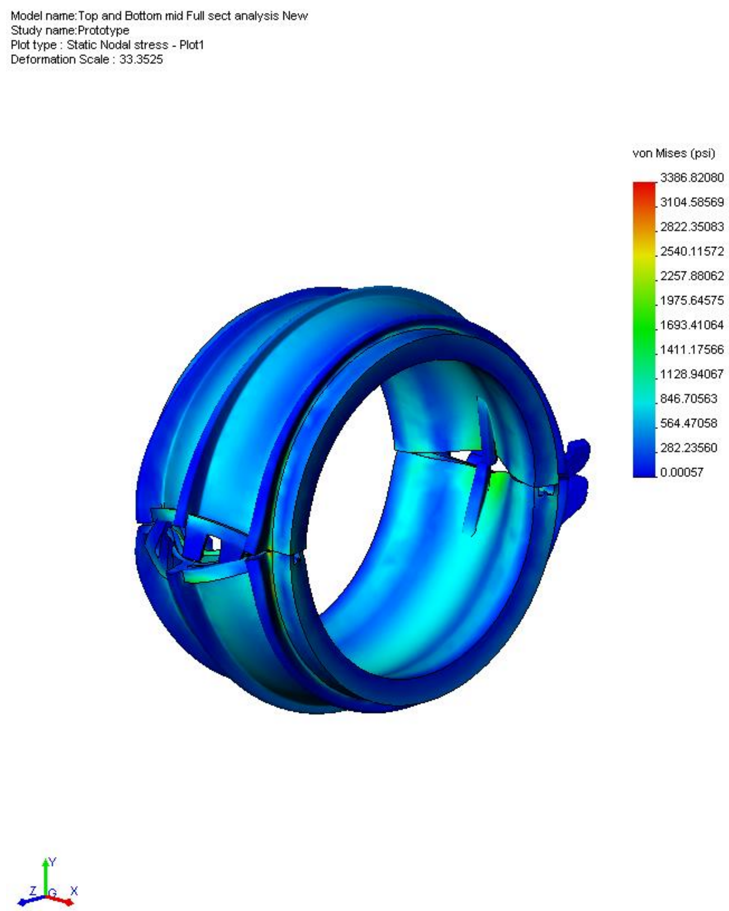

Figure 4: FEA Model to characterize deformation at clamp interface

Conceptual Design Process – Modified Design (1st Generation Concept)

Leveraging the understanding from the first iteration, GTI and R.W.Lyall performed additional finite element analysis to reduce the amount of deflection (bulging) in the fitting between the collar structure through design enhancements, as shown in Figure 5. The fitting was modeled with the properties of Polyamide 11 (Rilsan B). The rib depth at the horizontal plane was slightly increased to be nearly constant all the way around the fitting. A rib flange was added on the center rib between the clamp areas. A solid spar was added to the model fixed on both ends as if attached to the clamp structure and then spanning between the clamp area. A rib structure was added on both the top and bottom for extra strength around the purge towers (which are omitted from this model for simplicity) and to provide features for attaching an assembly tool should one be desired in the future.

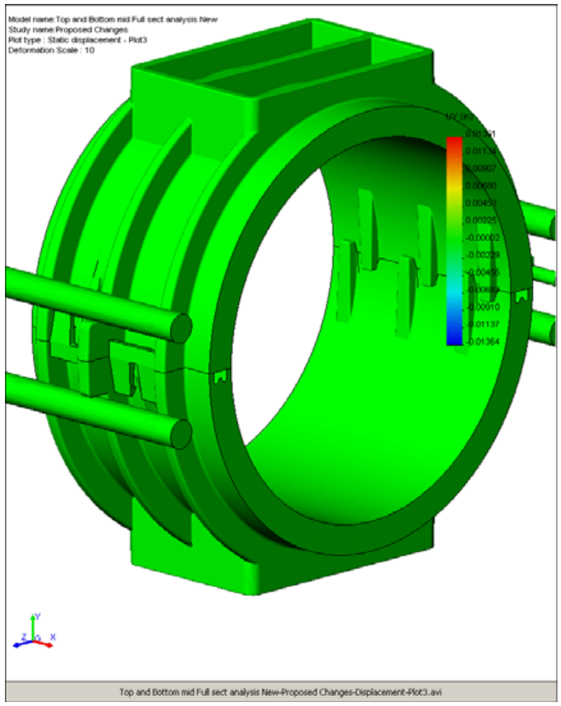

Figure 5: Design Modification to resolve the "bulging"

With a greatly exaggerated deformation scale, Figure 6, the fitting is restrained from bulging at the OD but begins to separate at the ID, approximately 10 mils, due to the moment created by the spar.

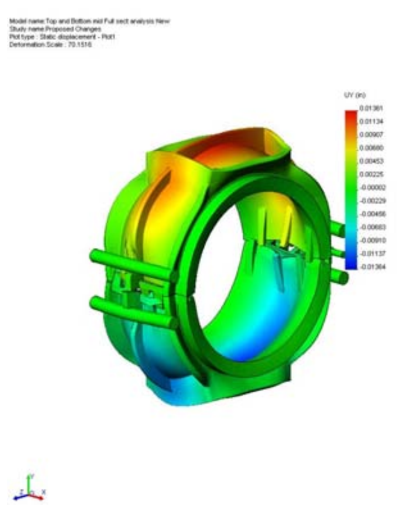

Figure 6: Design Modification to resolve the *"bulging" – Stress Distribution under load*

The separation of the fitting halves have been reduced and the stresses on the fitting are less than necessary to maintain a 3.125 safety factor to the yield strength of the PA 11 material.

To better understand how the fitting reacts as a system, its stresses and flexural modes under pre-load and internal pressure, a finite element model was created to look at the deformation of the fitting as it is restrained by the collar clamp structure. Several iterations of changes were modeled to try and find a solution that could still be cost effectively manufactured and assembled but only one will be presented here.

The fitting was modified in the following ways: The circumferential rib depth was increased by 250 mils to gain some stiffness in the fitting. No rib flange was added as was in the previous models. Additional internal and external interlocking ribs were added to provide more support along the bottom fitting seal gland. (The seal gland is not included in the following model)

Changes were also made to the collar clamp mechanism. In the previous models the clamp surface was restrained as fixed. In real life this is not the case. Because the collar clamp is a big spring and because of the moment put on the clamp by the fitting as it expands under pressure the height of the channel was increased to even out the stresses through the clamp. This additional height also allowed for spars to be spanned across the fitting from clamp to clamp at two places. Because the fitting is elongating, out of round, under pressure, the additional spars were necessary to maintain adequate contact pressure between the fitting halves, keeping the outside edge of the fitting closed and preventing the seal from extruding. The clamp also wraps around the fitting farther than it did in the previous design adding additional support near the parting line of the fitting halves. The clamp bar is now one common piece instead of individually machined pieces as was the case in the previous design. The common clamp bar is now the spar represented in the previous models and lays along the OD of the ribs on the fitting. The clamp hinge links were modified for the new clamp geometry. The hinge pin is now a one-piece tube that acts as a spar on the hinge side of the fitting. Additional bolts were added to allow for a greater pre-load and to accommodate changing to a ¼-20 thread from a ¼-28 thread.

The new design was modeled as half the fitting contacting a stationary plate. Approximately 700-lbs. contact forced between the fitting and contact plate was modeled through displacement of the bolts.

Figure 7 illustrates the displacement of the fitting in the “Y-axis” as viewed from the hinge side of the fitting with a deformation scale of 1. Figure 8 illustrates the displacement of the fitting in the Y-axis as viewed from the latch side of the fitting with a deformation scale of 5. These plots show separation of the fitting at the inside edge in the range of 3 mils to 7 mils per side or a total of 6 mils to 14 mils. The greatest amount of separation is at the corners of the model shown which would correspond to the center of the bulge in the previous models. It is observed that through the proposed design enhancements the outside edge of the fitting is held together preventing extrusion of the seal. The stress appears to be reasonable and the strain will well within the limits of the material (4%),as shown in Figures 9 and 10, respectively.

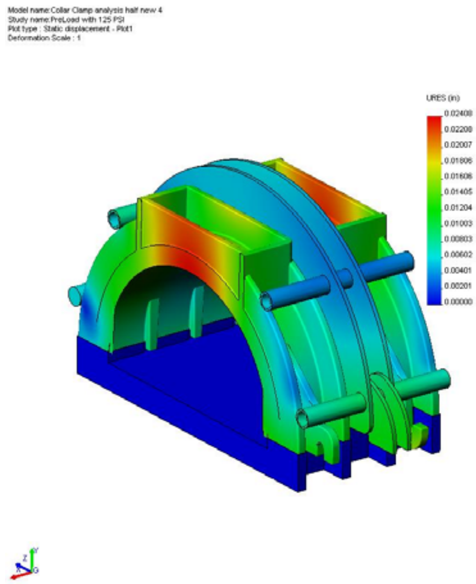

Figure 7: Displacement as viewed from the hinge side (Scale = 1.0)

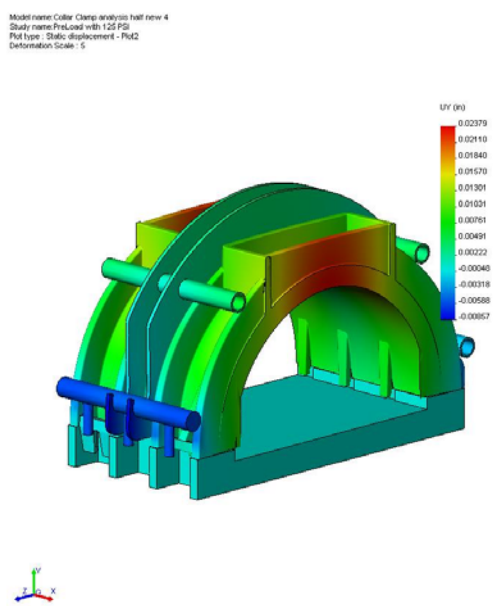

Figure 8: Displacement as viewed from the latch side (Scale = 5.0)

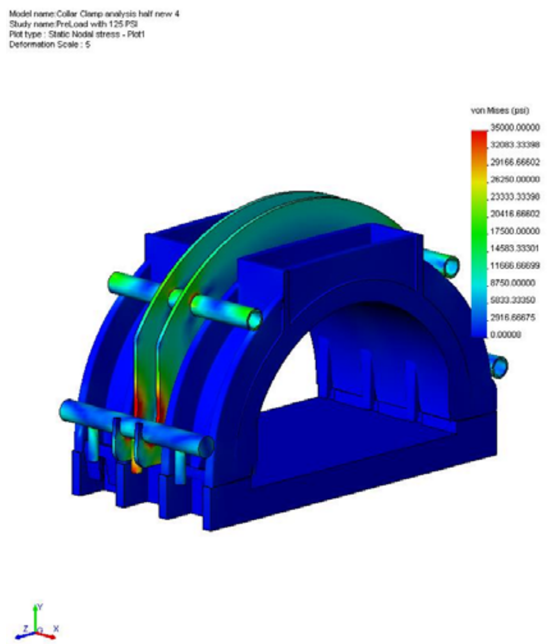

Figure 9: Stress distribution based on proposed design enhancements

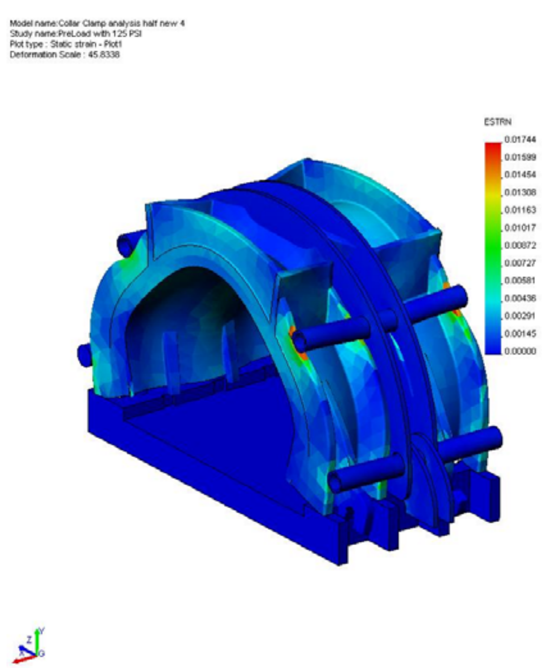

Figure 10: Strain Limits (<4%) based on proposed design enhancements

Based on the aforementioned finite element modeling, a final design concept has been established that resolves all of the pertinent issues, i.e. “bulging”, as shown in Figures 11 and 12 below.

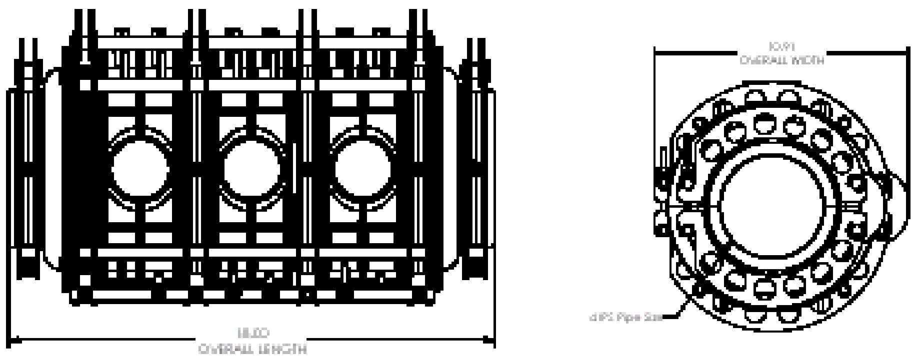

Figure 11: Schematic Illustration of the 2nd Generation Mechanical Repair Fitting – Top View and Side View

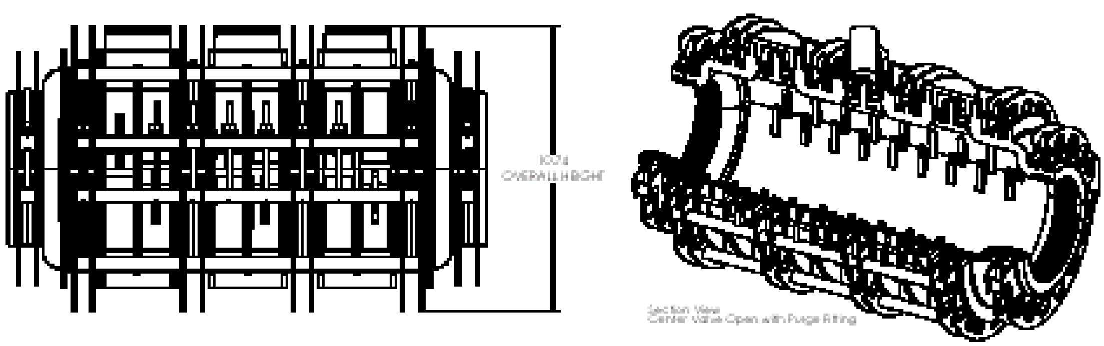

Figure 12: Schematic Illustration of the 2nd Generation Mechanical Repair Fitting – Front View and Cut-out

Results and Discussion

In essence, the mechanical repair fitting design consists of two half circular cylindrical parts that are hinged together. After they have encircled a pipe segment that has been damaged, these two parts can be mechanically fastened to each other to contain the damage. The repair fitting is not chemically bonded to the pipe. It is expected to stay in place by friction that is induced by tightening the bolts sufficiently that pressure is transmitted through compressed elastomeric rings at the ends of the sleeve. As these rings are the only portion of the sleeve that actually contact the pipe, there is an annular cavity between the inner wall of the fitting sleeve and the outer wall of the damaged portion of the pipe that is contained within the fitting body.

Because the mechanical repair fitting is intended to cope with the entire range of damage that can occur in service, the principal design challenge is the repair of a "blowing" failure; i.e., a through wall opening in the pipe wall through which pressurized gas escapes. Thus, the unique feature of the mechanical repair fitting is three axially-aligned holes that will allow gas to escape during the repair procedure. However, because the mechanical repair fitting is also intended for the repair of surface damage, a modified design is contemplated in which one hole will be used for a pipe wall puncture device. This would effectively equalize stresses exerted on the inner and outer pipe wall surfaces, thus eliminating the main driving force for SCG. While in principle a mechanical repair fitting equipped with a mechanism for puncturing the wall of a pipe with part through wall damage will be well protected against a long term SCG failure, good engineering design must consider the possibility that this portion of an installation procedure might be performed inadequately, or even neglected altogether. Accordingly, it is imperative for the MRS project to quantify the potential for axial direction SCG to occur in the repair of part through wall damage.

Conclusion

GTI, under the sponsorship of the DOE-NETL Contract: 03-NT41880.000 and utility sponsors, has been engaged in a program to design and develop a plastic pipe repair sleeve; a simple, mechanical device that can be installed on damaged (scratched / gouged) 4" polyethylene (PE) pipe under system operating pressure. An initial design concept has been developed. A program to perform comprehensive testing and evaluation in order to ensure conformity to current standards and codes has been outlined for the proposed design.

GTI recommends proceeding with prototype fabrication and subsequent testing. On the basis of the testing, GTI believes that the proposed design concept can be finalized, which meets the product definition requirements set forth at the onset of the program.

References

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2. M.F. Kanninen and C.H. Popelar, Advanced Fracture Mechanics. Oxford University Press, 1985: 23-24.

3. M.F. Kanninen et al. Brief Guide for the Use of Slow Crack Growth Test for Modeling and Predicting the Long-Term Performance of Polyethylene Gas Pipes. Southwest Research Institute report to the Gas Research Institute, 1993.

List of Acronyms and Abbreviations

PE	Polyethylene
ASTM	American Society for Testing and Materials
SCG	Slow Crack Growth
LEFM	Linear Elastic Fracture Mechanics
MRS	Mechanical Repair Sleeve
OD	Outer Diameter
ID	Inner Diameter
PA 11	Polyamide 11
GTI	Gas Technology Institute
K	Stress intensity factor
a	crack depth
c	one-half of the surface length of the crack
h	wall thickness
σ	remote tensile stress
ϕ	angle of penetration
K_D	Stress intensity factor
t_i	time required for SCG to be initiated
B	material constant
A	material constant
m	material constant