

FALSE ARREST IN SMALL SCALE STEADY STATE (S4) RAPID CRACK PROPAGATION TESTING

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ABSTRACT

The Small Scale Steady State (S4) Rapid Crack Propagation (RCP) test methodology has proven to be an effective tool in assessing resistance to rapid crack propagation. At the same time, an evolution in polyethylene material performance has occurred that has produced materials with increasingly higher resistance to rapid crack propagation. This has resulted in RCP testing of materials at increasingly lower temperatures and increasingly higher pressures, pushing the limits of the S4 test methodology. This paper presents results for developmental PE materials demonstrating the phenomenon of 'false arrest' in S4 Critical Temperature testing and supporting the proposed revision to ISO 13477 of limiting the test pressure in Critical Temperature testing to 5 bar (72.5 psi). A higher Critical Temperature is observed for testing at 10 bar (145 psi) relative to testing at 5 bar (72.5 psi).

INTRODUCTION

The Small Scale Steady State (S4) Rapid Crack Propagation (RCP) test has been widely explored for evaluating resistance of polyethylene pipes to rapid crack propagation. During 1990s when the unimodal PE80 resin was commonly used in gas system installations, the method as defined in ISO13477 was effectively used in assessing the RCP resistance of the pipe materials and a correlation between the method and the Full Scale (FS) RCP testing procedure (ISO 13478) was developed. The critical pressure and critical temperature procedures provided both the resin suppliers and the pipe industry with effective tools to evaluate product quality.

With the advancement of polyethylene technology, however, higher rapid crack propagation resistance is commonly observed (1-4). The higher performance of resins requires RCP

testing at higher pressure and lower temperatures in order to achieve crack propagation and, hence, define material performance. The associated anomalous phenomena (such as false arrest and failure to satisfy crack initiation) have become more and more a challenge for reliable assessment of the RCP resistance of PE materials. Specifically, bell shaped curves of crack length versus pressure (i.e. a transition from arrest to propagation is observed with increasing test pressure followed by a transition back to arrest as test pressure continues to increase) have been observed for the bi-modal PE100 type pipe materials for years. The abnormal arrests, referred to as *cloche effect*, have been explained based on the possible role of high pressures causing premature decompression and changes in the stress state at the crack tip (2).

The presence of false arrests exposes problems for S4 RCP testing because a reliable RCP test must allow for a confident determination of true arrest versus a false arrest. The presence of false arrests at high pressure leads to uncertainty in characterization of new materials. The limitation of the S4 test methodology in this respect needs to be carefully considered.

In this paper, examples of the bell or *cloche* effects and also of the abnormal pressure dependence in S4 RCP testing of 4 inch and 8 inch Standard Diameter Ratio (SDR) 11 pipes of two PE100 type resins and of a 180mm SDR 11 pipe of another PE100 type resin are provided. The nature of the “false arrest” phenomenon is discussed relative to the potential contribution of high pressure in causing premature decompression and changes in stress at the crack tip.

EXPERIMENTAL

Testing was conducted in accordance with ISO 13477 (1997) ‘Thermoplastics pipes for the conveyance of fluids – Determination of resistance to rapid crack propagation (RCP) – Small-scale steady-state test (S4 test)’. Critical temperature testing was conducted for two bimodal PE100 type resins at both 0.5 for both 4 inch and 8 inch pipe sizes. Crack length versus pressure through the range of 1 bar (14.5 psi) to 10 bar (145 psi) was examined for a third bimodal PE100 type resin at 0, -3, -6 and -12 °C (32, 26.6, 21.2, and 10.4 °F, respectively).

ABNORMAL EFFECT OF PRESSURE ON CRITICAL TEMPERATURE

Figure I reports the normalized crack length versus temperature data for the 4 inch pipes of PE100 type Resin A at 5 bar (72.5 psi) and 10 bar (145 psi), respectively. As shown in the figure, critical temperature is readily defined at both 5 bar (72.5 psi) and 10 bar (145 psi) pressure levels for this pipe based on the transition from arrest to propagation ($a/D=4.7$). Based on the ISO 13477 definition of arrest ($a/D=4.7$), the critical temperatures (T_c) at 5 bar (72.5 psi) and 10 bar (145 psi) are -7°C (19.4°F) and -19°C (-2.2 °F), respectively. A more

limited dataset was generated for Resin B to confirm the observed phenomenon. Similarly, the critical temperatures for 4 inch pipe of Resin B are 4°C (39.2 °F) at 5 bar (72.5 psi) and < 0°C (32 °F) at 10 bar(145 psi) (Figure II).

The lower T_c values at higher pressure as shown in Figure I and Figure II are obviously abnormal as higher pressure, through providing a higher driving force, is expected to increase the potential for a RCP event. Through the temperature range of -7 to -19 °C (19.4 to -2.2 °F), propagation is observed at 5 bar (72.5 psi) while arrest is observed at 10 bar (145 psi) for resin A. Although a more limited dataset was generated for Resin B, similar behavior is observed. Propagation is observed for testing at 5 bar (72.5 psi) at temperatures where arrest is observed in the testing at 10 bar (145 psi). The arrests at the higher pressure level are what is often termed ‘false’ arrests. As will be discussed later, it is important to note that the observed ‘arrests’ for the 10 bar (145 psi) test condition generally have a crack length >2 pipe diameters long. For such arrests, crack propagation is expected to have reached a steady state condition, as seen in the speed measurements of Yayla (1).

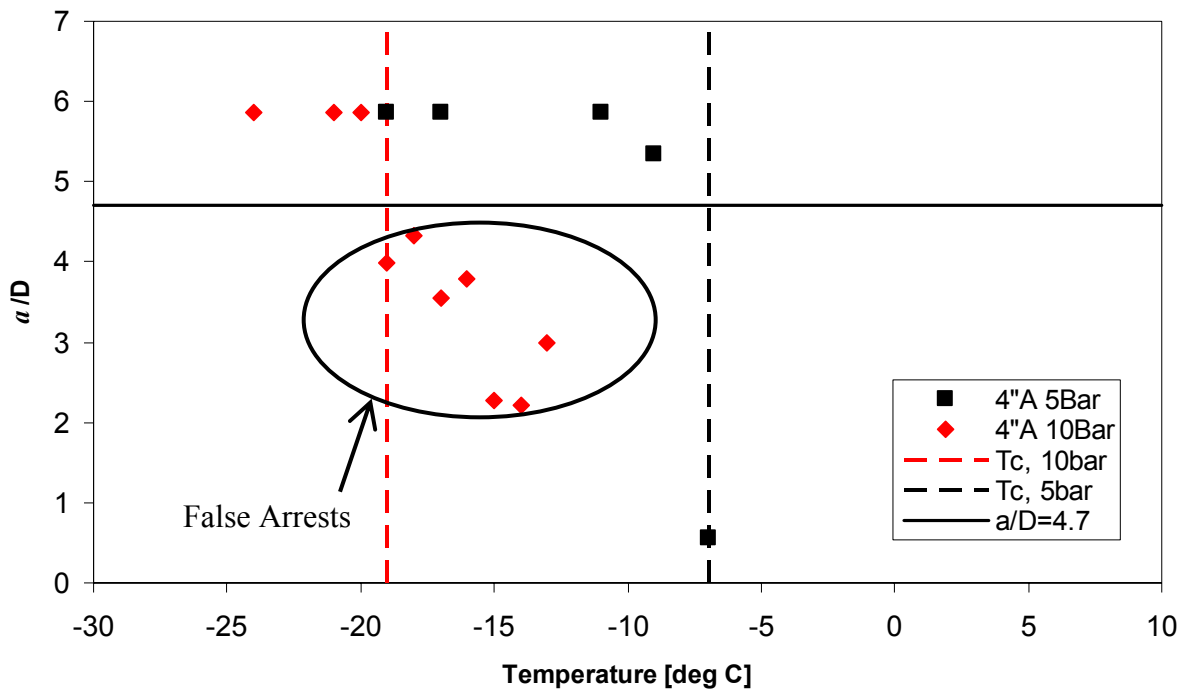


Figure I: Crack Length against Temperature of 4 inch pipe of Resin A at 5 bar (72.5 psi) and 10 bar (145 psi) Pressures

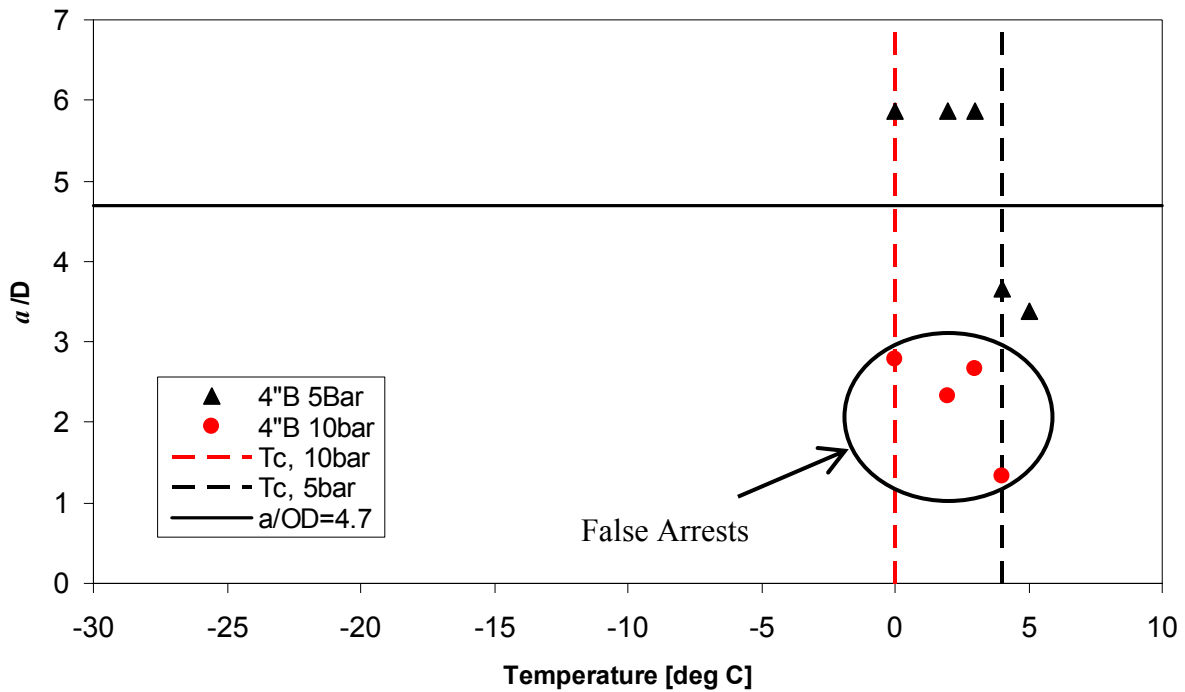


Figure II: Crack Length against Temperature of 4 inch Pipe of Resin B at 5 bar (72.5 psi) and 10 bar (145 psi) Pressures

The same abnormality was also observed for the 8 inch pipes of these same two resins. As shown in Figure III the critical temperatures of 8 inch pipe of Resin A are -2°C (28.4°F) at 5 bar (72.5 psi) and -17°C (1.4°F) at 10 bar (145 psi). Again a more limited dataset was generated for Resin B to confirm the phenomenon. The T_c values for Resin B of the same pipe diameter are 9°C (48.2°F) for 5 bar and $<0^{\circ}\text{C}$ (32°F) for 10 bar (145 psi). As observed in the testing of the 4 inch diameter pipe, the observed critical temperature is lower for testing with 10 bar (145 psi) pressure than with 5 bar (72.5 psi) for both materials. False arrests are evident at least near -5°C (23°F) for the 8 inch pipe of resin A and near 5°C (41°F) for the 8 inch pipe of resin B. The false arrests appear on a wide temperature range for the pipe of Resin A. The observed crack lengths for the ‘arrests’ in the 10 bar (145 psi) testing are generally >2 pipe diameters.

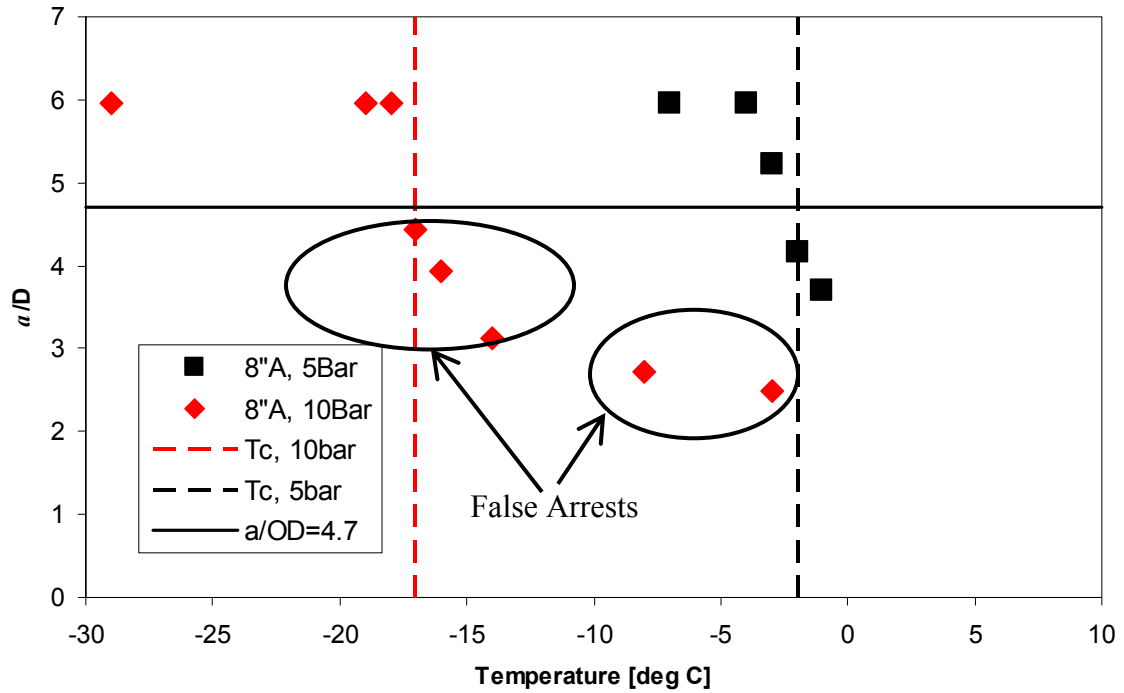


Figure III: Crack Length against Temperature of 8 inch Pipe of Resin A at 5 bar (72.5 psi) and 10 bar (145 psi) Pressures

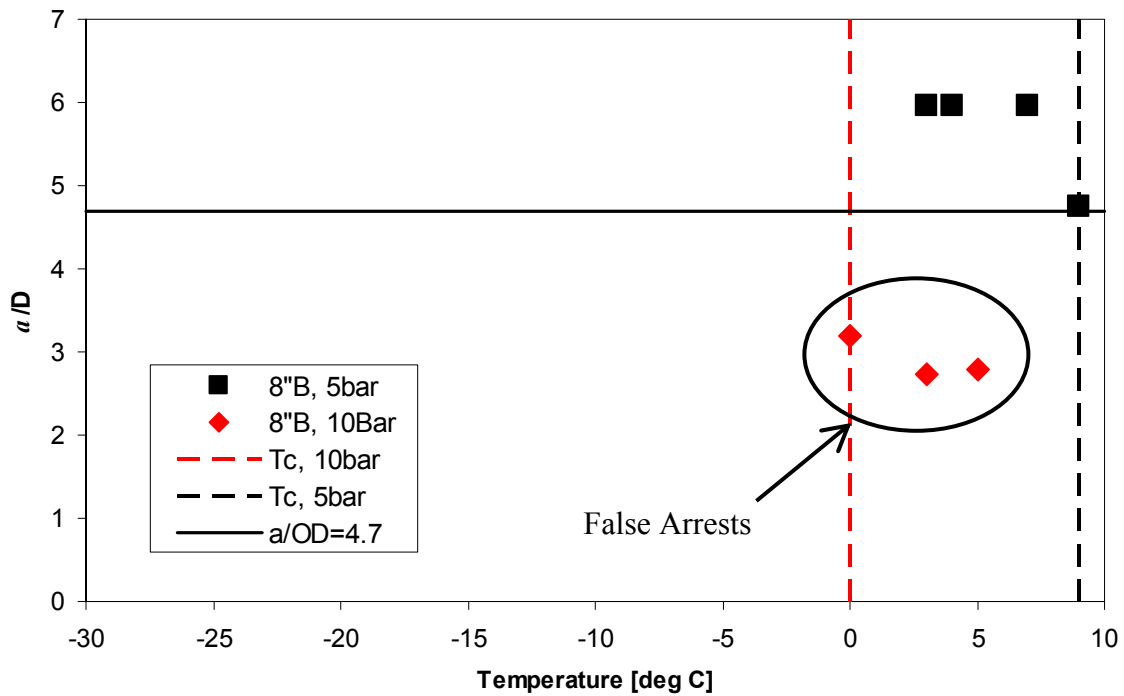


Figure IV: Crack Length against Temperature of 8 inch Pipe of Resin B at 5 bar (72.5 psi) and 10 bar (145 psi) Pressures

BELL SHAPE DEPENDENCE OF CRACK LENGTH ON PRESSURE

Figure V presents the pressure dependence of crack length for the bimodal PE100 type Resin C at various temperatures. The results provide a further example of the transition from propagation to arrest at higher pressures (where propagation is expected).

At 0°C (32 °F), propagation is not observed up to 10 bar (145 psi). At -3°C (26.6 °F), an initial transition from arrest to propagation occurs near 2 bar (29 psi). This is followed by a transition back to arrest above 6 bar (87 psi). Similar transitions are observed at -6 and -12 °C (21.2 and 10.4 °F, respectively). In general, the false arrests are observed at pressures above 6 bar (87 psi) below 0 °C (32 °F).

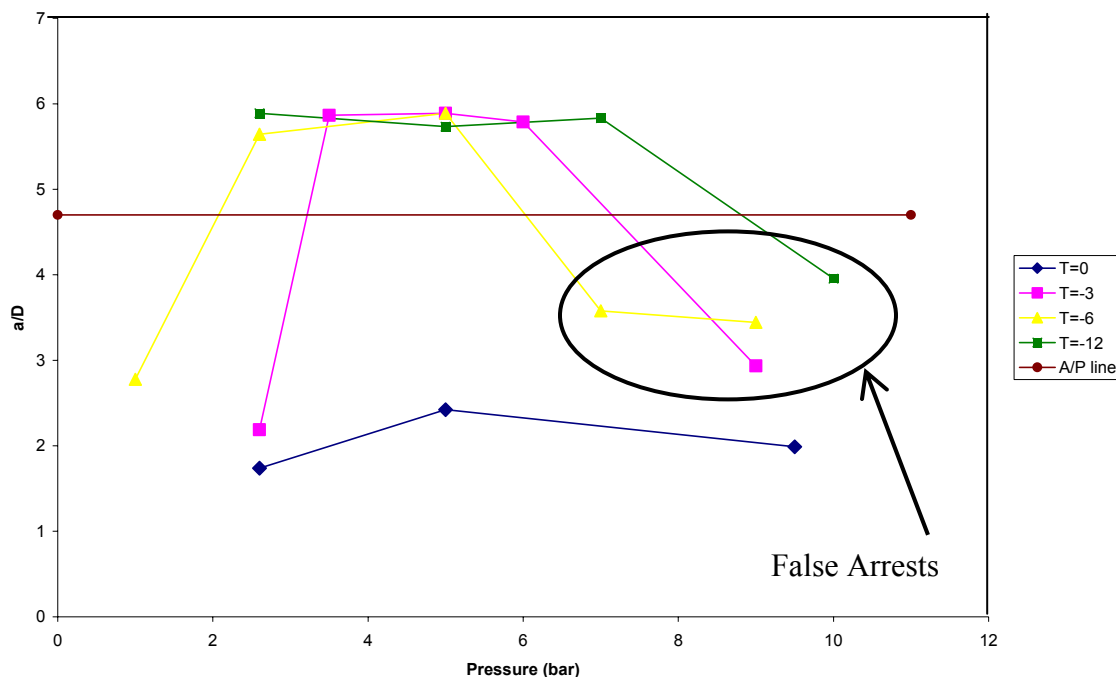


Figure V: Dependence of Crack Length on Pressure for Pipes of PE100 Type Resin C at Various Temperatures

FALSE ARREST AT HIGH PRESSURE

False arrests have been previously attributed to both abnormal procedures and genuine variability in pipe specimens (2). Abnormal procedures, such as an improper cage clearance or eccentricity can lead to abnormal decompression and hence cause false arrests. False arrest has also been attributed to inconsistent surface temperatures in testing. Certain intrinsic properties of pipe, such as the anisotropy owing to specific processing histories have also been attributed to single point false arrest.

The observed false arrest phenomenon for the three resins examined in this paper, however, cannot be explained by these phenomena. The false arrests observed are not scattered or single point false arrests. They are observed to follow a predictable pattern of transition from propagation to arrest at higher pressure. The testing was conducted at two different laboratories on equipment meeting the requirements of ISO 13477 and so they are not particular to a specific test set-up. The false arrest phenomenon is also observed for different pipe sizes and different materials processed on different extrusion equipment.

The observed 'false' arrest phenomenon in this testing is, therefore, believed to be a true artifact of the S4 test itself. As discussed by Leever (2), the S4 test relies on retarding gas decompression to provide the increased driving force for crack propagation. This is accomplished through the use of internal baffles and use of a containment cage to restrict flaring. In fact, the assumption of zero gas decompression underlies the derivation of the full-scale/S4 critical pressure correlation (2):

$$p_c = 3.6 p_{cS4} + 2.6$$

where both p_c and p_{cS4} are in the units of bar.

At test pressures in the region of 5 bar (72.5 psi), this is believed to be a reasonable assumption. As test pressures are increased, however, the circumferential strain in the pipe increases, which in turn increases the effective clearance between the internal baffles and the pipe. This increases the area of the baffle leakage path, which enhances gas decompression. Further, at high pressures flaring of the pipe could also allow downstream chambers to decompress through radial outflow of the gas (2). The combined effect of these two phenomena is an increase in gas decompression rates with increasing test pressure. The point at which this increased decompression with increasing test pressure overshadows the increase in crack driving force due to increased test pressure is believed to mark the transition to 'false' arrest. This provides an explanation for the bell shaped curves observed for crack length versus test pressure.

It has been suggested by Leever that the S4 striker alone, at sub-critical pressure, could not sustain propagation of a crack greater than 2 pipe diameters long. Such 'long arrests' may, therefore, actually indicate a propagation condition that has arrested due to excessive gas decompression resulting from excessively high test pressures. It is interesting to note that for the three resins examined in this testing, the apparent 'false' arrest crack propagation lengths are all in excess of 2 pipe diameters.

Following the modeling based on Leever (2), the outflow process, by which pressure is lost, takes place over a length of 2-3 diameters behind the crack. Over one or two pipe diameters nearest the crack tip, the pressure is still high enough to help drive the crack by pushing forward on the flaps. This 'outflow length' is already a significant fraction of the total length available for RCP to settle into a steady state. As the test pressure increases, the decompression time also increases, so the outflow length is expected to increase. There is

not sufficient pipe length, however, to accommodate this increased outflow length and enable steady state conditions to develop.

The ‘false’ arrest phenomenon hence is a true artifact of the S4 test and poses limitations on the test pressures that may be employed in testing. As application of S4 testing is extended to different materials, understanding of the test pressures resulting in ‘false’ arrest is believed to be critical to ensuring that testing is conducted under conditions that will provide an appropriate representation of pipe performance.

CONCLUSIONS

False arrest in S4 testing is observed for three different PE100 type resins, for different pipe sizes, through a range of temperatures and for testing at two different laboratories. The false arrest phenomenon is believed to be a true artifact of the S4 test methodology. Higher test pressures appear to result in increased gas decompression due to increased axial strain in the pipe and increased flaring of the pipe during the initial propagation phase. The ‘false’ arrest phenomenon is believed to occur at the point at which increased decompression with increasing test pressure overshadows the increase in crack driving force due to increased test pressure. As application of S4 testing is extended to different materials, understanding of the test pressures resulting in ‘false’ arrest is believed to be critical to ensuring that testing is conducted under conditions that will provide an appropriate representation of pipe performance.

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