MODELING RUNNING FRACTURE IN PIPELINES – PAST, PRESENT, AND PLAUSIBLE FUTURE DIRECTIONS

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ABSTRACT

Running fracture in gas-transmission and certain hazardous liquid pipelines has consequences that require pipeline design effectively preclude its occurrence. Because the phenomenology is complex, design against such incidents has relied on full-scale demonstration experiments, which have been coupled with semi-empirical and other more fundamental models. But, as economics driver toward larger diameter pipelines in higher-strength grades made of higher toughness steels to transport "rich" gases at higher pressure, the available technology has been severely stretched. High toughness was first to confound available models, which now are stretched even further as very high strength grades are introduced. This paper explores the historical development of technology to characterize fracture arrest, from the 1970s to present, and on that basis postulates plausible future directions to deal with the continuing push to more demanding pipeline designs.

1 INTRODUCTION

Running fracture refers to rapid axial propagation of a fracture along a transmission pipeline pressurized with natural gas or certain fluids whose decompression response shows some time delay. It is well known that running fracture is controlled by the speed that the decompression front propagates into the product stream as compared to the speed of the fracture. The balance between these speeds is dependent on the fluid's properties, the line-pipe's size and its flow and fracture properties, and the backfill conditions.

The consequences of running fracture require that pipelines be designed to avoid related incidents with a high level of certainty. The line pipe steels of the 1960s and before offered little resistance to running fracture, which in these steels occurred in a brittle mode and ran at speeds the order of the acoustic velocity in the pressurizing media. As the significance of fracture mode was understood, steels were developed that overcame brittle fracture with the expectation that problems with running fracture would be resolved. However, full-scale experiments done with such steels in the late 1960s and into the early 1970s showed that fracture propagation remained a problem, even at hoop stress levels typical of service.

Approaches to assess running ductile fracture resistance of a pipeline relied initially on semi-empirical analysis of full-scale tests done on segments of pipelines. This was necessary in the 1970s because fracture theory then was rather rudimentary. Battelle developed its model in the early 1970s (Maxey [1]), coupling independent expressions of gas-decompression behavior and fracture resistance through what was termed a backfill coefficient. The approach to characterize decompression was analytical and based on a robust equation of state that became a semi-analytic expression of decompression speed through its calibration across the spectrum of gas compositions then of interest. This fundamentally sound formulation proved viable then and remains so even for the rich compositions of interest today. Fracture propagation speed also was expressed in analytic form, with its roots in mechanics analysis for plastic wave propagation that became semi-analytic through its calibration of fracture resistance. These independent one-dimensional formulations for decompression speed and fracture speed were empirically coupled by the above-noted backfill coefficient. The determination of the toughness for fracture arrest came by identifying the toughness that caused these two expressions to become just tangent. Because two curves were involved, this model became known as the Battelle Two-Curve Model (BTCM).

The BTCM became the standard by which to judge fracture arrest where fracture propagation was a design or service consideration by virtue of being the only such model capable of dealing with this phenomenon. Because the BTCM required iterative solution, its use was difficult until software developed in the mid 1990s automated its solution. In the interim, and because its complexity was necessary when dealing with two-phase decompression, the BTCM was used to solve a range of single-phase decompression scenarios dealing with large diameter gas pipelines pressurized at levels typical of cross-country pipelines, with the results curve-fitted to produce the Battelle simplified model (Maxey [2]). While the Battelle simplified model was calibrated in reference to analyses done with the BTCM, contemporary simplified models of fracture arrest toughness followed that were calibrated using the full-scale running fracture database. Not surprisingly, these models implied arrest toughness is a function of the pressure-induced wall stress, pressure's effect on acoustic velocity, the pipeline's geometry, and the depth of the backfill.

2 LIMITATIONS INHERENT IN EARLY FRACTURE-ARREST MODELS

The BTCM and the Battelle simplified model derived based on BTCM results embed calibration in reference to Grade 448 (X65) or below, with toughness of 100 J and less. Related limitations exist for all simplified models, depending on the specifics of the underlying database. The BTCM also embeds constraints that reflect strength characterization including strain hardening response and toughness, the latter involving both fracture initiation and fracture propagation. Fracture initiation enters this formulation through consideration of the fracture arrest pressure, which for this model carries back to the log-secant-based NG-18 equations. Fracture propagation for this formulation embeds both the deformation response and fracture resistance.

Because the BTCM and the simplified models involved empirical calibration for steels with Charpy vee-notch (CVN) plateau (CVP) energy typically the order of 100 J or less, in strengths in Grade 448 and below, problems should be anticipated in their application to significantly higher toughness or grade. Such problems first became evident in 1983 in regard to steels of similar grade, but with much higher toughness (e.g., Vogt [3]). Results typical of predictions for such cases are shown in Figure 1, which makes use of the AISI (AISI [4]) simplified model to illustrate this point. From Figure 1 it is clear that as toughness increases beyond 100 J this criterion fails to provide adequate toughness to arrest running fracture. This tendency to underestimate required arrest toughness is consistent for all grades represented, which for the results shown is dominated by steels of Grade 482 (X70), which is close to the Grade 448 empirical limit

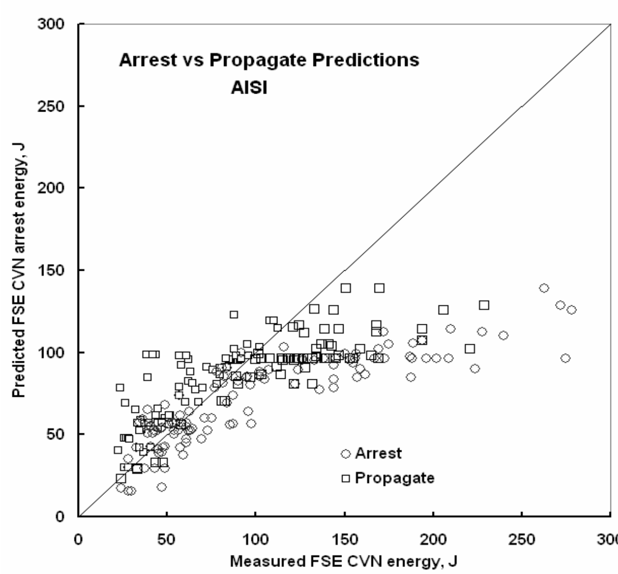

Figure 1. AISI Simplified model

of the BTCM, and below. Similar trends to those shown in Figure 1 develop for all criteria that utilize a CVN-based measure of fracture resistance (Leis [5]).

3 MORE RECENT DEVELOPMENTS AND CTOA

Shortly after the shortcoming in CVN-based models evident in Figure 1 was recognized, a major effort was initiated by the PRCI to develop alternative technology, through a plan that abandoned earlier efforts tied to CVN-based measures of fracture resistance. This work was initiated in 1984 (e.g., Kanninen [6]). About the same time a major effort began in Europe with a comparable purpose, the work being focused at CSM (e.g., Venzi [7]). Collaboration between these efforts ensued that focused on better characterizing both the driving force and resistance measures for running fracture. Most significant in this work was the evolution of crack-tip opening angle (CTOA) as a measure of fracture resistance (e.g., Martinelli [8], Demofonti [9]), and independent as well as related attempts to develop new specimens and test procedures to characterize fracture resistance.

The emphasis of the recent developments has been isolating crack propagation resistance, coupled with a measure of this resistance and testing practices to characterize it. Schemes to isolate crack propagation resistance have ranged from changes in: 1) the notch configuration or its processing, 2) the back surface opposite the notch, and 3) the test practice or specimen geometry. The merits of this effort are unclear as such approaches to fracture arrest tend to embed only energy dissipation due to propagation, whereas many other factors can contribute to arrest in the pipeline. Schemes to characterize fracture resistance have centered on CTOA now for almost a decade, with the initial test practice to measure CTOA undergoing at one significant shift in its practice (Mannucci [10]). Values of fracture resistance measured by CTOA to date involve levels up to 25 degrees, although typically they are less than 15 degrees. Finally, while still tied to CTOA, one group has focused on a fundamentally different practice to measure this parameter, which appears to hold promise after about five years of work (Hashimi [11]).

4 CHALLENGE POSED BY FRACTURE CONTROL FOR THE ALLIANCE PIPELINE

Work along the path initiated in the early to mid 1980s continued for about a decade, with much new work published in reference to numerical models and new tests to measure fracture-arrest resistance tied to CTOA. The advent of the Alliance Pipeline provided the first major challenge for this new fracture arrest technology, and as well posed a challenge that could be responded to by recognizing potential causes of the trend evident in Figure 1 and accounting for them.

The proposed design conditions for the Alliance Pipeline posed significant potential problems in developing its fracture control plan (FCP), in reference to both decompression response and fracture resistance (Jantzen [12]). This design proposed the use of a very rich (dense-phase) gas, the richest yet considered, which was planned for transmission by a large diameter (914 mm) pipeline operating at a high design factor typical of cross-country service. While Grade 551 (X80) was considered early in their design process, Grade 482 was eventually adopted for a variety of reasons. Thus, while the toughness levels required for fracture arrest in the Alliance Pipeline could be anticipated to carry well past the limit of 100 J where after Figure 1 indicates clear problems for the BTCM and other CVN-based schemes, concern for the complications of grade much beyond X65 was unlikely to be a factor in adapting the BTCM. In contrast, the CTOA approach had yet to be evaluated in reference to blind prediction of toughness required for fracture arrest, so both decompression as well as fracture resistance embedded in such approaches could be critically tested in predicting the response of running fracture for the Alliance design.

Blind predictions were made for the Alliance Pipeline under contract to the developers of CTOA-based fracture arrest technology (Peterson [13]). Such predictions, which were made while developing the FCP and as part of the preparation for the hearing to certify this pipeline, indicated the CTOA required for fracture arrest was ~25 degrees. Fracture resistance at that level was not unprecedented, however this value of CTOA was at the upper end for steels previously characterized, which had values ~15 degrees or less, often much less.

Overcoming the limitations embedded in the BTCM through its historical calibration was also independently explored. This work was done at Battelle under contract to Alliance Pipeline as part of developing their FCP (Leis [5, 14]). This work addressed the constraints imposed in calibrating the BTCM by steels with CVP energy of 100 J or less, in strengths made of Grade 448 and below. Consideration of the flow properties embedded in the BTCM and its calibration database indicated these aspects and their influence on arrest pressure and fracture propagation were likely second-order factors. However, evaluation of a range of steels whose toughness ranged from 24 J to 350 J (Leis [5]) indicated that the distribution of energy dissipated in a CVN specimen changed significantly as toughness increased through the range anticipated for necessary for fracture arrest in this design. The distribution of dissipation was found to be relatively constant over the interval that calibrates the BTCM, but as toughness increased beyond ~100 J the fracture initiation energy increased as did dissipation in the specimen remote to the notch /crack plane. Accounting for the decreased fraction of measured fracture energy available to resist crack extension led to a correction (Leis [5]) for the BTCM that increased as CVN energy increased, which as has been noted was viable for applications to Grade 482 or below, although it might be viable for some Grade 551 steels.

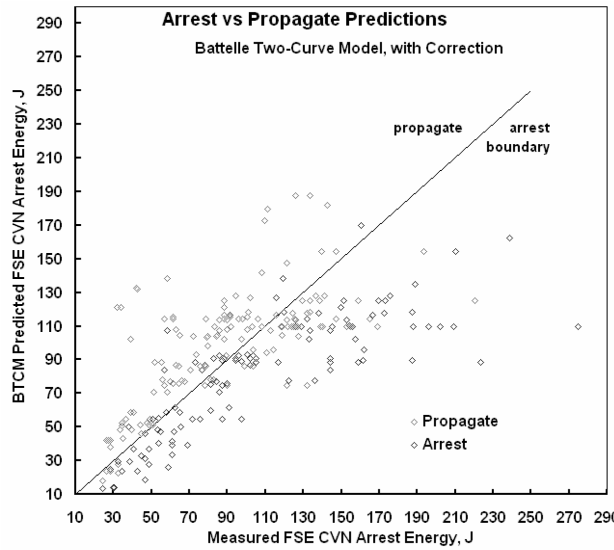

Figure 2. BTCM with correction

Both CTOA-based models and the BTCM corrected as just noted were considered in designing the full-scale experiments developed to evaluate and/or validate such technologies and the FCP for the Alliance Pipeline, results for which have been published (Eiber [15]). Blind predictions of the Alliance full-scale tests based on the corrected BTCM validated the toughness correction, but not the CTOA as it was then implemented. It was found that the corrected BTCM predictions matched the observed arrest toughness within a few percent of each other for each of four arrests, while CTOA was not so successful. The results of these tests and success in their prediction led to certification of this pipeline in the US and Canada. Figure 2 indicates that the correction developed to address the higher-toughness required for the Alliance design achieves excellent predictions when applied to the database of full-scale tests available openly circa 2001. It is noteworthy that these data span quite high toughness levels (≤270 J). While the Alliance design involved rich gas, these results all reflect single-phase decompression.

5 CHALLENGE POSED BY HIGHER-STRENGTH GRADES

The economics of pipeline construction and operation motivate the development of higher-strength grades, which in turn further stretches fracture arrest technology and leads to full-scale testing to evaluate that technology. Initially much of this work, which involves Grades 689 and beyond, was considered proprietary. However, recently much of this data has become available. As yet CTOA-based schemes are being applied to these data retrospectively, or in conjunction with some empirical calibration (e.g., Demofonti [16]). As anticipated, use of the BTCM, even with the above-noted toughness correction falls well short of the observed trends, which reflects the limitations embedded through its empirical calibration using data in Grade 448 and below. The effects of this limitation have been demonstrated in regard to the fracture initiation shortcomings of the NG-18 formulation embedded in the fracture arrest pressure since the 1980s, which motivated formulation of the PRCI ductile-flaw-growth model (e.g., Brust [17]). Work is currently underway to address this limitation pursuing the approach applied by Battelle in the Alliance Pipeline work, which then concluded the concern was secondary when dealing with Grade 482.

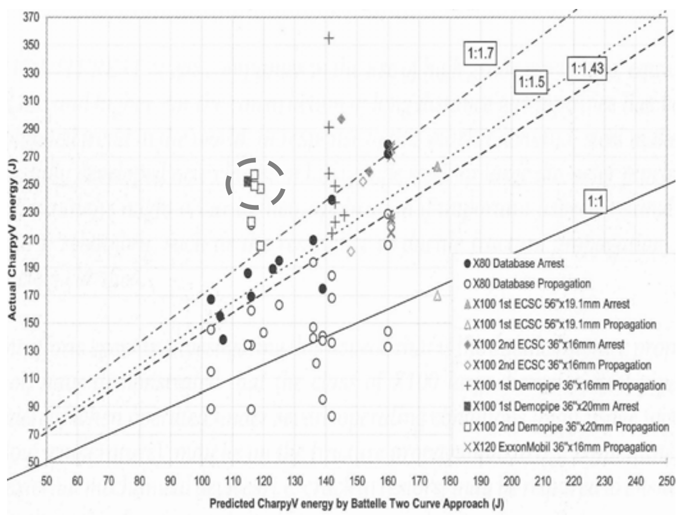

Figure 3. CSM database for X80 and X100 tests

6 PLAUSIBLE FUTURE DIRECTIONS

Work with Grades 689 and beyond indicates that regardless of how toughness is characterized analytically or measured experimentally it no longer is uniquely controlling arrest versus propagation. This is most evident in recently published work of CSM shown in Figure 3. The format of this figure is comparable to Figure 2, except the axes are switched. The inconsistent trends therein indicate that a toughness correction such as used for Alliance by itself falls well short of correctly correlating these data. More importantly, the circled data in this figure indicate that toughness as used herein no longer discriminates arrest versus propagate in such testing. Because the highest toughness in Figure 3 is comparable to that in Figures 1 and 2 where arrest versus propagate was no longer confounded at higher toughness, one must conclude aspects other than toughness confound discriminating arrest versus propagate in Figure 3.

Unfortunately, too little has been made of full-scale fracture propagation tests wherein the results show such conflicts in data trends. Such results could be used to evaluate the suitability of emerging measures of fracture resistance – do they achieve discrimination or not – but as yet this has not been done. Such results indicate the effect of strength levels well beyond that embedded in calibrating the BTCM is very significant, which motivates removing the constraint in the BTCM due to its empirical calibration up to Grade 482. Work with fracture initiation in Grade 551 at Battelle points to errors in the NG-18 formulation the order of that evident for this grade in Figure 3 (e.g., Leis [18]). Too little is known in reference to Grade 689 but based on the trend with grade for Grade 551 it is not unreasonable to expect the trends in Figure 3 can likewise be explained. As noted above, such work is currently underway.

The results in Figure 3 hint that whereas fracture resistance dominates arrest at lower toughness, as toughness continues to increase other processes and properties might become important, thus confounding the ability of toughness to uniquely discriminate between propagation and arrest. By analogy to fracture initiation, one can assert there is a toughness level beyond which the failure process transitions to flow-controlled behavior. If such occurs, plastic-collapse dictates structural behavior and failure, which implies running "fracture" is more a propagating tensile instability than an extending crack. In this case, dissipation other than that due to cracking becomes important and eventually central to evaluating what controls arrest in a pipeline. In turn, this suggests that different material properties are or could be important, and potentially implies a need for new tests to measure these properties.

Until we fully understand what new processes might be involved, if any, and can characterize them without resort to empirical calibration, full-scale testing will remain the standard by which to prove the viability of a pipeline design and its FCP. As such testing is expensive and specific to the test parameters, there remains the need to characterize relationships between pipeline design parameters and arrest. Numerically this requires evaluating three processes – the flow and fracture behavior, the decompression behavior, and the soil-structure or water-structure interaction – each of which are complex, nonlinear, and interact with each other. Numerical analysis therefore will likely require some degree of calibration, which will require uncoupling otherwise interacting processes. One approach, while generally unpopular is to return to above-ground testing – which is where the BTCM started.

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