INCREASING HDPE BUTT FUSION PRODUCTIVITY BY OPTIMIZING THE COOL TIME BASED ON THERMAL MASS CHARACTERISTICS WITHOUT COMPROMISING JOINT STRENGTH

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KEYWORDS

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ABSTRACT

High Density Polyethylene pipes are used in various applications due to the material's superior chemical resistance, pressure capability, and ductility. For the material to perform at the optimal design criteria, the connections and fabrications must be fused using repeatable procedures that specify proper fusion temperature, pressure, and process times that allow for the semi-crystalline structures to re-form to achieve appropriate material performance. With the growing acceptance of HDPE into markets dominated by traditional materials like steel, ductile iron, and PVC, improving job site productivity is a key objective to further demonstrating the benefit of using HDPE. Understanding the contribution of different parameters like heat time and ambient temperature is crucial to predicting when the joint has cooled adequately so the machine and operator may move to the next joint. The current industry standards using the single high force pressure method (ASTM F2620-13 and ISO 21307:2017 SHP) evolved from efforts to harmonize the welding procedures from multiple pipe producers and they are conservative given the expectation that the fusion operator must perform the fusion process consistently across a wide range of possible job site conditions. This paper explores the feasibility of accounting for applicable fusion parameters to accurately predict shorter cool times, therefore increasing jobsite productivity. It is recognized that any productivity improvements must not impair the mechanical performance of these joints, as measured by failure energy. This work demonstrates that the failure energy of the fusion joints remains constant whether cooled per the existing ASTM F2620- 13 standard, reducing the fusion cooling time under pressure, or by altering the cooling rate based on ambient temperature conditions.

INTRODUCTION

On job sites across many applications, owners, contractors and operators are seeking ways to improve productivity when building HDPE piping systems. The fusion process itself should be examined to determine if it can be optimized for increased productivity. Although significant productivity improvements have been offered by currently available fusion and pipe handling equipment, it is evident that a process that would reduce the specified heat fusion cool time could dramatically improve the overall productivity of the fusion operator. Existing commercial systems claim improvement in the productivity of the fusion process by reducing cool time through forced cooling but these performance and process variables are not well understood. Intuitively, heat soak time and cool time are two related factors, but there are other variables that affect the final cool time of the fused joint. Through many years of pipe fusion experience, reducing heat soak time can lead to sub-par fusion quality and thus was not investigated in this study.

Preliminary research demonstrates that the cooling time of an 18-inch DR 7 pipe could be reduced by up to 70% (as specified by ASTM F2620-13) without negatively affecting failure energy demonstrated by ASTM F2634-15. However, to accurately predict this reduced time to cool, it is imperative that the independent factors that affect cool time are fully understood.

This study is intended to explore 3 different areas of pipe fusion cooling:

- *Identify independent factors*: Identify independent factors that contribute to changing the cool time and quantify their contribution

- *Determining core temperature*: Determine appropriate temperature in the center of the wall of the fusion joint at which fusion cooling pressure may be released from the machine without negatively impacting joint strength
- *Accelerated cooling*: Quantify the cooling effects that external methods can have on the cooling rate of the joint core temperature

NOMENCLATURE

ASTM	*American Society for Testing and Materials*
HDPE	*High density polyethylene*
DR	*Diameter ratio*
ISO	*International Standards Organization*
SHP	*Single high pressure*

EXPERIMENTAL AND DISCUSSION

Tests were performed on PE 4710 high density polyethylene pipe (HDPE) 18 inches in diameter with two different wall thicknesses, DR 7 (2.5-inch wall thickness) and DR 32.5 (0.55-inch wall thickness). The internal core temperature of the fusion during the cooling process—defined as when the two pipe ends come together directly after the heating and open/close procedure defined by ASTM F2620-13— was determined by placing 8 thermocouples at 8 different locations around the circumference of the pipe, Figure 3. It was determined that the circumferential temperature gradient during the cool time of the fusion was homogenous, as shown in Figure 4, and mounting one thermocouple in the 12 o'clock position would simplify the measurement process for other tests in this study. This method of thermocouple mounting ensured the thermocouple remained in the center of the wall thickness during heating and cooling. A fixture, Figure 2, was used to drill a hole at an angle from the outside wall of the pipe to the inner face of the pipe end, as seen in Figure 1.

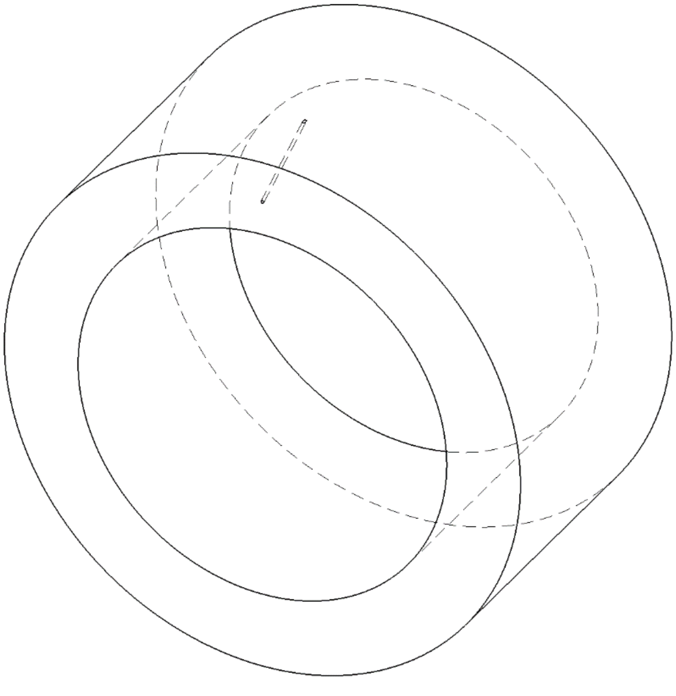

Figure 1 - Location of 12 o'clock position thermocouple

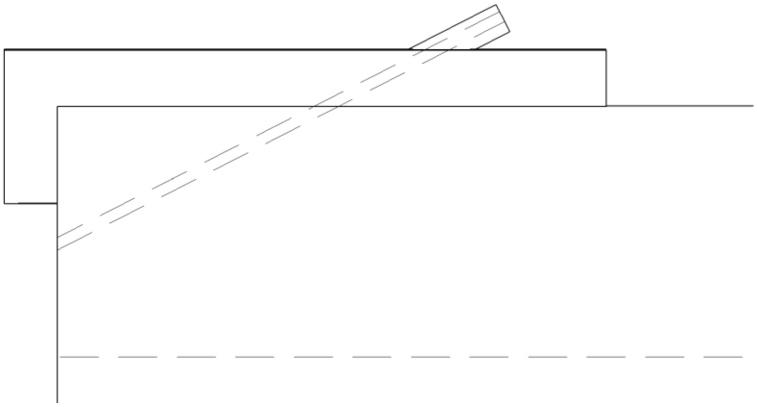

Figure 2 - Drill fixture

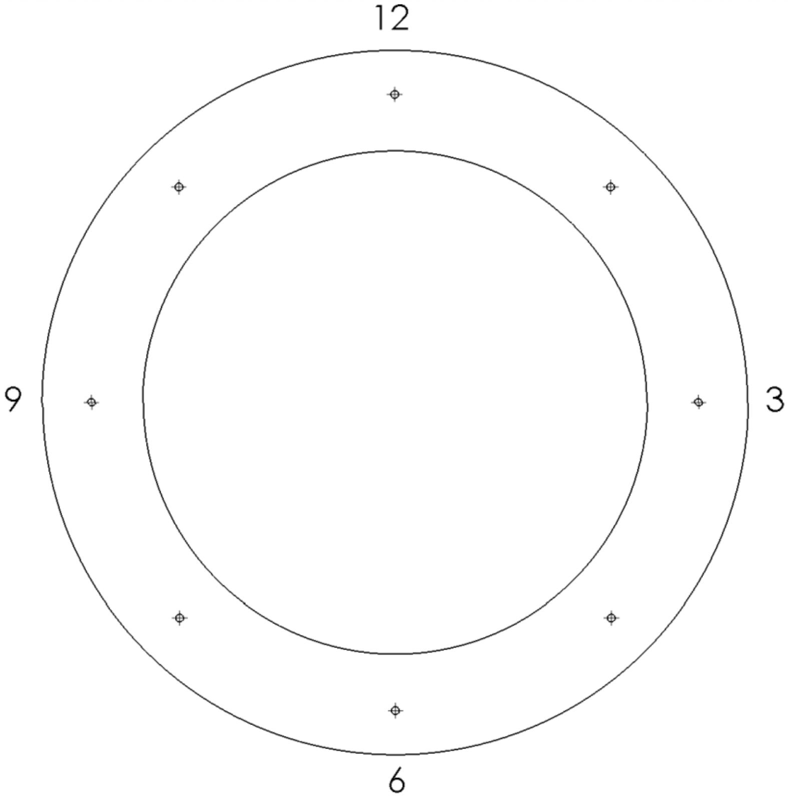

Figure 3 - Thermocouple measurement points

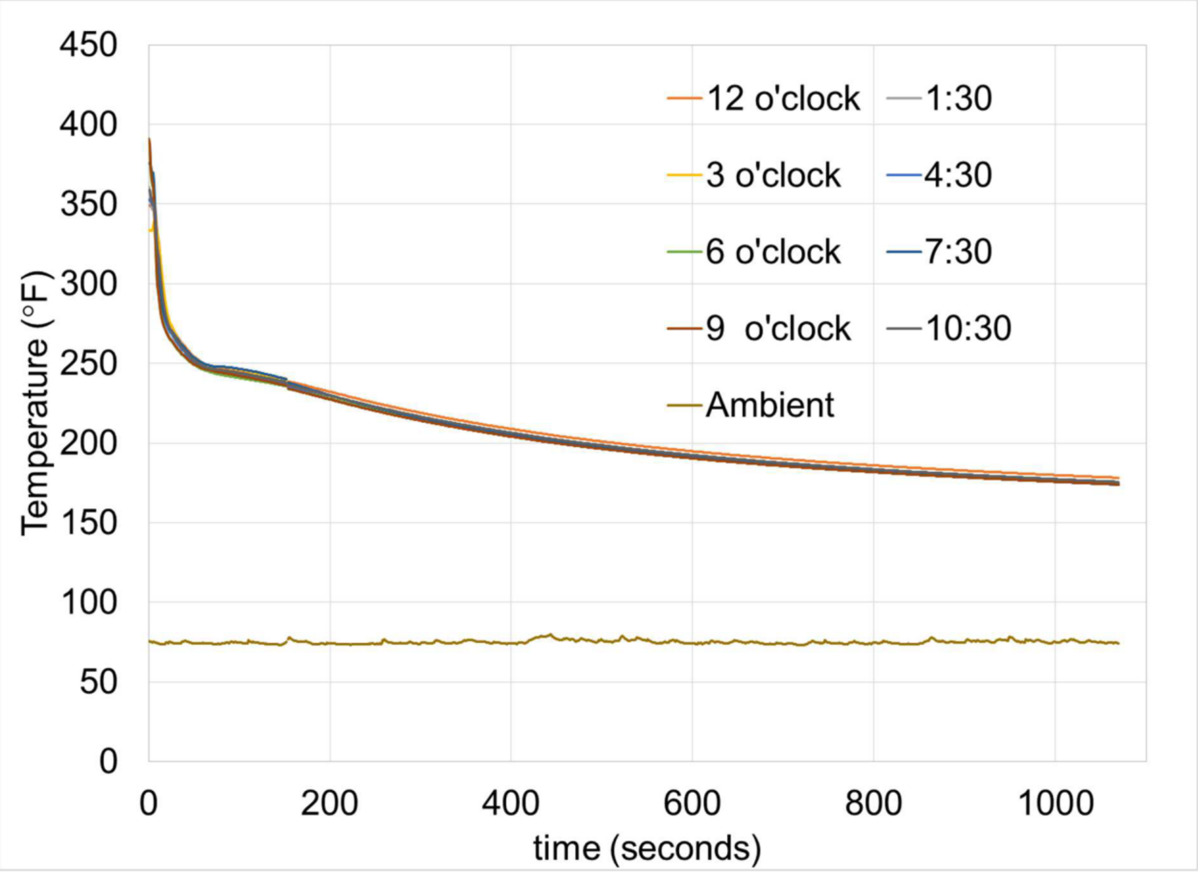

Figure 4 – Cooling test with 8 thermocouples around circumference

Identify independent factors

Intuitively, factors that could significantly affect the joint core temperature of the pipe during the fusion cooling cycle are the heater temperature, the heat soak time, the open/close time during the joining process, ambient temperature, the diameter of the pipe, and the wall thickness of the pipe. For this work, two factors are quantified. In particular, the wall thickness and the ambient temperature.

For factors such as heat time and heater temperature the ASTM F2620-13 standard was followed explicitly for the pipe size and wall specification tested. Open/close times across all tests were consistent and were achieved in approximately 50% of the time specified by ASTM F2620-13. The interfacial pressure of 75-psi was used in this study, to reflect generally used field practice.

The ASTM F2620-13 standard directly addresses wall thickness having an effect on the cooling rate of HDPE by specifying a cool time solely based on the pipe wall thickness, 11 minutes per 1-inch of wall thickness. Both ASTM F2620-13 and ISO 21307:2017 SHPspecify that an increased cool time should be considered when working in high ambient temperatures. However, both standards fail to stipulate what additional time should be added to the procedure. The testing in this study performed fusions in three different ambient temperature ranges to determine the maximum and minimum cooling rates experienced in in-field applications, 40°F (4°C), 70°F (21°C), and 120°F (49°C). These temperatures were achieved by use of a temperature controlled environmental chamber, with the pipe sections and fusion equipment fully conditioned at the set point temperature prior to beginning the fusion process.

See Table 1 for the test matrix used for this portion of the testing. Table 2 and Table 3 show the fusion parameters that were used in this study and will be referred back to later in the paper.

Table 1 - Cooling tests specimen matrix

Pipe size	Ambient temperature
18-inch DR 7	40°F (4°C)
	70°F (21°C)
	120°F (49°C)
18-inch DR 32.5	40°F (4°C)
	70°F (21°C)
	120°F (49°C)

Table 2 - Fusion parameters for 18-inch DR 7 pipe according to ASTM F2620-13

Description	Ambient Conditions during test		Average heater temperature		Interfacial pressure - bar (psi)		Heat soak time (seconds)	Open/close time (seconds)
	°C	°F	°C	°F	bar	psi		
ASTM specifications for 18-inch DR 7			204-232	400-450	5.2	75	694	25
Standard fusion with 8 thermocouples	24	74	211	412	5.2	75	697	3
Standard fusion	22	71	216	421	5.2	75	700	5
High ambient fusion	49	119	213	416	5.2	75	696	8
Low ambient fusion	6	43	217	423	5.2	75	698	5
1 minute hold during cool	21	69	210	411	5.2	75	697	7
Fusion cooled by ice water	26	79	213	415	5.2	75	698	10

Table 3 - Fusion parameters for 18-inch DR 32.5 pipe according to ASTM F2620-13

Description	**Ambient Conditions during test**		**Average heater temperature**		**Interfacial pressure - bar (psi)**		**Heat soak time (seconds)**	**Open/close time (seconds)**
	°C	**°F**	**°C**	**°F**	**bar**	**psi**		
ASTM specifications for 18-inch DR 32.5			204-232	400-450	5.2	75	149	15
Standard fusion	23	73.9	214	417	5.2	75	153	6
High ambient fusion	48	118.1	214	417	5.2	75	152	9
Low ambient fusion	6	42.3	216	420	5.2	75	152	7
1 minute hold during cool	21	70.4	217	422	5.2	75	151	7

Determining core temperature during fusion

Knowing that ambient temperature has a significant effect on cool time, these tests were performed at 40°F (4°C), 70°F (21°C), and 120°F (49°C). Figure 5 and Figure 6 show the cooling curves for the two different pipe sizes shown in Table 1.

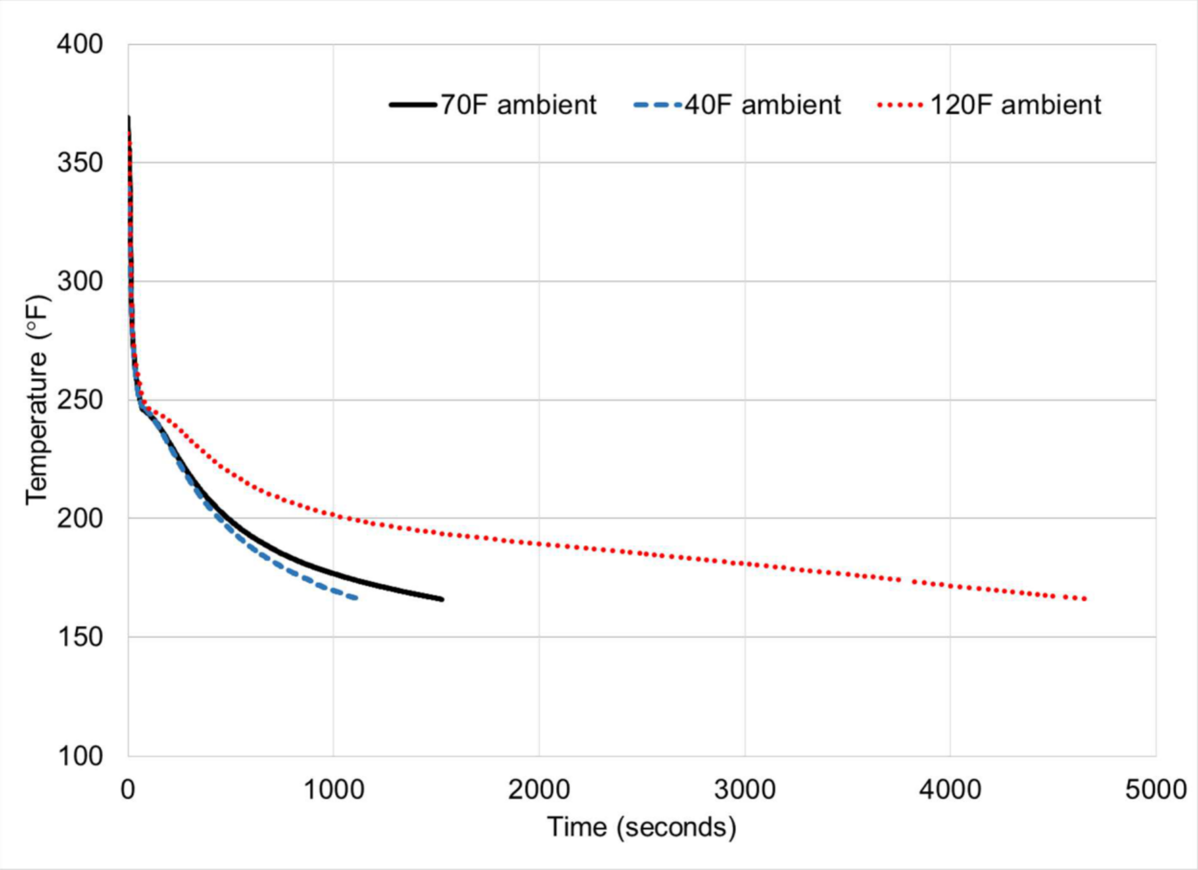

Figure 5 - 18-inch DR 7 cooling curves at various ambient temperatures

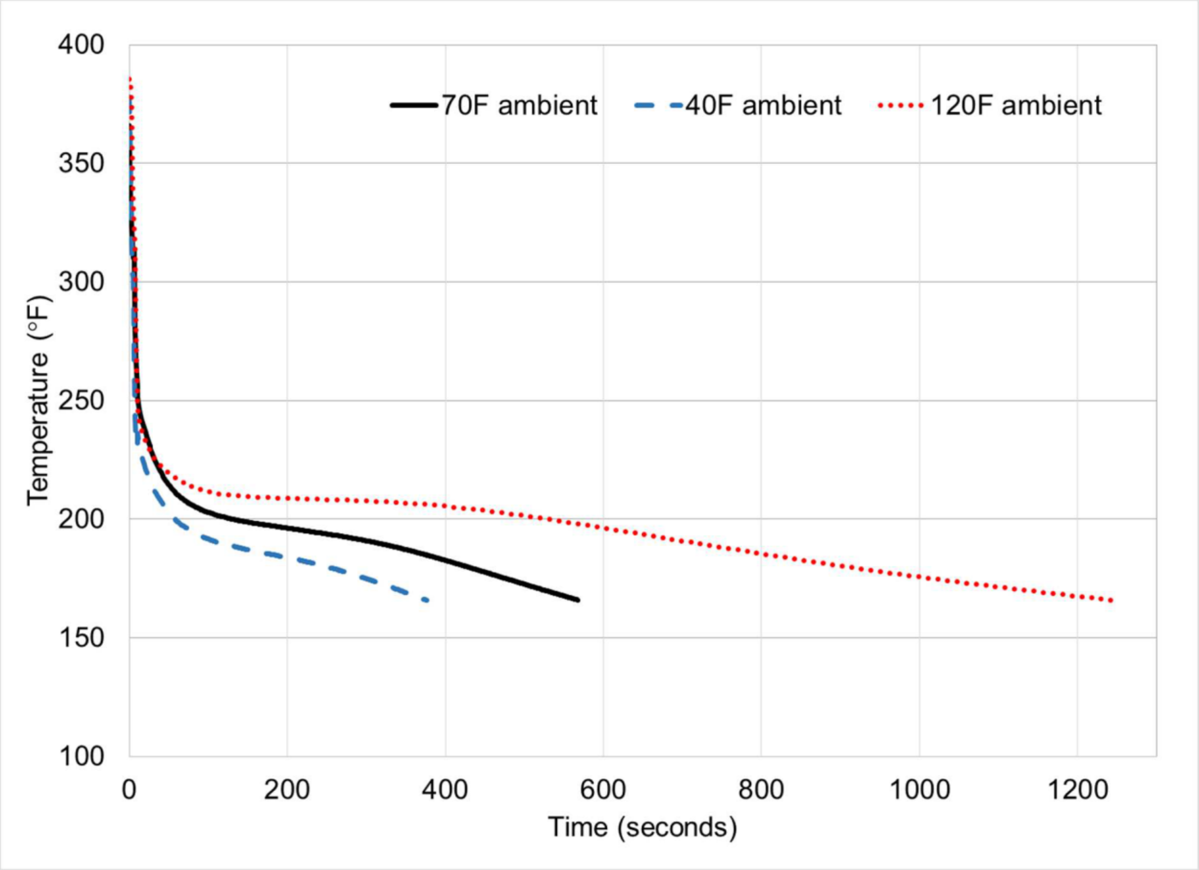

Figure 6 - 18-inch 32.5 cooling curves at various ambient temperatures

Consistent across all tests and as shown in Figure 5 and Figure 6, there was a rapid initial temperature drop immediately following the butt fusion, down to approximately 245°F (118°C) for the DR 7, and 190°F-220°F (88°C-104°C) for the DR 32.5. Beyond this point, the cooling rate slows significantly. This "elbow" in the cooling curve can be attributed to the recrystallization of the material as the polymer cools below the VICAT temperature range. The bulk of the recrystallization occurs around this point, below which the material completes the transition from a soft melt back to a solid. Below this "elbow," ambient temperature conditions do affect the remaining cooling rate of the pipe. For both the 18-inch DR7 and 18-inch DR 32.5 tested in this study, the time for the core joint temperature to cool to 200°F (93°C) roughly doubles when increasing the ambient temperature from 70°F (21°C) to 120°F (49°C).

It was theorized that as long as yielding stresses are not applied by means of handling the joint below this "elbow" in the cooling curve, the interfacial pressure can be released. To test this theory, joints were made according to ASTM F2620-13 specifications, except the cool time at fusion pressure was lowered to one minute. After one minute of being held at fusion pressure, the pressure was released, the jaws unclamped, and the pipe allowed to continue to cool under no additional pressure. Figure 7 and Table 4 show the cooling curves and the strengths for these one-minute cool time under pressure specimens. Destructive tests shown in Table 4 were performed after all joints were prepared and conditioned according to ASTM F2634-15 – Laboratory Testing of Polyethylene (PE) Butt Fusion Joints using Tensile-Impact Method.

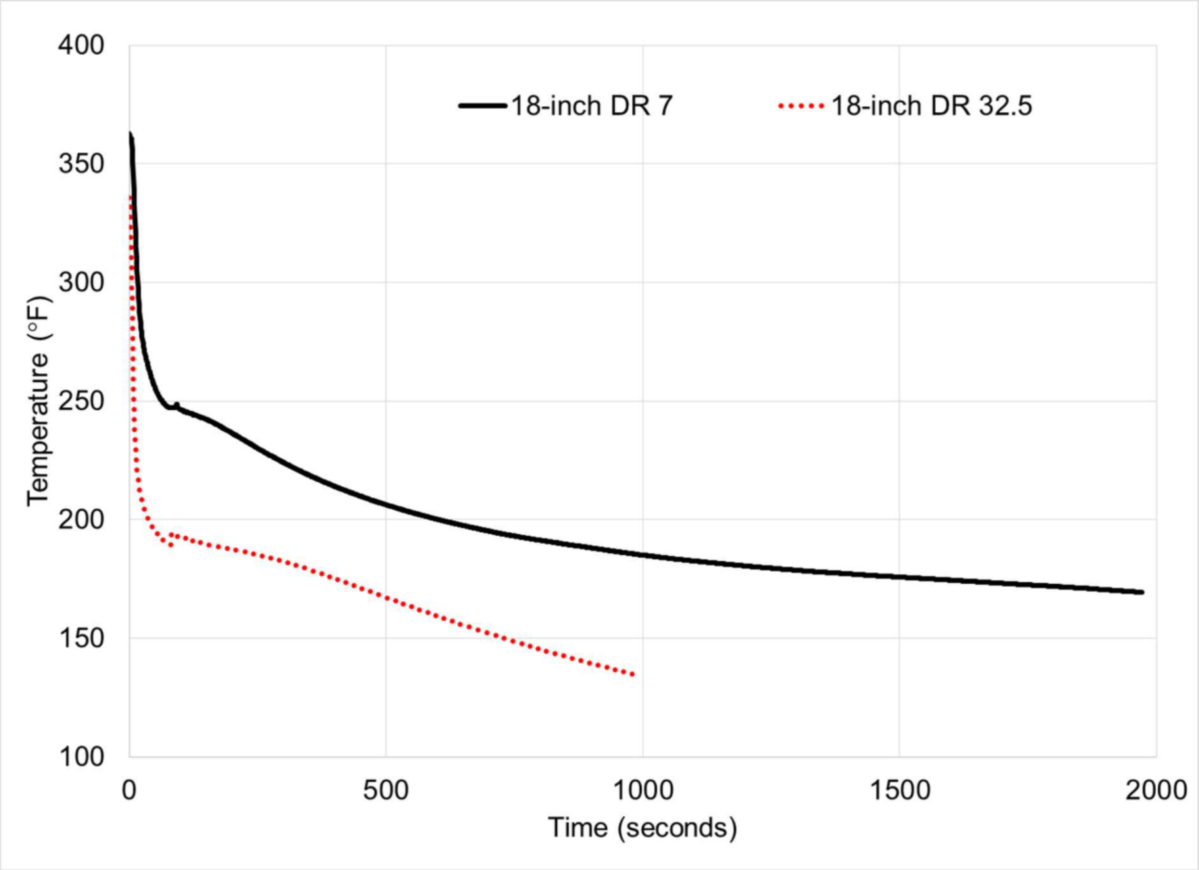

Figure 7 - Cooling curves for 18-inch DR 7 and DR 32.5 held at fusion pressure for one minute of cool time

Table 4 – ASTM F2634 failure energy and temperature values for joints held at fusion pressure for 1 minute of the cool cycle

Pipe size	Ambient temperature °F (°C)	Joint failure energy compared to the standard fusion joint failure energy	Approx. internal joint temperature at pressure release °F (°C)
18-inch DR 7	70 (21)	108%	251 (122)
18-inch DR 32.5	69 (20)	109%	192 (89)

In Table 4, the strength values of the joints cooled for one minute before releasing the interfacial pressure show that there is no reduction in failure energy by reducing the interfacial pressure during the cooling phase of the fusion. The DR 7 pipe achieved 108% of the standard fusion failure energy, and the DR 32.5 pipe achieved 109% of the standard fusion's failure energy. While the joints that were cooled for one minute demonstrated slightly higher failure energy than the standard fusions, the results between the one minute cool and full ASTM time cool are statistically the same. On the jobsite, the joint would be expected to be handled under normal handling conditions, which means avoiding rough handling that would add undo bending or tensile stresses to the fusion joint. The release of interfacial pressure does not have a negative effect on the failure energy of the joint according to ASTM F2634 tests. According to Striplin 2010, the pipe strength at this elevated temperature is approximately 41% of the fully cooled strength which is 51% of the fully cooled strength. It is noted that very little joint strength is gained when allowed to cool for the full ASTM specified cool time.

For this study, normal pipe handling would be considered:

- Elevating the pipe above the lower jaws of the machine with the pipe lifts fitted to the machine;
- Pulling the pipe horizontally with support provided by pipe stands and/or rollers downstream of the machine per industry practice;
- Lifting the pipe on both sides of the joint so that the joint is supported but the machine is able to be removed;
- Using a pipe handling system that limits stresses to similar levels as the methods mentioned above.

For this study, rough handling would be considered:

- Lifting the pipe directly at the butt fusion thereby inducing bending stress directly on the joint;
- Pulling the pipe horizontally out of the machine without adequate support and allowing the fused section to fall to the ground.

Exaggerated fusion cooling tests

HDPE is a notoriously good insulator, which becomes more evident as the wall thickness increases. Figure 8 shows the joint core temperature of an 18-inch DR 7 pipe, cooled via two different methods: standard cooling according to ASTM F2620-13 and circulating ice water. The cooling rate of the joint cores are virtually the same, demonstrating that given the low thermal conductivity of HDPE, accelerated means for cooling the material are not effective in heavy wall HDPE pipes.

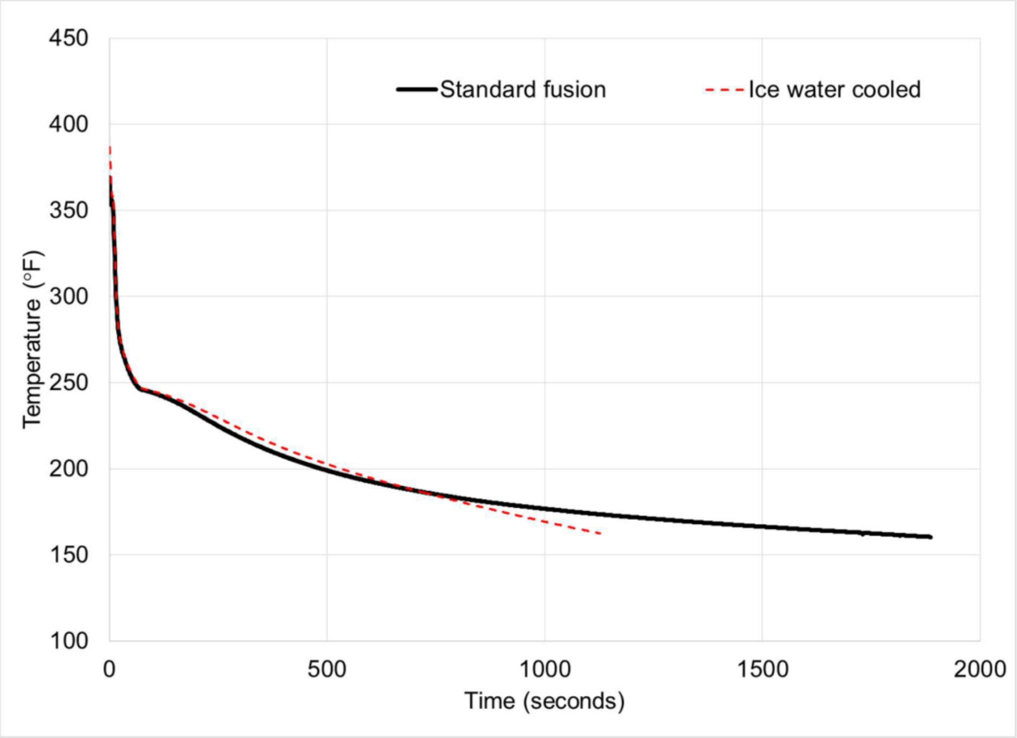

Figure 8 - Cooling curve of 18-inch DR 7

CONCLUSIONS

The following conclusions can be made about the research presented in this study.

- Ambient temperature and wall thickness have an effect on the overall cooling rate of the HDPE pipe.
- Tensile impact tests, according to ASTM F2634, indicate no change in the failure energy for joints cooled without an interfacial pressure applied for the full ASTM F2620-13 specified cool time.
- Given the insulative properties of HDPE, it is difficult to dramatically affect the joint core temperature of heavy wall HDPE pipe
- If factors like heater temperature, heat soak time, and ambient temperature can be evaluated (according to ASTM 3124-15, for example), the cool time can likely be significantly lowered from the ASTM F2620-13 specified time, based on the interdependencies of these variables.
- Normal and rough handling procedures can be defined as to limit the handling stresses and enable productivity

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ASTM F2634-15 – Standard Test Method for Laboratory Testing of Polyethylene (PE) Butt Fusion Joints using Tensile Impact Method

ASTM F3124-15 – Standard Practice for Data Recording the Procedure used to Produce Heat Butt Fusion Joints in Plastic Piping Systems or Fittings