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

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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 may move to the next joint. The current industry standards evolved from efforts to harmonize the welding procedures from multiple pipe producers and they are exceptionally conservative given the expectation that the fusion operator is expected to perform a manually controlled fusion process 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 productivity improvements that could impair the mechanical performance of these joints, as measured by failure energy is not acceptable. This work demonstrates that the failure energy of the fusion joints remain constant whether cooled per the existing standard, reducing the fusion cooling time under pressure, nor the different cooling rates caused by changes in ambient temperatures.

INTRODUCTION

On job sites across many applications, owners, contractors and operators are seeking ways to improve productivity when building HDPE systems. The fusion process itself should be examined to determine if it can be optimized for productivity.

Given the productivity offered by currently available fusion equipment it is evident that the specified heat soak time and fusion cool time are two significant aspects of the process that dramatically limit the overall productivity of the fusion operator.

Existing commercial systems claim improvement in the productivity of the fusion process but the performance and influencing process variables are not well understood. Intuitively, heat soak time and cool time are two related factors, but there are likely other variables that affect the final cool time of the fused joint.

Through many years of pipe fusion experience, reducing heat soak time often leads to sub-par fusion quality and 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. 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

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 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 largely homogenous, as shown in Figure 4, and mounting one thermocouple in the 12 o'clock position would help to simplify the measurement process for other tests in this study. This method of thermocouple mounting also helped to ensure the thermocouple stayed in the center of the wall 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.

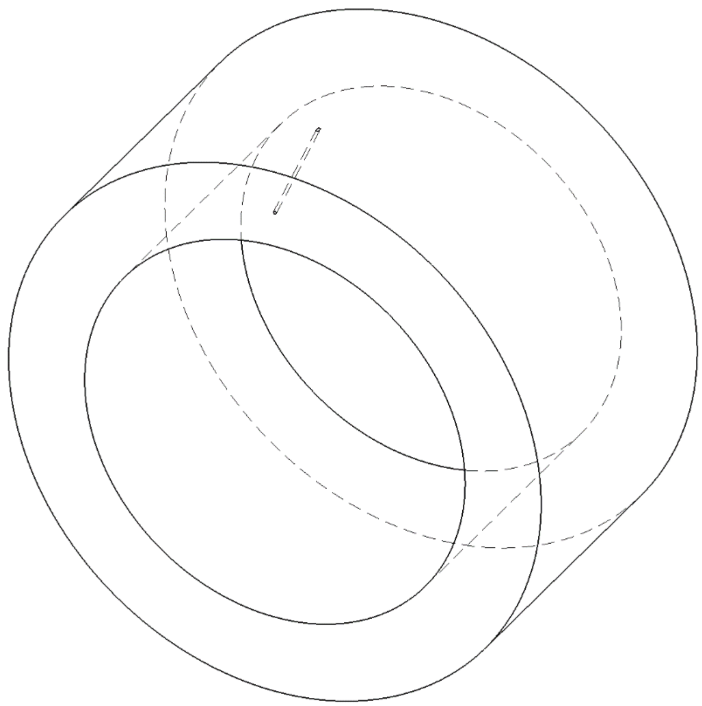

Figure 1 - Location of 12 o'clock position thermocouple

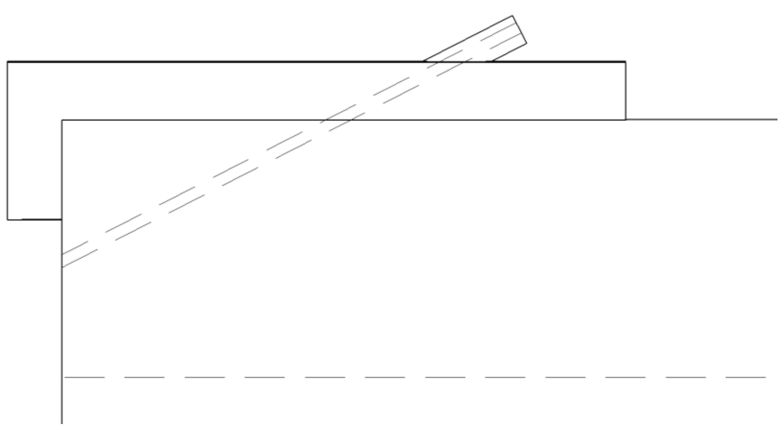

Figure 2 - Drill fixture

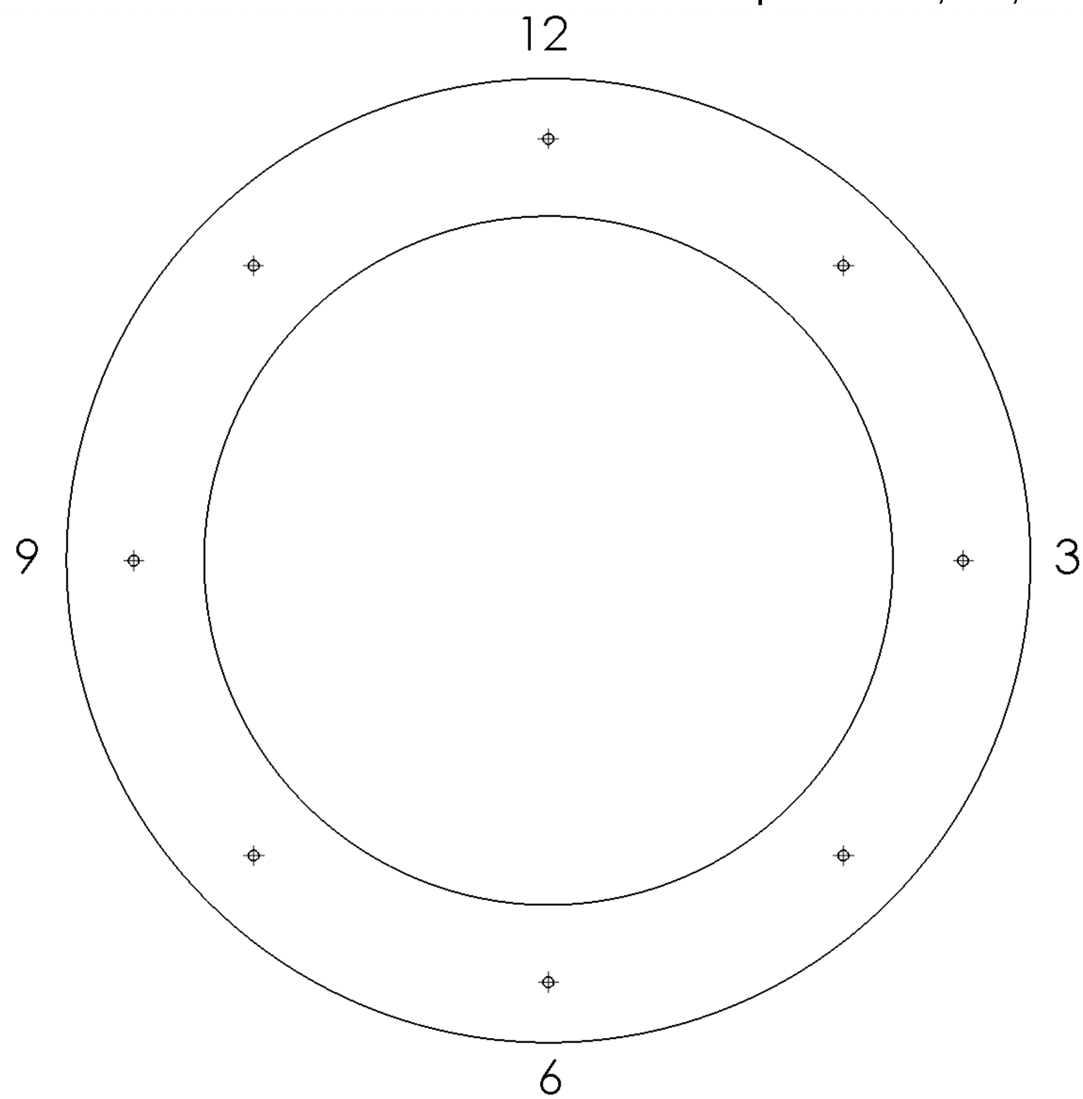

Figure 3 - Thermocouple measurement points

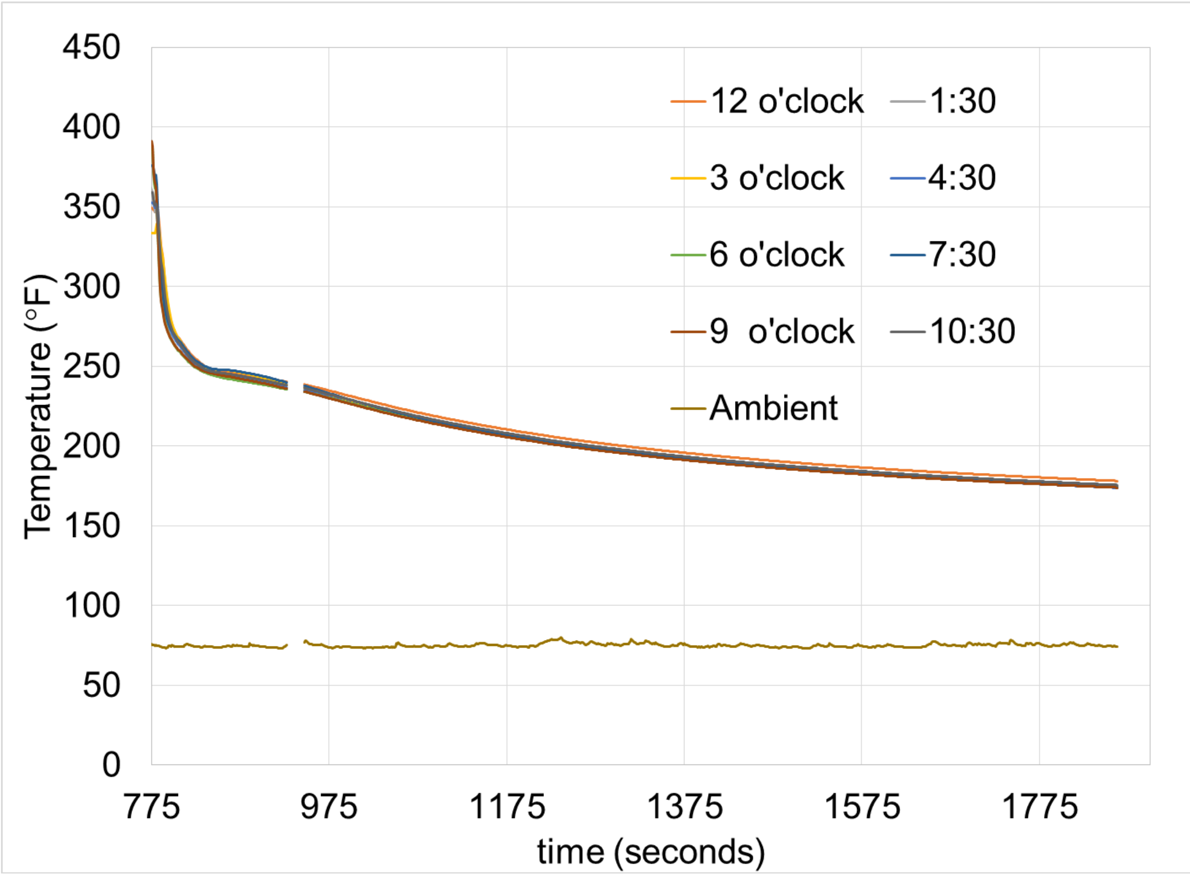

Figure 4 – Cooling test with 8 thermocouples around circumference

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 and bulk temperature of the pipe, and the wall thickness of the pipe. For this work, we quantify two factors 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 appropriate pipe size that was tested. Open/close time across all tests were consistent and was achieved in less than 60% of the time specified by ASTM F2620-13. The interfacial pressure of 75-psi was used in this study, to reflect general used 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, however, it does not address the effect of ambient temperature on the joint cooling. The ISO 21307, on the other hand, does address the ambient temperature effect by specifying an adjustment to the cool time based on ambient temperature. The testing in this study performed fusions in three different temperature ranges to determine the maximum and minimum cooling rates experienced in in-field applications, 4°C (40°F), 21°C (70°F) and 49°C (120°F). 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. See Table 1 for the test matrix used for this portion of the testing. Table 2 and Table 3 shows 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	(4°C) 40°F
	(21°C) 70°F
	(49°C) 120°F
18-inch DR 32.5	(4°C) 40°F
	(21°C) 70°F
	(49°C) 120°F

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

These fusions were performed according to the ASTM F2620-13 standard at approximately 21°C (70°F) ambient conditions. Specifics related to these tests are shown in Table 2 and Table 3. Knowing that ambient temperature has a significant effect on cool time, these tests were performed at 4°C (40°F), 21°C (70°F), and 49°C (120°F). Once the appropriate temperature measurement location has been established, the optimal internal core temperature before the pressure can be released and the pipe can be investigated. Cooling tests similar to the test shown in Figure 4 were performed on 18-inch DR 7 and 18-inch DR 32.5 on PE 4710 material. Figure 5 and Figure 6 show the cooling curves for the two different pipe sizes.

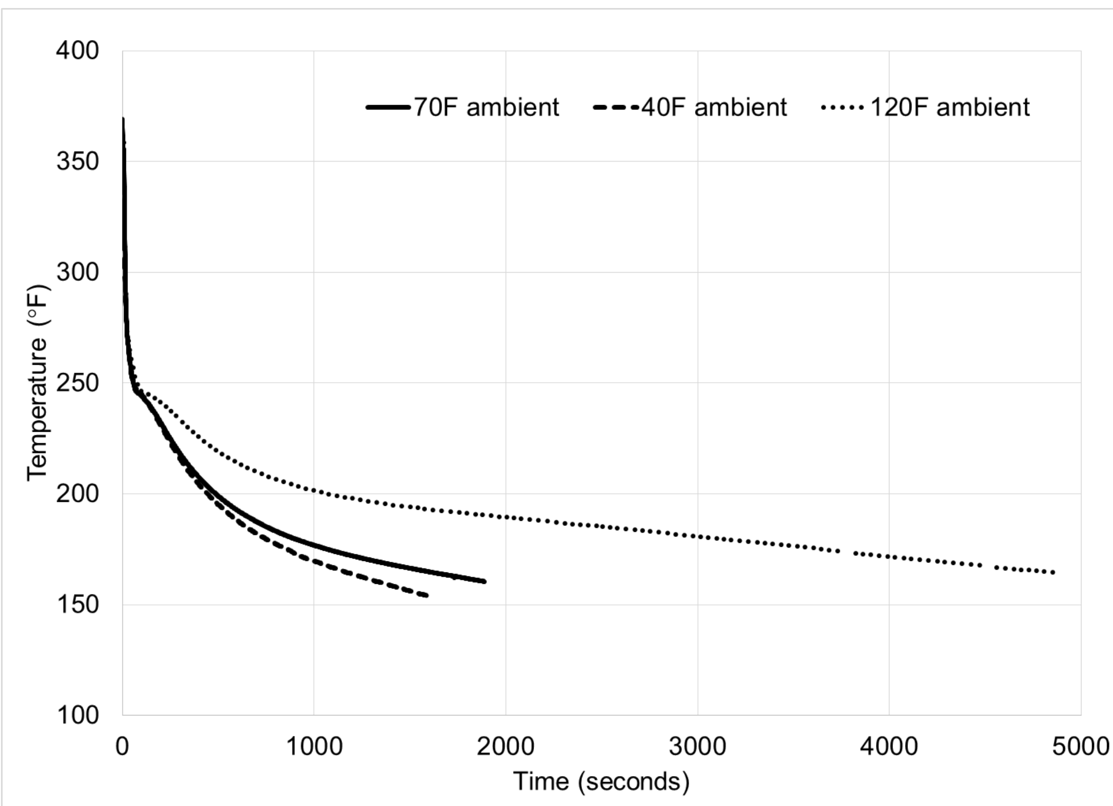

Figure 5 - 18-inch DR 7 cooling curves at various ambient temperatures

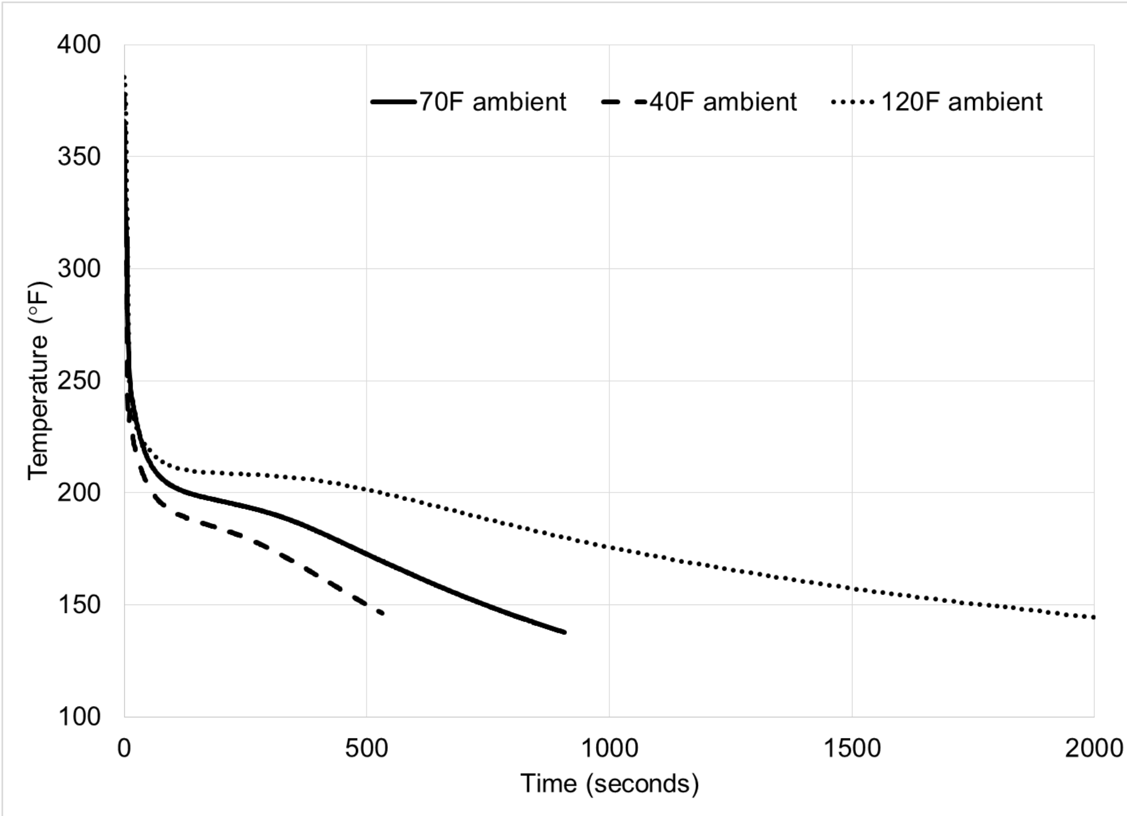

Figure 6 - 18-inch 32.5 cooling curves at various ambient temperatures

Consistent in 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 118°C (245°F) for the DR 7, and 88°C-104°C (190°F-220°F) 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 and the material is in the process of transitioning from a soft melt to a solid. Below this "elbow," ambient temperature condition 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 cooling time for core joint temperature roughly doubles when increasing the ambient temperature from 21°C (70°F) to 49°C (120°F).

It was theorized that as long as yielding stresses are not applied to 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 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.

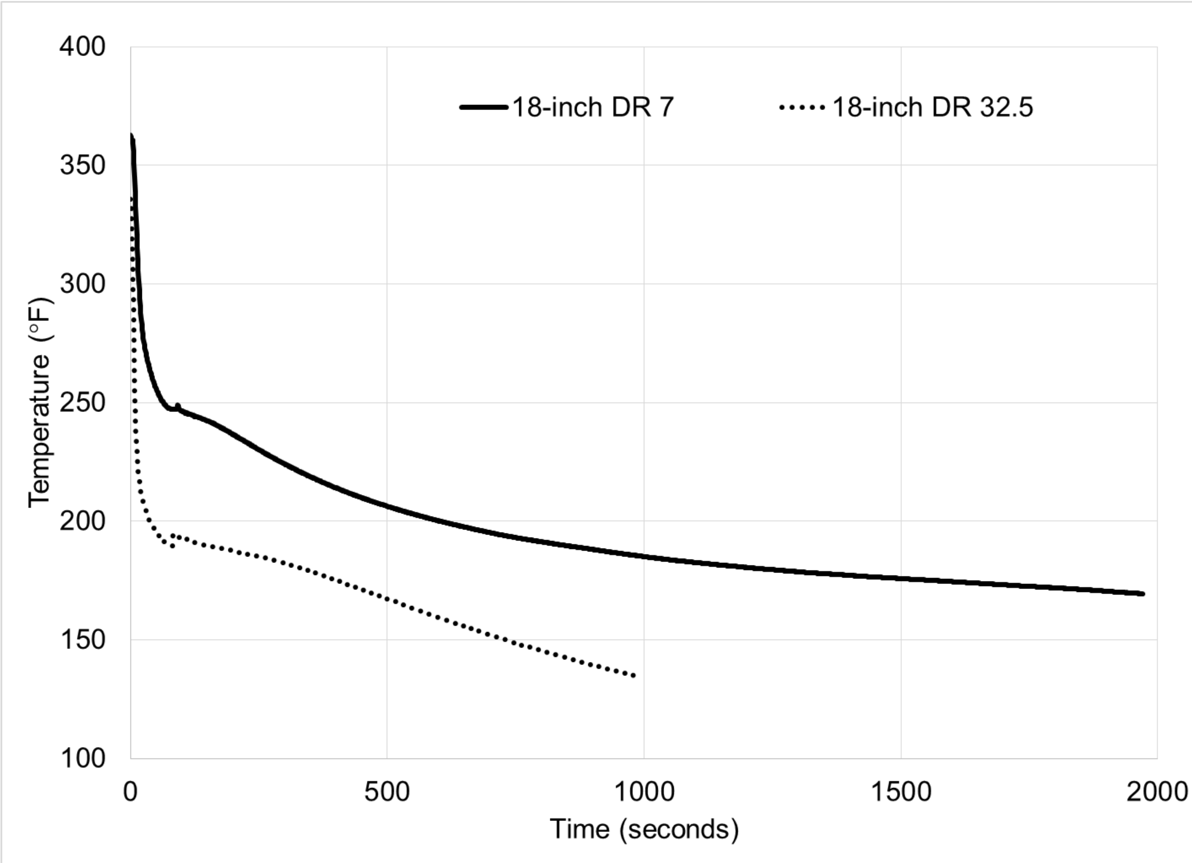

Figure 7 - Cooling curves for 18-inch DR 7 and DR 32.5 held at fusion pressure for one minute of cool time

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 °C (°F)	Joint failure energy compared to the standard fusion joint failure energy	Approx. internal joint temperature at pressure release °C (°F)
18-inch DR 7	21 (70)	108%	122 (251)
18-inch DR 32.5	20 (69)	231%	89 (192)

In Table 4, the strength values of the joints cooled for 1 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 231% of the standard fusion's failure energy. On the jobsite, the joint would be expected to be handled under normal conditions, avoiding rough handling because even though the release of interfacial pressure doesn't have a negative effect on the failure energy of the joint according to ASTM F2634, according to Striplin 2010, the strength at this elevated temperature is at about 40% of the fully cooled strength.

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 downstream of the machine provided by pipe stands or rollers;
- 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 concentrating the 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 these joints are virtually the same demonstrating that given the low thermal conductivity of HDPE, accelerated means for cooling the material are not effective in these heavy wall pipes.

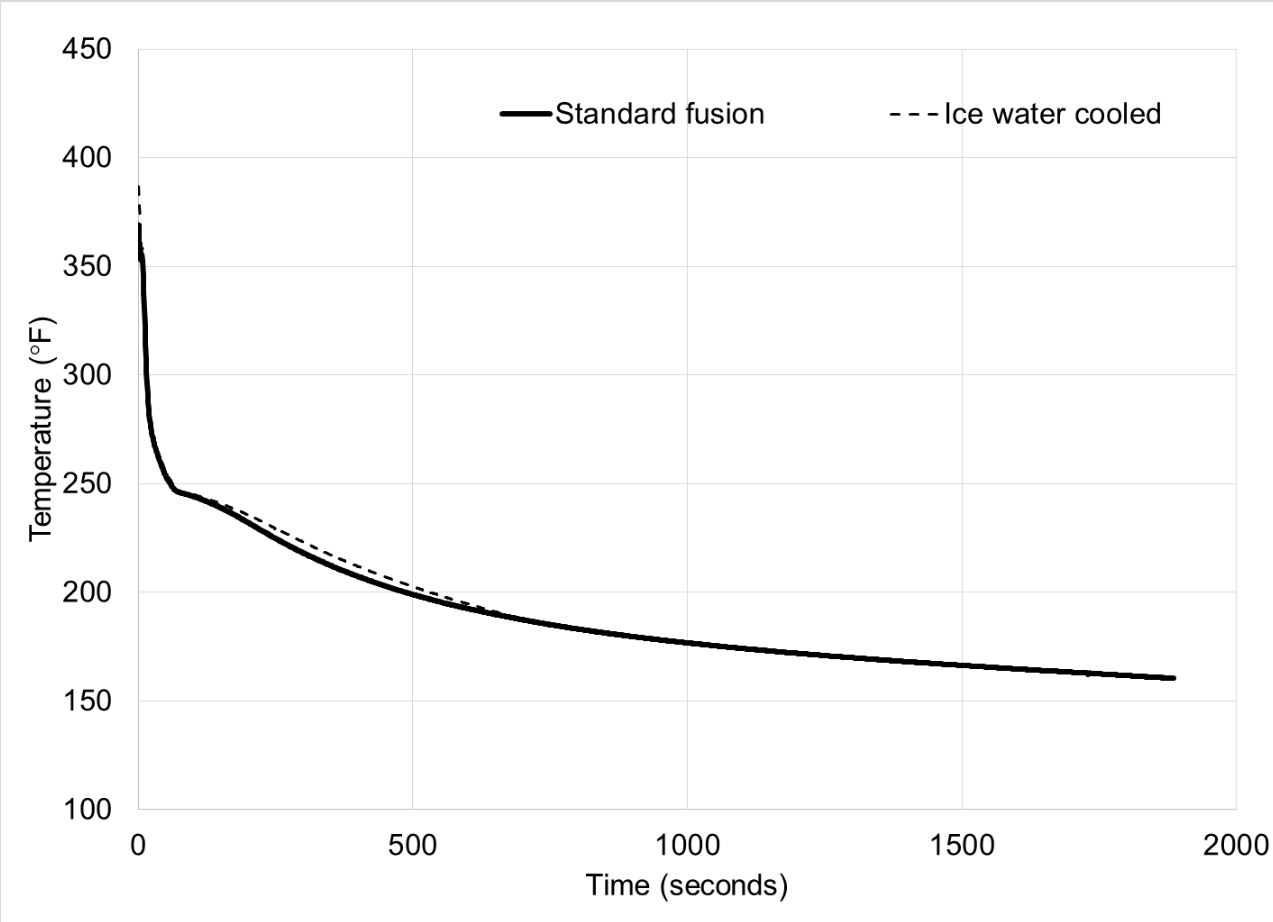

Figure 8 - Cooling curve of 18-inch DR 7

CONCLUSIONS

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

- Given the insulative properties of HDPE, it is difficult to dramatically affect the joint core temperature of heavy wall HDPE
- Ambient temperature and wall thickness have an effect on the overall cooling rate of the 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 cool time.
- The joints with the shortened cool time have a higher failure energy than the joints that were cooled under pressure for the full cool time according the ASTM F2620-13 standard.
- If factors like heat time, heater temperature, ambient temperature, interfacial pressure, and temperature of the pipe before fusion can be tracked and recorded (according to ASTM 3124-15, for example), the cool time can likely be lowered from the ASTM F2620-13 specified time.
- Normal and rough handling procedures can be defined as to limit the handling stresses and enable productivity

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ASTM F2620-13 – Standard Practice for Heat Fusion Joining of Polyethylene Pipe and Fittings

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

