TECHNICAL REFERENCE REPORT
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COMPREHENSIVE DATA MODEL TO CHARACTERIZE LONG TERM INTEGRITY AND PROCESS PARAMETER INTERACTIONS GOVERNING THE BUTT FUSION PROCESS

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EXECUTIVE SUMMARY

The overall integrity of the plastic piping system is predicated on the long term strength of its weakest link which often occurs at fitting and joint interfaces, e.g. electrofusion, mechanical, heat fusion, etc. In order to maximize the overall joint strength, the process must effectively balance both the fabrication considerations and the resulting responses of the materials with actual in-service stress states.

In general, heat fusion joining[1] uses a combination of heat and force that results in two melted surfaces flowing together to make a joint. While seemingly straightforward, there are several factors/variables that can influence the overall strength and integrity of the joint including: ambient temperature, heater iron temperature, interfacial pressure, heating times, etc.

One of the critical points in optimizing the heat fusion process requires establishing quantitative limits (ranges) for the key process parameters – fabrication considerations. In the absence of stochastic events (operator error, procedural deviations, climatic influences, etc), the strength and integrity of the heat fusion joint is then a function of the respective thermal and mechanical limits (ranges) of these parameters, i.e. ***macroscopic conditions***.

Changes to the macroscopic conditions (thermal and mechanical) are manifested at the microscopic level which can lead to changes in the molecular orientation and thermophysical properties at the joint interface – response considerations. That is, given the viscoelastic nature of thermoplastics (non-linear response in terms of its viscous and thermal properties), changes in the macroscopic conditions can strongly influence the motion and mixing of the polymer at the joint interface, i.e. changes in the ***microscopic levels***.

In order to effectively characterize the impact of the changes at the molecular level, it is not simply sufficient to establish a battery of tests or codify a standardized procedure without a thorough understanding of the factors which can lead to failures in the short term and long term. To do this effectively requires some level of understanding of the complex thermal-fluidic interactions, the associated stress fields, and the material response that underlies the practical in-service performance of butt heat fusion joints.

Since 2007, NYSEARCH and TEJ with the support of the Department of Transportation have been performing comprehensive technical work to better understand the thermal and mechanical interactions governing the integrity of heat fusion joints. The overall program was performed in two independent phases. To promote an objective peer review of the technical data and provide technical guidance with respect to the overall step-by-step approach, a joint industry steering committee was established from the onset consisting of members from each of the respective stakeholder groups: gas utility companies, pipe/resin/equipment manufacturers, and regulatory staff.

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[1] References to heat fusion joining and butt heat fusion or butt fusion are being used interchangeably throughout the remainder of this document.

Phase I – Key Findings

The objective of the Phase I portion of the program was to better understand the thermal-mechanical interaction governing the heat fusion process noting the numerous variables and inherent complexities associated with the process. A hybrid approach of analytical modeling and experimentation was used.

The key findings from the Phase I program included:

- There is tremendous variability in the ranges for the key process parameters specified by various operators. However, regardless of the ranges for the respective process parameters, , the common practice is to utilize a visual approach for the melt bead width; while elsewhere in the world, quantitative limits are provided for the heating time.
- The cumulative results of the analytical models demonstrated that the melt depth penetration along the axial direction of the pipe is correlated to heating tme factor, ambient temperature, and pipe size.
- The results of standardized tests (short term tests and long term stress-rupture tests) cannot be used to quantify the impact of changes to process parameters but may have some meaningful uses as a quality control measures.
- The Whole Pipe Creep Rupture (WPCR) test is a potentially useful test to provide insight into integrity of heat fusion joints made in a parametrically controlled manner.

While the results of Phase I helped to further the overall understanding and means of evaluating the strength and integrity of heat fusion joints, it was noted that additional work was needed. Specifically, there was a need to develop additional data to ensure the statistical reliability of the results. Leveraging this understanding, a comprehensive testing program was performed as part of the Phase II work using the design of experiments (DOE) structured approach.

Design of experiments is a useful statistical tool or approach to investigate a system or process using a series of structured tests that take into account planned changes to the inputs while measuring the response for the effects of these changes on a pre-defined output. By applying the DOE approach, a single experimental test matrix was established. Representative joint specimens were made under parametrically controlled conditions by Southern California Gas Company (SoCal) and were subjected to whole pipe creep rupture testing at The Welding Institute (TWI) in the United Kingdom.

The key findings from the Phase II efforts include:

- There are strong interactions two-way interactive affects between respective fusion process variables.
- The data demonstrates that the overall fusion process can be optimized by establishing distinct limits for the respective fusion process variables. Most important finding from this study is that the heater iron temperature needs be

oriented towards higher heater iron temperature ranges. In addition, the results demonstrate that interfacial pressure has a second order influence on the overall strength and integrity of the joint – a point which was also observed in the Phase I portion of the program.

In a cumulative sense, the overall results of the Phase I and Phase II portion of this program have helped to further the understanding of the interactive effects governing the heat fusion process and established statistically significant quantitative ranges for key heat fusion process parameters.

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SECTION 1
INTRODUCTION AND BACKGROUND

By definition, thermoplastic materials are materials that soften upon heating and re-harden upon cooling. This characteristic allows for joining thermoplastic materials by various means including heat fusion, saddle heat fusion, and electrofusion.

Heat fusion joining[2] uses a combination of heat and force that results in two melted surfaces flowing together to make a joint. Typically, the heat fusion joining process consists of the following steps:

1. Cleaning, Facing, and Aligning the pipe ends to be joined
2. Melting the two pipe ends at a prescribed heater iron temperature
3. Joining the two profiles together under a specified interfacial pressure
4. Maintaining the joining pressure while the joint is allowed to cool and solidify

While seemingly straightforward, there are several factors/variables that can influence the overall strength and integrity of the joint including:

- Ambient Temperature
- Heater Iron Temperature
- Interfacial pressure or joining force
- Heating time / Cooling time
- Joining surface condition (alignment, contamination free, no visible cracks, etc)

In general, if the relationship between the joining conditions and joint quality can be established through meaningful litmus test(s), then the allowable tolerances or deviations within the quantitative limits for the respective butt heat fusion process parameters can be reasonably established. This in turn would result in an optimized set of butt heat fusion process (thermal and mechanical) which can consistently produce high quality heat fusion joints in the field.

Since 2007, NYSEARCH and TEJ have been performing comprehensive technical work to better understand the thermal and mechanical interactions governing the integrity of heat fusion joints in order to establish the necessary foundations or criterion for the continued development of advanced NDE technologies in a phased approach. From the onset, to promote an objective peer review of the technical data and provide technical guidance with respect to the overall step-by-step approach, a joint industry steering committee was established from the onset consisting of members from each of the respective stakeholder groups: gas utility companies, pipe/resin/equipment manufacturers, and regulatory staff.

[2] References to heat fusion joining and butt heat fusion or butt fusion are being used interchangeably throughout the remainder of this document.

Given the numerous variables and inherent complexities associated with the heat fusion joining process, the objective of the Phase I portion of the overall program was to utilize a hybrid approach consisting of analytical modeling and experimentation (short term and long term) to analyze the interactions for the respective fusion process parameters and evaluate the efficacy of various short-term and long-term tests to characterize the long term strength of butt fusion joints subjected to combined loading while in-service.

Leveraging the understanding from Phase I, the objective of Phase II was to develop a statistical data model for the butt fusion process taking into account various process parameters of interest using a novel test methodology (i.e. whole pipe creep rupture test) as a measure of long term strength. The remainder of this report presents a summary of the key finding from the Phase II portion of the program.

SECTION 2
DESIGN OF EXPERIMENTS (DOE) MODEL – PHASE II

2.1 Design of Experiments - Overview

Design of experiments is a useful statistical tool or approach to investigate a system or process using a series of structured tests that take into account planned changes to the inputs while measuring the response for the effects of these changes on a pre-defined output. That is, DOE is a formal way of gaining insight into the interactive effects of key process variables which could impact the final desired response.

To illustrate, for a complex process with multiple variables, simple parametric testing to evaluate the impact of changes of one variable at time creates the risk that this variable may significantly impact the desired response; yet, changing another variable may alter the effects of the first (i.e. interactive effects). This may lead to erroneous conclusions and/or creating a test matrix that is entirely too complex to account for all possible interactive effects.

2.2 Design of Experiments - Technical Considerations

A key consideration at the onset was to construct a suitable DOE model which took into account the respective macroscopic parameters of interest in order to evaluate key interactive effects and provide a basis for optimizing the heat fusion process.

The central question was: what are the most suitable ranges for each key variable including heater iron temperature, heating time, and interfacial as a function of pipe grade and geometry over a range of ambient temperature conditions observed in the field? This pragmatic approach helped to establish technically sound limits for each parameter.

Based on a review of historical guidance and existing practices, the suitable ranges for the key process parameters of interest (inputs to the DOE model) were established as shown in Table 1 below.

Parameter	Range
Heater Iron Temperature	400 – 500F
Ambient Temperature	0 – 120F
Interfacial Pressure	60 – 90 psi
Pipe Size	2-inch through 8-inch
Pipe Grade	PE2708 (Material A) PE4710 (Material B)
Heating Time Factor	3 – 12 times wall thickness

Table 1: Ranges for key process parameters used as inputs into DOE model

Using the ranges shown in Table 1 above, the final test matrix based on the DOE approach is shown in Table 2 below.

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
Run	Heating Iron Temperature	Ambient Temperature	Interfacial Pressure	Heating Time Factor	Pipe Size	PE Type
	F	F	psi	(x min. wall)	inches	
1	400	120	90	11	8	HDPE
2	500	60	60	12	8	HDPE
3	500	0	60	3	4	HDPE
4	500	120	60	12	8	MDPE
5	500	30	60	9	2	MDPE
6	450	80	60	3	4	MDPE
7	500	0	60	3	4	HDPE
8	400	120	60	3	8	HDPE
9	400	0	60	10	2	MDPE
10	500	30	60	3	8	MDPE
11	400	0	90	12	2	HDPE
12	400	120	90	11	8	HDPE
13	500	120	60	3	2	HDPE
14	400	120	60	11	4	HDPE
15	400	30	90	3	8	MDPE
16	400	90	90	8	4	MDPE
17	500	120	60	12	2	HDPE
18	450	40	90	5	8	HDPE
19	500	0	90	12	2	HDPE
20	450	120	90	12	2	MDPE
21	400	0	60	10	2	MDPE
22	450	80	60	3	4	MDPE
23	450	0	90	7	4	MDPE
24	500	120	90	6	8	MDPE
25	450	60	60	12	8	MDPE
26	500	120	60	5	8	HDPE
27	400	30	60	4	2	HDPE
28	400	0	60	6	8	HDPE
29	500	0	90	12	4	MDPE
30	400	0	90	3	2	HDPE
31	400	0	90	10	8	HDPE
32	500	120	90	6	8	MDPE
33	500	0	90	3	2	MDPE
34	400	120	90	3	2	HDPE
35	400	120	60	7	2	MDPE
36	500	80	90	7	4	HDPE

Table 2: Final test matrix based on DOE approach

SECTION 3
WHOLE PIPE CREEP RUPTURE TESTING – PHASE II

3.1 EXPERIMENTAL APPARATUS

Under the whole pipe creep rupture test, the heat fusion joint is subjected to a constant axial tensile load at an elevated temperature. The tensile load is applied to the test specimen via an internal push rod (Note: the design of the pipe loading apparatus is proprietary to TWI). This is shown schematically in Figure 1 below[3].

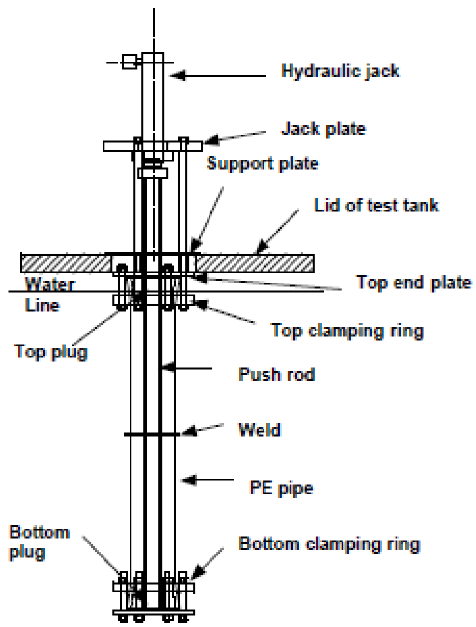

Figure 1: Schematic illustration of the whole pipe tensile creep rupture test by The Welding Institute (TWI), U.K.

In order to ensure that under the specified test specimen geometry and test condition, the specimens would be within the maximum extension of the hydraulic jack assembly, a series of preliminary screening tests were performed using both MDPE and HDPE materials.

After confirming the test set-up and test conditions, a series of iterative WPCR tests were performed on the actual samples per the DOE model (See Table 3 above) that were fabricated at Southern California Gas Company (SoCal). The results of the testing were consistent with expectations, i.e. the WPCR test was a useful test to quantify the impact of changes to key heat fusion process parameters with failure times ranging between 0.1 hours to greater than 5000 hours.

[3] Troughton, M. Scandurra, A. "Predicting the long term integrity of butt fusion joint in polyethylene pipes", 17th International Plastic Fuel Gas Pipe Symposium, San Francisco, October 2002

Representative illustrations of the brittle-like facture surface for selected specimens are presented in Figures 2-4 below.

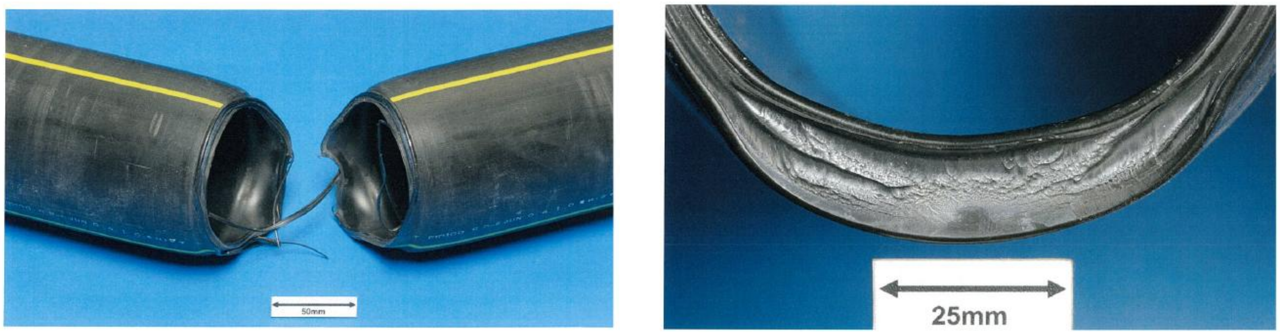

Figure 2: Failed sample and fracture surface for Run 7

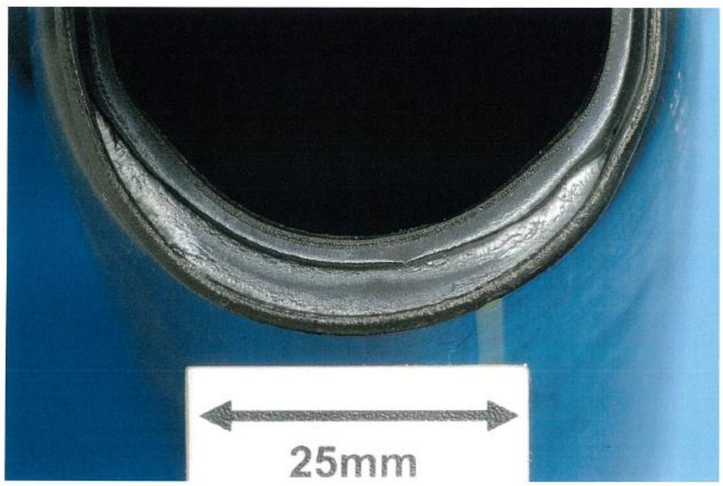

Figure 3: Image of fracture surface for Run 27.

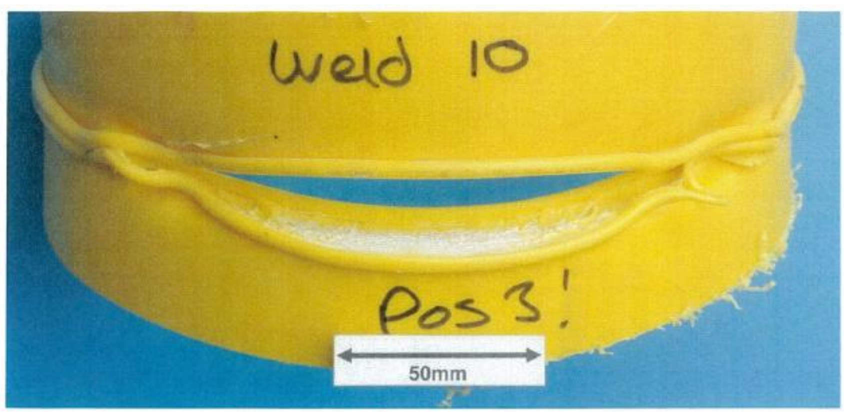

Figure 4: Failed specimen and fracture surface for Run 10

SECTION 4
ANALYSIS AND DISCUSSION – PHASE II

Test of Statistical Significance and Analysis of Variance (ANOVA) Results

A reduced quadratic model was fit to the empirical data in term of the control factors, linking changes in the key process variables including heater iron temperature, ambient temperature, heat time factor, pipe size and material type to changes in the time to failure data. The resulting quadratic model reveals strong non-linear effects relative to heater iron temperature and pipe size. In addition, the model also reveals interactions between material type pipe grade with ambient temperature, and pipe grade and heating time factor. A few key points of emphasis from the ANOVA results:

- The Model F-Value of 6.03 (p-value = 0.0001) implies that the **model is statistically significant.** This implies that there is only a 0.01% chance that a Model F-Value this large could occur due to noise.
- The “Pred R-Squared” value of 0.3832 is in reasonable agreement with the Adj. R-Squared value of 0.5640.
- The “Adeq Precision” measures the signal to noise – ratios greater than 4 are desirable. For our case, the ratio was equal to 9.212 indicating that the model can be used to navigate the design space.

In order to evaluate whether or not the model is doing an acceptable job of predicting the observations, a “predicted vs. actual” plot was developed as shown in Figure 5 below. This plot shows the relationship of the observations (Y axis) to the predictions from the fitted model (X axis). If the data points on the plot converge (cluster) around the 45 degree trend line, then it can be reasonably inferred that the model is doing an acceptable job of predicting the observations.

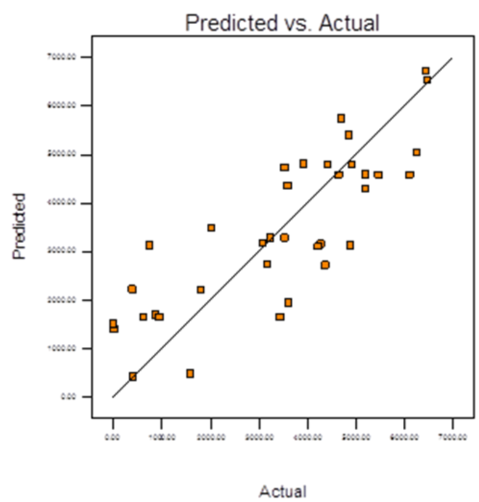

Figure 5: Predicted vs. Actual plot

From Figure 5, it is observed that the DOE model used as part of this effort does an acceptable job of predicting the observations. The data points are mode closely clustered around the 45 degree trend line.In addition to the prediceted vs. actial plot, an "externally studentized residual plot" was developed as shown in Figure 6 below. This plot provides the ability to detect outliers in the data.

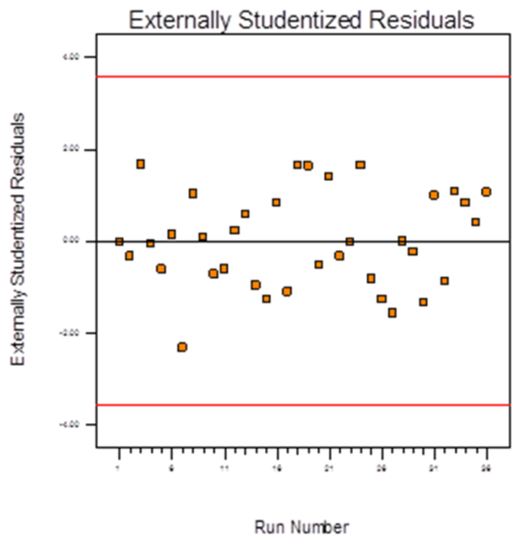

Figure 6: Externally studentized residual plot

From Figure 6, it is observed that that the data model is explaining changes in the response. In general, the externally studentized residual plot helps to detect outliers in the data, i.e. points that are outside the red lines. For our particular model, it is observed that all of the points are between the red lines and the model can be used to explain the changes in the response.

In order to illustrate these respective interactions, a series of three-dimensional (3D) and surface contour plots were developed as shown in Figures 7-8 below.

Effects of Ambient Temperature as a function of Heating Time Factor and Heater Iron Temperature for MDPE and HDPE Materials

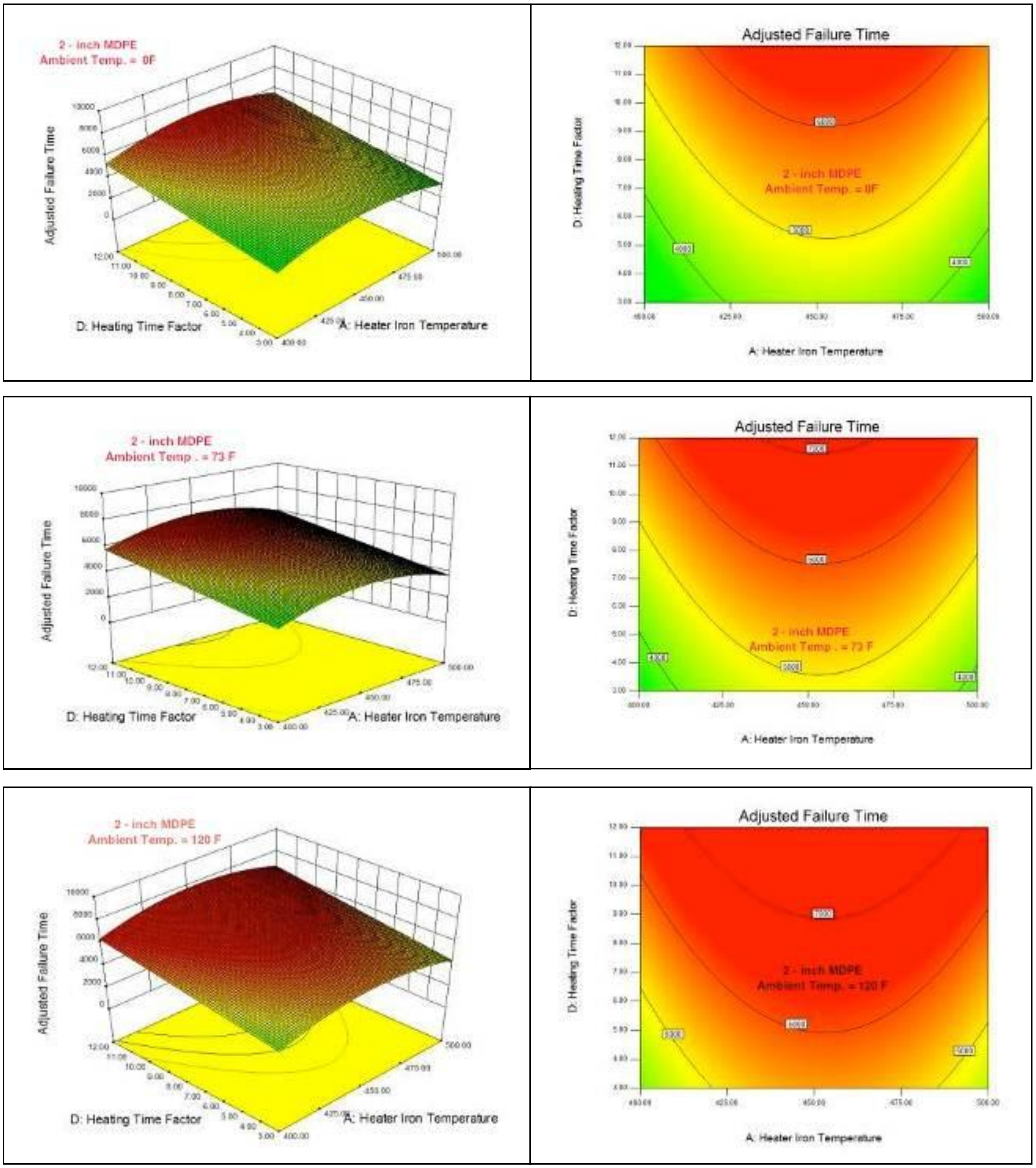

Figure 7: 3D and contour plots for 2-inch MDPE pipe

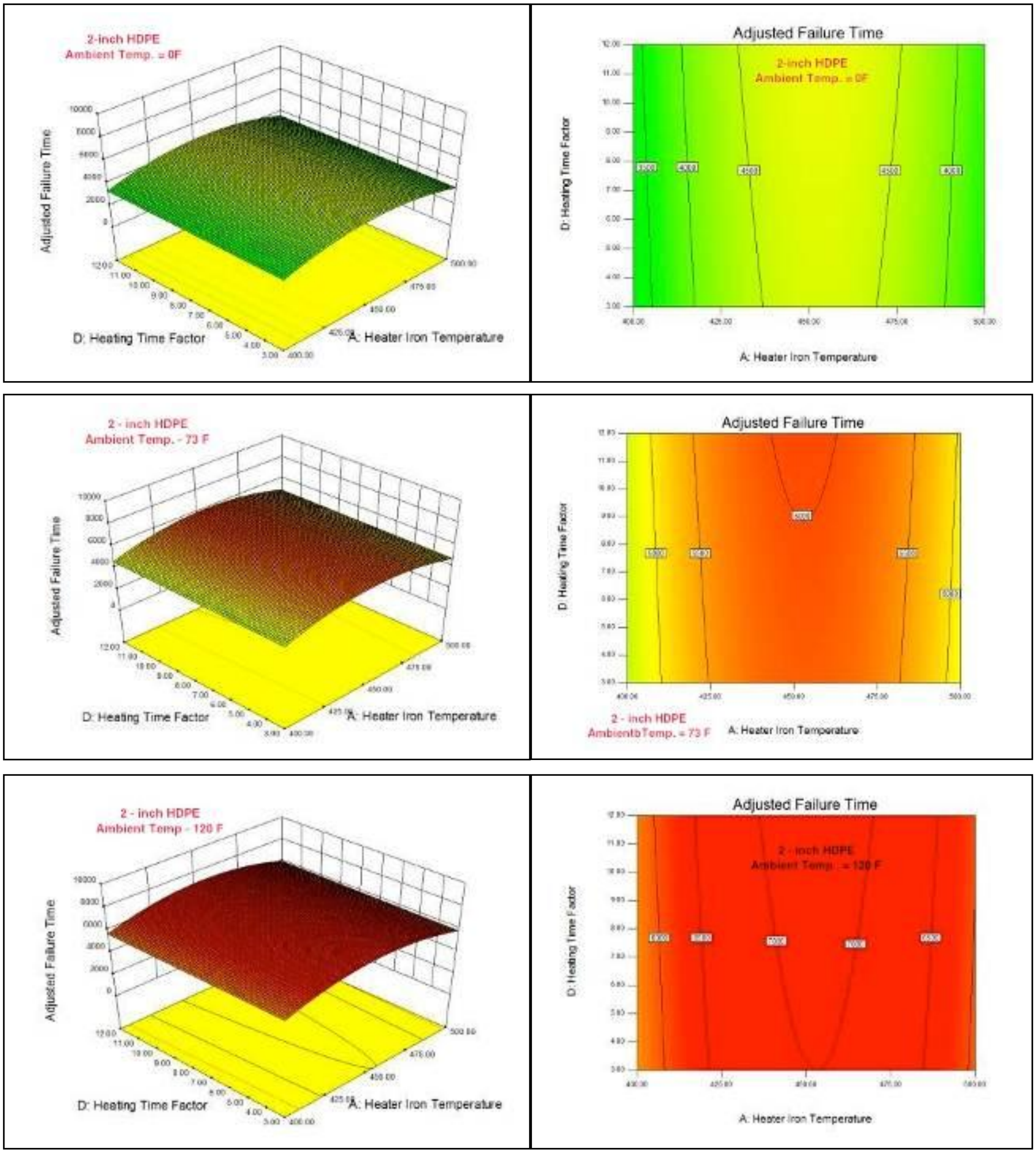

Figure 8: 3D and contour plots for 2-inch HDPE pipe

Putting it all together

In a cumulative sense, the data and the subsequent analysis models demonstrate the interactive effects among heater iron temperature, ambient temperature, and pipe grade.

Key points of emphasis include:

- The data demonstrates that in order to maximize the time to failure (alternatively, increased joint strength in a relative sense)
    - The heater iron temperature should be oriented towards higher heater iron temperature values that are between 450-490F.
    - The interfacial pressure range has limited impact on the overall strength and integrity of the subsequent joint. However, as shown in Phase I results of the program, operators should instruct their company personnel NOT to apply any force or pressure during the heating phase of the joining process. Applying some force to accelerate the formation of the bead can lead to cold fusion joints which may often pass visual inspection, but still result in a defective joint.

SECTION 5
SUMMARY AND CONCLUSIONS – PHASE II

A comprehensive program was undertaken by TEJ Group Inc. under the auspices of NYSEARCH and the Department of Transportation to characterize the long term performance of heat fusion joints as a function of changes to key process variables. To accomplish the intended program objectives, a phased approach was undertaken.

The key findings from the Phase I program included:

- There is tremendous variability in the ranges for the key process parameters specified by various operators. However, regardless of the ranges for the respective process parameters, , the common practice is to utilize a visual approach for the melt bead width; while elsewhere in the world, quantitative limits are provided for the heating time.
- The cumulative results of the analytical models demonstrated that the melt depth penetration along the axial direction of the pipe is correlated to heating tme factor, ambient temperature, and pipe size.
- The results of standardized tests (short term tests and long term stress-rupture tests) cannot be used to quantify the impact of changes to process parameters but may have some meaningful uses as a quality control measures.
- The Whole Pipe Creep Rupture (WPCR) test is a potentially useful test to provide insight into integrity of heat fusion joints made in a parametrically controlled manner.

The key findings from the Phase II efforts include:

- There are strong interactions two-way interactive affects between respective fusion process variables.
- The data demonstrates that the overall fusion process can be optimized by establishing distinct limits for the respective fusion process variables. Most important finding from this study is that the heater iron temperature needs be oriented towards higher heater iron temperature ranges. In addition, the results demonstrate that interfacial pressure has a second order influence on the overall strength and integrity of the joint – a point which was also observed in the Phase I portion of the program.

In a cumulative sense, the overall results of the Phase I and Phase II portion of this program have helped to further the understanding of the interactive effects governing the heat fusion process and established statistically significant quantitative ranges for key heat fusion process parameters.