TECHNICAL NOTE

Polyethylene Pipe Butt Fusion Structure, Process, and Terminology

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Foreword

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This Technical Note provides interested parties with a basic understanding of the fusion joint and its substructure.

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For further information, contact:

The Plastics Pipe Institute
105 Decker Court
Suite 825
Irving, Texas, 75062
469.499.1044
plasticpipe.org

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1. Introduction

The purpose of this Technical Note is to provide a basic understanding of the processes that form a polyethylene pipe butt fusion joint and its substructure. Critical to the joint is the "plane of co-crystallization" across which the long polyethylene molecules inter-diffuse (knit together) to form the full-strength joint. This document describes how the plane of co-crystallization is formed at the molecular level during the fusion procedure.

2. Outline

Figure 1 shows the structural elements of a fusion joint as discussed in this document. The actual shape of the fusion beads will vary, and these images are not to be used to assess joint quality (see ASTM F2620[1] for examples of acceptable joint criteria). **Section 3** discusses the importance of following an established and validated fusion procedure. **Section 4** explains how the fusion procedure leads to the formation of the different parts of the joint. **Section 5** discusses the joint interface. **Section 6** provides insights into the frequently asked questions related to fusion bead removal.

Appendix A provides details of the autohesion phenomenon and its role in polyethylene fusion. Some history of the development of polyethylene pipe fusion is in **Appendix B**. **Appendix C** describes the fusion box of temperature and pressure used in fusion.

3. Importance of Established Fusion Procedures

It is important for the polyethylene pipe butt fusion process that the operator follows standard fusion procedures to achieve a sound joint with sufficient strength, durability and reliability (see **Appendix C**). The plane of co-crystallization, as will be discussed further below, lies between the “beads” so it is not visible without destructive evaluation. While the shape of the fusion beads is often used as an indicator of a correctly made joint, the fusion beads themselves do not contribute to the overall strength of the joint. It is critical to follow a qualified fusion procedure to ensure joining practices used meet codes, standards, and project requirements.

Validated fusion procedures dictate the pipe/fitting and equipment selection and preparation, such as allowable fusion temperatures, pressures, and cooling times to obtain reliable joints. Variation from these procedures may lead to compromised integrity of the joints, which has the potential to impact safety and performance.

[1] ASTM F2620 *Standard Practice for Heat Fusion Joining of Polyethylene Pipe and Fittings*, ASTM International, West Conshohocken, PA, USA.

Fusion equipment and operating technicians installing pipe should be trained according to an appropriate fusion procedure (e.g., ASTM F3190[2]).

4. Fusion Process

Fusion occurs when the molten ends of polyethylene pipe or fittings are held in intimate contact allowing molecular interdiffusion to occur. The molecular interdiffusion creates a plane of co-crystallization as the joint cools that co-entangles virtually all molecules from each surface. The fusion process is designed to clean pipe or fitting ends of foreign material and bring them into intimate contact while molten. It should be noted that polyethylene is an autohesive, or self-bonding, material (see **Appendix C**). The pressure selected (high vs low) is not critical to joint formation but instead facilitates wetting of the molten polyethylene surface while in intimate contact creating time for intermolecular diffusion across the interface.

The basic process steps are to first clean, face and align the ends to be fused. This is followed by heating and melting the ends to be joined against a heater plate. Melt beads start to form against the heater plate as the material thermally expands. The heater plate is removed, and the molten ends of the pipe are brought in contact with pressure to ensure that the ends are in intimate contact with each other. The pressure results in some material outflow of the joint space, creating inner and outer beads. The pipes are held in place until the joint has sufficiently cooled so that it can be handled without damage.

These steps are detailed in the subsections below with reference to **Figure 1**. These diagram show the seven zones in a polyethylene pipe fusion joint.

4.1 Heating and Melting

In the butt fusion process, the faced surfaces to be joined are placed against a heater plate, typically in a range of 400 to 450°F (205 to 235°C), warming the surfaces during the “Heat Soak” step. As the polyethylene reaches around 260°F (125°C), the crystalline structure of the semi-crystalline polyethylene material begins to melt and the material softens. This change marks the breakdown of ordered crystal regions into an amorphous (i.e., lacking order) viscous fluid, known as the “melt.” The melt is a mass of molecular chains[3] that have become mobile due to the absorbed heat energy. As the melt temperature rises further, the viscosity of the polymer melt decreases further on a macroscopic scale due to increased molecular motion.

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[2] ASTM F3190 *Standard Practice for Heat Fusion Equipment (HFE) Operator Qualification on Polyethylene (PE) and Polyamide (PA) Pipe and Fittings*, ASTM International, West Conshohocken, PA, USA.

[3] Polyethylene material is made of long polyethylene chain molecules. When below the melting temperature, some of these chains can become ordered and crystals can form. Between the crystals, the chains are disordered and these regions are said to be amorphous. Above the melting temperature, the crystals disappear. See Chapter 3 - Material Properties of the PPI Handbook of Polyethylene Pipe for more information.

4.2 Start of Circumferential Bead Formation

During the heating process, the crystalline regions of polyethylene chains begin to unfold as they transition into a molten state. This phase change leads to an increase in the material's volume (approximately 28%). The volume expansion causes the molten polymer to flow radially outward and inward around the perimeter of the melt face. This forms the heat soak melt beads, a circumferential melt bead, at the pipe ends. This occurs as the fusion machine clamps securely hold the pipe in place so the expansion can only occur radially. Larger pipe diameters and thicker walls naturally produce proportionally larger melt beads due to the increased volume of molten material.

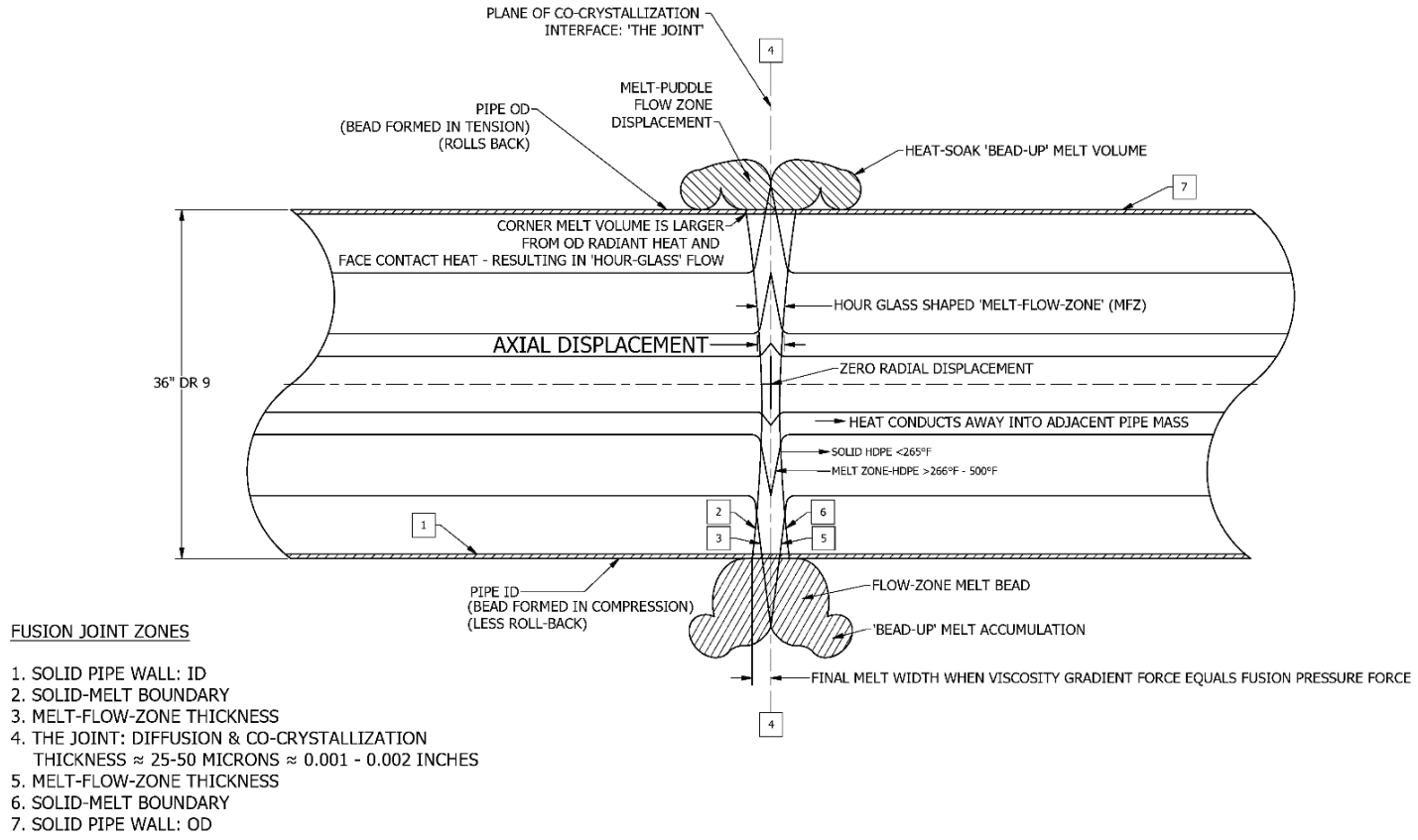

Figure 1 - Schematic of Fusion Interface Cross Section

4.3 Heat Soak Axial Melt Development

As the pipe is held against the heater plate, heat conduction occurs axially down the pipe. The axial depth of melt rises with increasing contact duration, up to a particular axial limit. There is a thermal gradient in the pipe's axial direction from heater plate temperature to ambient. This could have a total distance or axial "depth" of roughly ¼ inch (6 mm) or deeper depending on the pipe diameter, wall thickness and Heat Soak duration. As the temperature drops moving axially away from the heated end, there is a point of transition where the polyethylene reaches its recrystallization temperature and it crystallizes, i.e., hardens. At this point, the polyethylene is molten on one side and hot but solid on

the other. The resulting melt boundary is preserved in the final joint as shown as the “Solid Melt Boundary” in **Figure 1**, which has a somewhat hourglass shape centered on the pipe mid-wall.

4.4 Fusion and Hold Time

Once the prescribed Heat Soak time is complete, the pipes are backed off the heater plate, the heater plate removed, and the molten pipe ends brought together with the prescribed pressure. This constant pressure pushes further melt out radially forming the “Flow Zone’ beads, adding to the existing beads, as shown schematically in **Figure 1** and in an actual fusion in **Figure 2**.

During this step, when the two molten faces are pressed together with this axial force, the polyethylene melt flows radially outward until the axial force is counterbalanced by the hydraulic pressure generated by the material's resistance to flow[4]. The temperature-dependent viscosity plays a crucial role in this process; as the viscosity increases with decreasing temperature, the resistance to flow rises, helping to achieve equilibrium between the applied axial force and the material's flow dynamics.

It is during this time in which interfacial molecular diffusion (i.e., fusion) starts and the plane of co-crystallization, as discussed in **Section 5**, begins to form.

4.5 Cooling

It is during the cooling period that the fusion and the plane of co-crystallization is fully formed (see **Section 5**). Through the cooling time, the clamps are not “locked” and the hydraulic pressure remains applied to compensate for shrinkage due to the crystallization and further axial thermal contraction when the molten mass cools thermally. The clamps move slightly towards each other to compensate for this axial shrinkage.[5]

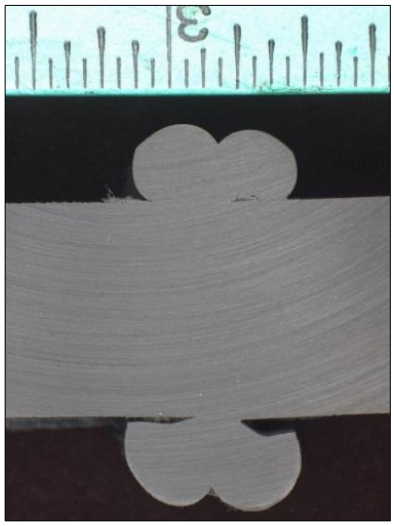

Figure 2 - NPS 12 DR 11 Pipe, Fusion Joint Cross-Section (ground flat)

4.6 Bead Shape

Figure 2 shows the inner (bottom) and outer (top) beads in a cross-section of a NPS 12 DR 11 (~300 mm) pipe that was butt-fused.

As illustrated in **Figure 1** and observable in **Figure 2**, the outer bead (OD bead) typically flows outward and rolls back towards the pipe's outer surface due to the tension created by radial melt flow. In contrast, the inner bead (ID bead) is formed under circumferential compression, which can push the bead away from the pipe's inner

[4] The viscosity of polyethylene melt decreases as the temperature rises, enabling easier flow at higher temperatures. For example, at 425°F (220°C), the melt flows more readily than at 350°F (180°C), while at 240°F (115°C), polyethylene becomes malleable but remains solid, unable to flow under pressure.

[5] If the clamps became ‘locked’ after initial bead formation, the thermal contraction of the melt volume could pull the interface apart, partially or totally; so one clamp must move with the axial melt shrinkage.

surface. For larger pipe diameters and thicker walls, the ID bead may not fully adhere to or lie against the pipe's inner surface, as the melt flow can move radially inward. For these reasons, the internal bead is not considered in visual inspection criteria.

5. The Joint Interface Formation – Plane of Co-Crystallization

The following sections describe the formation of the joint interface and potential issues that can arise from not following procedure.

5.1 Plane of Co-Crystallization Formation

Figure 3 shows the same cross-section in **Figure 2** that has seen subjected to some mild "heat reversion" that results in relaxation of “frozen-in” molecular flows, making the flow patterns in the joint visible.[6]

The heat reversion process, as shown in **Figure 3** and **Figure 4**, reveals the lines of separation between the solid pipe wall and the melted area. This region is **Melt-Flow Zone** (**MFZ**). This zone represents the transitional region where molecular mobility facilitates the bonding process. The **Plane of Co-Crystallization** is at the center of the MFZ. The plane of co-crystallization is where the faces of the two pipe ends molecularly entangle. Following fusion, the plane of co-crystallization is usually between 0.001 and 0.002 inches (25 and 50 µm) thick, which is the approximate depth limit of intermolecular diffusion at the melt temperature.

This entanglement is through contact diffusion and thermal mobility of the polyethylene chains. This plane is the actual "JOINT" that provides the structure joining the two segments of pipe. The melt flow zones and the beads are an artifact of the fusion process and they are not integral to the strength of the “JOINT.” This thickness ensures a strong and durable bond between the pipe ends.

Two blocks of striped material are fused together in **Figure 5** to illustrate the resulting flow and displacement of material in the fusion process. Following the colored flow lines, it is apparent that it is principally the middle third of the pipe wall thickness from which the fusion joint's plane of co-crystallization is mainly formed. It is also apparent that the material in the two outer thirds principally flow to become the beads via the radial outflows.

The middle third is stretched outward radially. Molecular wetting occurs and is the process by which mobile molecules from each pipe end come into intimate contact with one another along this stretched surface, such that molecular van der Waals forces pull the molecules from the two faces together (See **Appendix A** for more details).

[6] In the heat reversion procedure, heat, such as hot gas, is carefully administered to the fusion joint cross-section resulting in relaxation of the material.

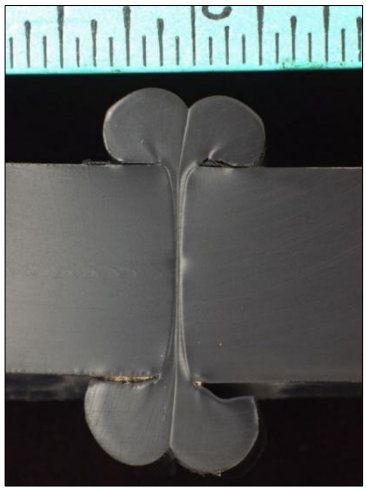

Figure 3 - NPS 12 DR11 Pipe, Fusion Joint Cross-section after Heat-Reversion

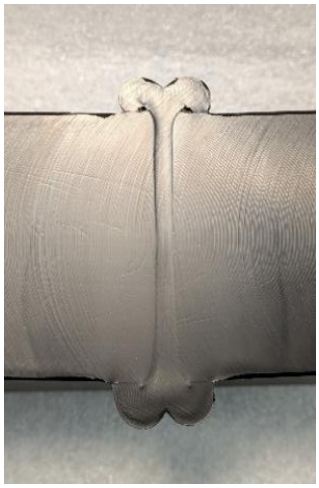

Figure 4 - Heat-Reversion Machined Pipe Wall Showing Possible Bead Shape - Left: NPS 16 DR11, Right: NPS 36 DR9

The long-chain polyethylene polymers from both pipe ends interdiffuse. This interdiffusion gradually slows as the molecules reach maximum diffusion penetration depth. As the thermal conduction of the near-by cooler, solid pipe draws heat away from the melt, the solidification process advances forward to the plane of co-crystallization. As the temperature drops below the crystallization temperature within the MFZ, the material transitions from a molten to a semi-crystalline state. At this stage, molecular diffusion and growth in chain entanglement cease, creating a strong, seamless and homogeneous connection between the two pipe ends.

The strength and fracture resistance of a properly fused polyethylene joint depend on the number and quality of molecular "crossings" achieved during the fusion process. Polymer chains that actively support fracture resistance through processes like chain scission or viscoelastic dissipation are known as effective crossings. Specifically, the strength of the joint is equal to the total energy required to either fracture all the molecular chains and/or to pull these molecules out of the “tube” created by their surrounding physical entanglements and back across the interface. The greater the number of effective molecular crossings, the longer the molecule, or the deeper the interpenetration distance, the greater will be the resistance to joint fracture.

This fusion process allows for a strong bond between the two materials in question and one that can also stand both mechanical and environmental forces. When properly performed the “JOINT” is as strong or stronger than the parent material, both in hoop stress and also under tensional stress.

Figure 5 - Illustration of melt flow during fusion process.

5.2 Non-Fusion Joint

A **Non-fusion** joint can be defined as:

> *A fusion in which insufficient cohesive entanglement throughout the "plane of co-crystallization" because of insufficient interdiffusion. If the number of molecules that interdiffuse between the two surfaces is too small, or if the depth of interpenetration diffusion does not extend deep enough into the parent polymer melt-flow-zone, it can result in a joint with less than acceptable properties, performance characteristics, or longevity.*

Intermolecular diffusion and entanglement are a time and temperature driven function. Temperature creates molecular vibration because of the heat energy imparted into the molecule. Heat is a reflection of molecular motion. Time is required for all the molecules to diffuse into the molecules in the opposite interface.

If normal fusion parameters and best practices are not respected, a non-fusion joint may occur (sometimes called a "cold fusion"). This is when excessive force or pressure radially squeezes out most of the melt volume into the melt bead. In such cases, the 'cooler' zone of the melt-solid pipe-wall boundary is forcibly moved toward the interfacial plane of co-crystallization. This leaves little residual heat between the pipe ends and the latent heat is sucked from the interfacial diffusion layer. Since this cooler material is more viscous molecular diffusion and sufficient molecular entanglement is much less likely to occur. Quenching occurs rapidly, solidifying the co-crystallization plane without achieving maximum diffusion entanglement depth.

6. Fusion Bead Removal

This section discusses the impact of intentional and unintentional bead removal on joint integrity. In most applications it is not necessary to remove the fusion joint bead.[7]

6.1 Intentional Bead Removal

As shown in **Figure 1**, the external roll-back beads (outer diameter [OD] and inner diameter [ID]) are byproducts of the fusion joining process. These beads are not part of the actual "JOINT." The actual "JOINT" is the coalesced zone, referred to as the "plane of co-crystallization" or "line of co-crystallization" as described in **Section 5**. This zone, visible as the center line in a polyethylene pipe fusion after heat reversion in **Figure 3**, represents the structural core of the joint. The roll-back beads are simply excess melt-flow-zone polymer that does not contribute to the tensile strength or hoop strength of the fusion "JOINT."

[7] The Hazen Williams C-Factor and Manning n-factor for polyethylene pipe were established with the internal beads present. The variance in open area, or ID, on a bell-and-spigot system is greater than the variance created by an internal fusion bead, such that fused polyethylene pipe is hydraulically as smooth as gasketed bell and spigot joints.

Roll-back beads on both the OD and ID can be removed using mechanical tools, such as routers, planers, skiving knives, or bead trim tools. However, care must be taken to avoid trimming below the surfaces of the adjoining pipes. Commercially available bead removal tools are available and preferred for this task. The use of power grinders or sanders for bead removal is not recommended due to the risk of damaging the joint or gouging the pipe surface. It is important to wait until the joint has sufficiently solidified before bead removal.

Although it is rare in North America, bead removal is occasionally used in certain applications, such as tight sidewall fusions, sidewall electro-fusion saddles, food processing, fish farming, and compressed polyethylene tubular liners in steel pipes. These practices have been employed successfully for over 40 years.

Commercially available tools may not work in certain instances with limited working space, such as with stub-ends and bolt rings. Oscillating a very sharp bent hand-skiving blade tool with a rounded front tip can be used with extreme care, as illustrated in **Figure 6**.

Figure 6 - Bead Removal Through Hand Skiving

The tool should be held tangent to the pipe surface to avoid gouging the pipe surface or trimming the co-joined bead root below the surfaces of the adjoining pipe (i.e., does not reduce the interfacial fusion area to less than the adjoining pipes' maximum contact wall area). Successful hand trimming can and has been done in the past with proper training, tooling modifications, meticulous technique, and careful use.

6.2 Unintentional Bead Removal

In cases of partial bead removal during fused pipe installation or handling[8], the fusion joint's integrity and strength are unaffected. This is because the roll-back beads are excess melt-flow-zone polymer, located outside the actual fusion zone through the pipe wall.

7. Conclusion

In conclusion, achieving a high-quality polyethylene fusion joint requires adherence to proper fusion parameters. Deviating from these parameters, particularly through excessive pressure or insufficient heat, can result in non-fusion joints with compromised structural integrity. The "fusion beads" created in the fusion process are not critical to the strength of the joint.

[8] Such as installation, insertion, construction, burial, pipe insertion, Horizontal Directional Drilling (HDD), etc.

Appendix A - Autohesion in Polyethylene Pipe

Pipe grade polyethylene polymer is an autohesive material. Autohesion is the spontaneous self-adherence and bonding by molecular diffusion and migration, of two adjacent surfaces of material, without the use of an adhesive. Autohesive materials diffusion bond only to themselves.

To form the autohesion bond during polyethylene pipe wall fusion, the polyethylene must be able to flow and coalesce after contact. It is a three-stage process, as illustrated in **Figure A1**:

1. **Molecular Wetting:** Wetting overcomes the surface tension of the material. In the first stage, wetting must be initiated (see **Figure A1**). This is achieved in the fusion process by melting and application of slight pressure to the interface, so the maximum number of molecules can come into intimate contact between the two surfaces.

2. **Molecular Contact:** In the second stage, progressive molecular contact is realized as the mating surfaces flow together under the action of attractive molecular forces and applied pressure.

3. **Coalescence:** In the third stage (see **Figure A1**), coalescence takes place by vanishing of the boundary between the two surfaces due to self-diffusion with molecular chain entanglement, which is the basis for autohesion theory established by Voyutskii and Vasenin[9,10].

Complete coalescence is:

- time dependent; it occurs primarily in proportion to the rheological viscosity and mobility of macromolecules and/or their segment lengths.
- accomplished by diffusion movement of macro-molecules (macro-Brownian movement) or their segments (micro-Brownian movement).

Coalescence of two surfaces into one solid involves a limited migration distance for molecular diffusion; there is a limit on the possible distance for diffusion of polyethylene molecules from one surface into another, based on various factors, such as the degree of temperature induced molecular mobility; molecular chain length or chain segment length; inter-and intra-chain free-volume “tubes” or void space; path-way tortuosity; adsorption; van-der-Waals hydrogen-bonding attraction force; flow agitation; contact pressure; etc.

For example, the self-diffusion coefficient of linear molecular chains varies inversely with molecular weight. In broad molecular-weight polyethylene, the shorter chains will tend to inter diffuse more rapidly than long ones.

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[9] Voyutskii, S. S. 1960. *Autohesion and Adhesion of High Polymers* (Izdatel'stvo nauchnotekhnicheskoi literatury, RSFSR, M.). See also S. S. Voyutskii, Autohesion and Adhesion of High Polymers (Interscience Publishers, N.Y., 1963)

[10] Vasenin, R. M. 1963. Collection, *Adhesion of Polymers*, 53, 58 Publishing House of the U.S.S.R. Academy of Science, M.

With sufficient time above the melt temperature, the interpenetration distance increases to its limit, and eventually the original contact faces vanish and the zone becomes indistinguishable from the bulk material as the molecules become fully entangled as one solid.

Once the optimum thickness of coalescence of melted polyethylene is achieved, the polyethylene molecular bonding is solidified by natural crystallization that occurs as the melt cools. At room temperature, the material in the coalescence zone is semi-crystalline as is the normal for polyethylene.

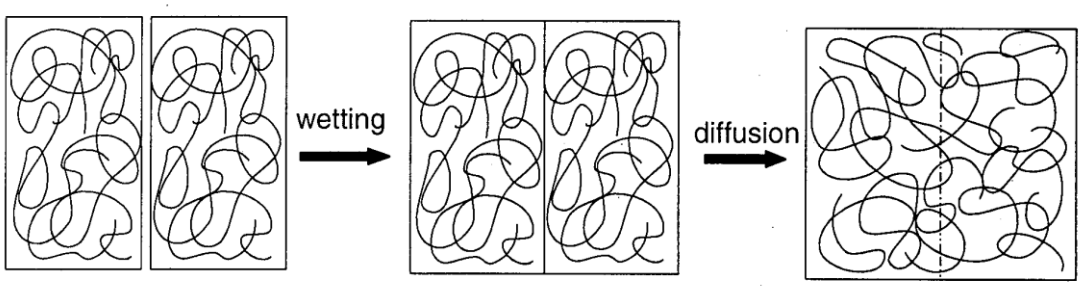

Figure A1 - Diffusion Entanglement and Co-Crystallization into one bulk solid

Appendix B - Historical Background

The butt fusion of polyethylene plastic pipes was developed in the United States at the end of the 1950s by the industry pioneers such as Ole Larsen, Bob Weaverling, Bud Bridenstine, John Merideth, Jean Louthan and Paul Petro. These individuals, working at Phillips Petroleum's Drilling Specialties Company (DRISCO), developed and advanced the process of extruding and fusing polyethylene pipes. With an integrated oven thermometer and an acetylene torch for heating, DRISCO unveiled the first manually driven flat-heater plate fusion equipment (see **Figure B1**).

In the late 1970s, DRISCO shifted its focus exclusively to the extrusion of high-density polyethylene pipes, delegating the manufacture of fusion equipment to an associate company. This strategic shift enabled the development of modern, high-quality fusion machines that are now used globally, setting the standard for polyethylene pipe joining technology.

Figure B1 - Natural Color Polyethylene Pipe being Fused, 1959, in Caney, Kansas

Appendix C - The “Fusion Box”

The combination of **Adequate Temperature**, to thermally melt the polyethylene crystals and to energize the molecular chains into diffusion (fusion) motion, and the **Adequate Interfacial Pressure (IFP),** which marries the two butt-ends and causes the melt to radially flow, are fundamental to achieving full joint strength and ductility. The temperature and IFP combination must be carefully selected and validated to qualify a procedure.

As described in this document, the interfacial pressure does not "force" polyethylene molecules into bonding. The IFP initially flattens the interface and intimately "wets" the two viscous surfaces so that autohesion diffusion (fusion) self-initiates and progresses. The lower IFP squeezes less melted polymer from the melt-flow-zone. Higher IFP radially squeezes more melted polymer from the pipe butt-ends, into a larger external roll-back melt-bead. Across the range of accepted low-pressure IFP to accepted high-pressure IFP, pipe grade polyethylene fuses to itself.

Figure C1 illustrates the width and range of combined temperatures and pressures which make quality fusion joints in conformance with various global standards. ASTM F2620 has defined a range of 60 to 90 psi IFP at heater-plate temperatures between 400 to 450°F (0.41 - 0.62 MPa, 204 - 232°C). ISO 21307[11] Single Low Pressure (SLP) procedure and DVS 2207-1[12] procedure have defined IFP pressure nominally in the range of 0.17 ± 0.02 MPa (between 22 and 28 psi), and 0.15 ± 0.01 MPa (between 20 and 23 psi), respectively. Other combinations of temperatures and pressure ranges may also be suitable with proper verification of the fusion procedure.

Important Note: Any fusion procedure must define the acceptable temperature and IFP ranges. The procedure must be validated at its specific combination of temperature and IFP through testing of fusion joints created using the procedure. Specifications, standards, codes and regulations may stipulate that specific standardized procedures must be utilized.

[11] International Organization for Standardization. 2017., ISO 21307:2017—*Polyethylene (PE) Pipes—Fusion Jointing Procedures*, Geneva: ISO.

[12] Deutscher Verband für Schweißen und verwandte Verfahren e.V. 2015, DVS 2207-1:2015-08—*Welding of Thermoplastics: Heated Element Welding of Pipes, Piping Parts and Panels Made out of Polyethylene*, Düsseldorf: DVS-Verlag GmbH.

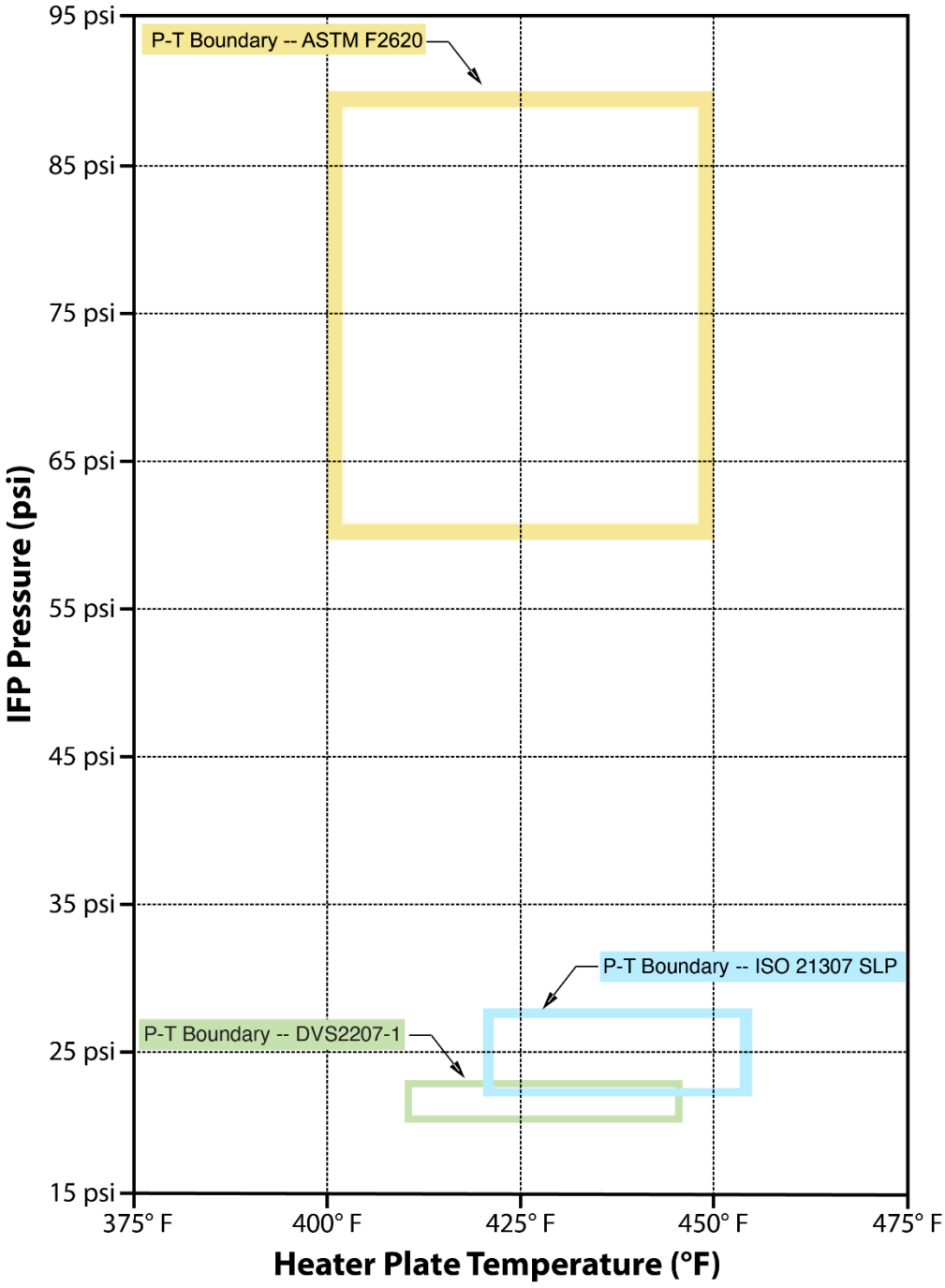

Figure C1 - Examples of Pressure and Temperature Fusion Boundaries. Other combinations of temperatures and pressure ranges may also be suitable with proper verification of the fusion procedure.