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Subsea Hydrocarbon Pipeline Failure: Survey of Available Prediction Schemes

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EXECUTIVE SUMMARY

The objective of the present work, as specified in Appendix A, is to provide a critical assessment of existing methods for predicting the outcome of subsea pipeline failure. The emphasis is on the availability and suitability of existing computational codes for this purpose. Only established codes are considered here on the basis of technical literature available in the public domain. Emerging products since notified to us are mentioned in our closing remarks.

Our report presented here is delivered in five main sections. The introduction (section 1) defines the context of existing capabilities with reference to a short historical perspective (section 1.1) on large codes originally introduced for pressurised water reactor safety evaluation and briefly reviews (section 1.2) more recent code developments associated particularly with the oil industry's perception of their needs for flow predictions. We then turn to the issues raised here, beginning with a preliminary classification (section 1.3) of scenario events in terms of their physical scaling and linking (section 1.4) these considerations to their main implications for prediction methods. The introduction closes with a statement (section 1.5) on the layout of the main body of the report, as follows.

In section 2 we provide an overview of generic fundamentals that ultimately dictate the quality and robustness of all practical calculation schemes. A brief preamble (section 2.1) is offered to define its context with reference to the scope and depth of contemporary modelling strategies. Special attention is paid to major aspects classified here as interphase topology (section 2.2), transport dynamics (section 2.3) and multicomponent exchanges (section 2.4). Within this framework we identify main elements of the prescriptions adopted in proprietary codes presently regarded as candidates for possible future extended application to the present need. We close with a brief recapitulation (section 2.5) emphasising important closure uncertainties and the continuing inaccessibility of rigorous descriptions for sensitive modelling elements. Recognising that HSE's wish is to acquire a compact and focused formulation suitable for friendly and fast execution as menued graphics PC-software, there may well be a case here for considering whether an 'intensive' approach based on short-cut but adequate approximations might not be more appropriate than any of the apparently generic but ultimately contentious 'extensive' schemes.

In section 3 we review key attributes of three main candidate codes (BLOWDOWN, PLAC, OLGA) with reference to the modelling aspects surveyed in section 2 - namely: interphase topology (section 3.1), transport dynamics (section 3.2) and multicomponent exchanges (section 3.3). The different origins of their main current purposes have resulted in distinctively complimentary qualities, as follows:

BLOWDOWN's main purpose was simulation of pressure vessel failure and this has resulted in emphasis on the third modelling aspect (multicomponent exchanges) whilst only lip service is paid to the first two (interphase topology and transport dynamics). PLAC's first purpose was modelling of terrain-induced slugging and the resulting documentation concentrates on its contemporary approach to the second aspect, with only a primitive treatment of the others. OLGA on the other hand appears to have been conceived as a diagnostic general purpose tool for oilfield operations and its modelling strategy reflects this claimed versatility, in particular the implicitly generalised characterisation of interphase topology within a 'minimum slip speed' closure model for the transport dynamics. As a bottom-line opinion of the best buy on demonstrated

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overall technical merit, OLGA has the edge at present, although we understand that revised versions of BLOWDOWN and PLAC are being developed which will overcome the limitations of their present releases.

In section 4 we survey (section 4.1) reported validation exercises on the candidate codes in relation to their relevance to the present need. BLOWDOWN's documentation (published papers) indicates that successful reproduction of real data on rapid depressurisations relies crucially on detailed thermodynamic description of multicomponent exchange but, apparently, it is remarkably insensitive to the topological and dynamical details. PLAC's documentation (publicity material, technical summary) suggests that terrain-induced slugging inception and translation velocities can be captured with a primitive topological prescription simply interpolating empirical regime maps for the horizontal and vertical flow limits. OLGA's documentation (published papers) includes such satisfactory test-case comparisons as slugging inception maps, both terrain-induced by riser entry geometry and composition-induced by step changing the gas rate. OLGA has also been run for a rapid depressurisation scenario following topside rupture of the riser line but its status here, for applications involving rapid transient adjustments, remains uncertain in the absence of comparisons against real test data.

Probably the biggest single need in this area is the establishment of a consensus framework of benchmark tests by which the relative merits of candidate codes might be properly assessed. Whilst real data comparisons are essential to achieve formal validations, it would still be of considerable diagnostic value to compare the predictions of different codes for defined sets of test conditions. Moreover, parametric sensitivity surveys on individual candidate codes within this common framework of tests would allow detailed probing of the plausibility of specific modelling closures and thereby afford systematic identification of opportunities for robust short-cut approximations. Our discussion in section 4 closes with tentative suggestions (section 4.2) on an extended set of benchmark tests of special relevance in the present context. Particular interest would attach to relaxation of the constant pressure external boundary condition in order to allow representation of the unsteadiness introduced by surging of the envelope of escaped gas; more futuristically, perhaps, would be accommodation of sea-water ingress as the internal pressure approaches the local external hydrostatic value.

Section 5 offers closing remarks on the prospects for incorporation of improved fundamentals to the individual modelling aspects (unlikely in the short-term) and for introduction of improved formulations in terms of object focused 'intensive' descriptions suitable for PC implementation (promising opportunities). As a bottom line statement on the present exercise, we urge that this avenue should now be pursued in parallel with the establishment of benchmark standards for quality assessment.

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1. INTRODUCTION

1.1 HISTORICAL PERSPECTIVE

The origins of present large code models for two-phase systems reside in thermal hydraulic computational schemes developed more than twenty years ago as accreditation guideline aids for regulatory bodies charged with assessing the safety of nuclear power generation plant. More particularly of relevance here, these codes were employed to evaluate critical scenarios for Loss of Coolant Accidents (LOCAs) with Pressurised Water Reactors (PWRs) and especially with reference to total system response during the evolution of rapid depressurisation events. Probably the best known examples of the genre are TRAC-PF1 (Transient Reactor Analysis Code; 1979) and RELAP 5 (1978), both intended to simulate rapid transients within the cooling system pipework following prescribed failure situations such as that described by Peterson et al (1985). However, the past decade especially has seen growing awareness of the limitations of these models as reliable predictive indicators of the extremely complicated transport dynamics associated with situations involving abrupt adjustment in two-phase composition and flow patterns, etc, as observed for example by Wallis (1980). There is perhaps now a broad consensus of opinion that such codes should best be viewed as illustrative and/or training tools for probing system response trends and sensitivities but not by any means regarded as delivering precise prognoses on the outcome of fault scenarios.

The major obstacle, an issue of basic principles, resides in the classical problem of characterising fluid motions encompassing enormous diversity in scales of motion (statistical closure uncertainties) compounded here by macroscale interphase topology which is determined both by the transport dynamics and by microscale heat fluxes themselves intimately coupled to motions on comparably fine scales. We shall return to this central issue in section 2, linking it with other important questions of uncertainties arising from the adoption of empirical closures secured under idealised conditions, usually from reduced scale modelling, frequently using quasi-steady conditions and commonly for fluids with simplified material properties.

1.2 OIL INDUSTRY CONTEXT

The past decade has seen a considerable upsurge of interest in the adoption of large code approaches for a variety of field applications in the oil industry. One example would be the considerable efforts given to modelling of multiphase production logging (Schlumberger, priv. comm.), to assess the influence of composition nonuniformities on the response of instrumentation tools and especially gas segregation effects in highly deviated wells. Another would be the recent introduction of the 'SIDEKICK' code as operator training software for guideline indications on the evolution of gas kicks in exploration oil wells (Hamilton, Swanson and Wand, 1992). A major challenge here (White, 1991) has been the prescription of realistic transport dynamics for rheological slug bubbles evolving in the eccentric annular geometry of deviated drilling wells, typically manifested as an explicit slip-speed closure formulation in existing calculation schemes. We return to this issue in section 2.

The implementation and introduction of this SIDEKICK code arose largely in response to pressure for improved training and practice following the North Sea 'Ocean Odyssey' incident in September 1988 (see Harrison, 1988), when an uncontrolled gas kick resulted in a serious fire under the rig . However, this incident was largely eclipsed by public concern about the Piper Alpha catastrophe in July of the same year, following which there was the major investigation that culminated in delivery of the Cullen report (1990). The report's call for measures to mitigate the effects of any accident has stimulated modelling initiatives which are centrally relevant here, in particular concerning the efficacy of computational schemes for simulating the relief of pressurised vessels, as briefly reviewed below.

Blowdown of process and storage vessels has long been of major concern to the oil and chemical industries (see Parry, 1991), to the extent that several modelling codes have been developed as design and operational guidelines for venting practices. We mention here SAFIRE (due to Grolmes and Leung, 1985), DIERS (see Klein, 1986; Skouloudis, 1992) and RELIEF, under development at JRC, ISPRA as typical examples which have recently been subjected (by Skouloudis, 1991) to comparative benchmark testing of situations involving laboratory and industrial process vessels. Unfortunately, these codes offer only primitive representations of the flow and thermofluid phenomenologies involved: viz homogeneous flow or simple drift flux model, ideal mixture or user supplied phase equilibrium data, etc (see section 2). So far as we know, these methods have not been implemented for the pipeline geometries of present concern. However, there is another code derived from the same background in process engineering which has been worked up from vessel blowdown scenarios to incorporate vent pipe simulations. Most significantly, this code (BLOWDOWN) offers a detailed characterisation of the thermodynamic response of a hydrocarbon fluid to rapid depressurisation. On the other hand, as described by Richarson and Saville (1991), BLOWDOWN presently provides only a crude representation of the fluid dynamics; see section 2.3. However we understand (priv comm.) that this aspect is presently being addressed with a view to implementing a contemporary model of the two-phase flows. Recognising that with this enhancement BLOWDOWN might well be a possible candidate for adoption here, we offer a critical review of its attributes in section 3. Two other possible candidates identified from our searches are introduced below.

Firstly, PLAC (Philbin, 1991). PLAC (Pipe Line Analysis Code) is directly descended from the PWR code TRAC and is therefore to be regarded as a general transient two-phase model although it has been utilised especially to simulate terrain-induced slugging in transportation pipelines. The flow dynamics are described by a contemporary two-fluid approach (see section 2) but its closure prescription in terms of regime interpolation on limiting maps for horizontal and vertical flow suggests limited robustness. Moreover, its thermodynamic formulation also is unclear from the documentation made available. A detailed critical review of these attributes appears in section 3.

Secondly, OLGA (Bendiksen *et al*, 1991). OLGA appears to be a general purpose field operations code developed in the early 1980's to assess system response to gradually varied conditions on production rate, including start-up and shut-down, but not intended to encompass the rapid transients associated with depressurisation failures. Whilst it seems likely that OLGA was derived from the nuclear origins mentioned earlier, the code has undoubtedly gained unique benefits from an extended period of in-house testing and augmentation focused on the specialist needs of its oil applications environment. As claimed in recently published papers, Bendiksen *et al* (1991) and Rygg and Ellul (1991), the current version of the code features an extended two-fluid approach unifying the closure models for interphase topology and transport dynamics. On the other hand its present prescription for multicomponent exchanges appears to be no better than the rudimentary thermodynamic formulation apparently offered in PLAC and certainly much less sophisticated than that employed in BLOWDOWN. Recognising that BLOWDOWN's formulation of the fluid dynamics is presently unsatisfactory, perhaps the most obvious *a priori* recommendation would be to seek appropriate upgrading of OLGA rather than vice versa. We say this because the computationally intensive demands, both on algorithm work-up and on code execution, reside very

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largely in the fluid dynamics rather than the thermodynamics. Reinforcing the prima facie case for this strategy is a very recent application of OLGA to offshore pipeline rupture scenarios as described by Rygg and Ellul (1991), although we caution that this paper gives no indications of recognising the need for careful formulation of the thermodynamics nor any evaluations of the predictions against real data. We return to a detailed discussion of these points in sections 3 and 4.

1.3 SUBSEA RUPTURE SCENARIO

The scenario envisaged is that an undersea pipeline which may be carrying gas, gas and liquid or gas condensate suffers a rupture or is vented through a safety valve either to a catch tank or to air. In the case of a subsea rupture the pipe contents will be vented to the sea.

The result will, in some cases, be pollution of the seawater, the atmosphere or both but we are primarily concerned here with the evolution of conditions within the pipeline. External conditions, which can change as a result of emissions from the pipe, may, however, feed back via the evolving boundary condition at the break to affect the internal situation.

In the case of an underwater hydrocarbon escape the sequence of events following the rupture will be more complex than in the case of an escape to atmosphere, where the pressure at the exit is constant so that the associated boundary conditions at that point are also steady. As far as is known to the present authors, no attempt has been made so far to produce a physical or mathematical model of the events at the break following an underwater pipeline rupture. To aid discussion of the possible sequence of events following the rupture, we can distinguish three affected zones: viz, internal to the pipe, external but adjacent to the pipe and far afield. These will be considered separately.

a) Internal to the pipe. In the short term, that is while the pipeline pressure at the exit remains sufficiently high, the excess pressure will be sufficient to regard external conditions as quasi-steady whilst the escaping gas is discharged as a locally steady jet or two phase mixture. The exit flow rate will decrease slowly as a result of the pressure decline within the pipe, with possible transitions between gas and two phase flow. Cycling, that is repetitive transitions between limit conditions, would not be expected as part of the short term response.

Once the pipeline exit pressure has dropped sufficiently, that is in the medium term, external instabilities on the escaping gas jet will introduce significant fluctuations in the exit pressure condition as a result of bubble formation. The boundary condition at the break, under these conditions will fluctuate. Further reduction in exit pressure means that the flow could take the form of gas flow from the pipe until the exit pressure approaches the external pressure at which time it could stop until the pressure recovers enough to cause a further escape. The boundary condition then becomes cyclically varying and the flow, particularly if liquid accumulation occurs at the exit, could take the form of slugging, that is periodic expulsion of relatively large volumes of liquid interspersed by a gas or two phase mixture.

In the long term, associated with the reducing pipeline pressure, is the possibility of seawater ingress during the low pressure part of the cycle and the further possibility that this might not be entirely expelled during the next. The presence of water and hydrocarbon within the pipeline may then lead to hydrate formation. The problems associated with hydrate formation in an under-sea gas condensate system are considered by Lingelem and Majeed (1989). As can be seen from the hydrate formation curves

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presented by Baker (1988), the pressure in the long term at seabed temperatures may be insufficient for this to occur.

b) External to the pipe. In the short term, as remarked above, when the pressure excess is sufficient in the immediate neighbourhood of the break there would be a plume of gas or two phase mixture which would evolve to form bubbles at a short distance from the pipe. Where both gas and liquid are leaving at the break, the buoyancy difference will lead to a difference in residence time in the water. In the presence of a sea current, the liquid could be expected to surface downstream of the gas. Heat transfer between gas and the surrounding sea water will need to be considered as the flashing of gas at the break will lead to low exit temperatures. Of particular interest will be the coupling of the hydrocarbon jetting and bubble formation via the water pressure at the break with the flows within the pipe.

c) Far afield. Although this region has no direct bearing on the events internal to the pipe, the progress of the gas and oil to the surface has important safety implications, in particular with reference to the exit temperature of the gas and heat transfer between sea water and gas. Gas which is still sufficiently cold on reaching the surface could form a gas blanket with composition in the explosive range. The ultimate dispersion depending on factors such as weather conditions, sea depth and location could also be included.

Finally account must be taken of the release of hydrocarbon from both ends of the pipe where the break occurs. The location of the break and the resulting pipe lengths on each side will materially affect the outcome, the length of the longer section being the controlling factor.

No computer code is at present available which is able to deal with these aspects of an underwater break. However the candidate codes as discussed later, if suitably modified, may allow this possibility.

1.4 PRESENT PURPOSE

The purpose of the present study is to identify methods by which the evolution of the internal flows following a subsea pipeline rupture can be predicted and, in so far as this defines the boundary condition for the internal flows, the external field. A suitable code is required capable of computing the changes in seawater pressure in the neighbourhood of the break which can be coupled with the pipeline code to provide the necessary boundary condition.

The report consists of three main sections, as follows:

Section 2 on generic fundamentals reviewing two phase modelling prescriptions used for interphase topology, transport dynamics and multicomponent exchanges. Section 3 on specific realisations describing the reported structure and features of the candidate codes namely BLOWDOWN, OLGA and PLAC. This will be in terms of the prescriptive facets specified in section 2 with special reference to main attributes, that is equations, closures, calibrations and validations summarised in Appendices B, C and D. Section 4 on practical recommendations recapitulates the present situation and outlines our views on how to proceed with special reference to the establishment of consensus benchmarks by which relative and absolute performance of candidate codes may be gauged.

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2. GENERIC FUNDAMENTALS

2.1 CONTEXT

The central challenge in all applications modelling of fluid motion is acceptable approximation of the unclosed terms introduced by statistical averaging of nonlinear convective fluxes. In one-phase fluids (or homogeneous approximations of two-phase fluids) the challenge resides merely in characterising eddy flux averages in terms of mean-field quantities - viz the classical turbulence closure problems associated with Reynolds' one-point averaging of the instantaneous equations, first principles of which are excellently covered in the foundation text by Tennekes and Lumley (1972). Whilst this obstacle is modest indeed compared with the additional complexities encountered in two-phase systems, it is important to recognise that adequate universal formulations have still not been achieved despite many decades of intensive effort underwritten by the considerable resources deployed by civil and military aerospace organisations worldwide. In fact, there now appears to be an emerging consensus (Hunt, 1990) that turbulence macrostatistics may well be so field specific that there is no real prospect of robust universal one-point closures and perhaps the only reliable way ahead is with algorithms which resolve at least the major scales of eddy motions and confine their statistically averaged closure modelling to the finer scales (eg Reynolds, 1990).

Two-phase flows exhibit overwhelmingly greater complexity associated with transport dynamical couplings between phases, especially when the interphase topology is also strongly coupled as in the gas-liquid systems of concern here. Contemporary practical calculation methods follow essentially the same statistical strategy as for one-phase fluids, with Eulerian (fixed point) quantities for each phase distinguished by an indicator flag whose long-term average measures the void fraction (Ishii, 1975). This procedure represents the fluids as interpenetrating statistically continuous media and the resulting two-fluid equations contain not only phase averaged eddy fluxes as unclosed terms but also phase interaction source terms associated with transferable quantities. Predictive success or failure is usually mainly determined by the semi-empirical closure prescriptions assigned to the source terms, more especially those describing the interphase momentum transfer. Before overviewing some typical closure strategies we offer the following cautionary remarks on the two-fluid formulation as a question of basic principle.

There is a continuing debate on the fundamental status of existing closure models employed for the momentum transfer terms, in particular the completeness of their formulation measured against first principles force laws elucidated as the set of individual forces experienced by individual elements of a discrete phase embedded in a shear turbulent continuous phase. At the heart of this debate (eg Deutsch and Simonin, 1991) are presently unresolved doubts about the statistical bias introduced by Eulerian sampling of quantities which separately follow different Lagrangian trajectories. As a simple physical illustration we mention (see Hunt *et al*, 1988) the high correlation manifested between individual bubble trajectories and instantaneous vorticity trajectories of the continuous phase (ie concentration amplification by eddy capture and retention), a phenomenology which is not readily characterised in terms of Eulerian time-averaged quantities that fail to resolve this structure. However, whilst the issue is undoubtedly important as a matter of principle, there are acutely more pressing issues about the practical implementation of two-fluid modelling which we now turn to, as follows.

2.2 INTERPHASE TOPOLOGY

Classification of two-phase flows by pattern or regime maps is a necessary precursor to formulation of sensible interphase transfer closure modelling; see Wallis (1969), also Dukler and Kelessidis (1989). Distinguishing the characteristic features of individual regimes is a relatively trivial exercise whether by direct visualisation or by inference from transducer signal records (eg IUTAM Symp., 1983). More uncertain is the assignment of regime transition conditions and there is now considerable literature, for example Taitel and Dukler (1976, 1987), Dukler and Taitel (1982) and Crowley *et al* (1992), devoted to the single issue of appropriate parametric representations for these boundaries, most commonly identified in terms of the superficial velocities (ie fluxes) of gas and liquid. In reality the differences are invariably attributable to the presence of uncontrolled sensitive factors - for example extraneous disturbances or interphase contaminants. Whilst much attention has been given to the importance of scale and material property distortions, (ie small pipe air/water laboratory tests do not reliably reflect field pipe hydrocarbon flows) in terms of dependence on Reynolds, Froude and Weber numbers (see Dukler, 1983), these groups alone do not suffice to characterise the role of interphase dilational elasticity introduced by surfactants or other film forming trace materials that may often be present in hydrocarbon pipelines. The uncertainty about mismatches between the assigned and the true regime transition boundaries must always be remembered for its impact on predictions. Ideally, all predictive calculations would be accompanied by a sensitivity survey of this aspect.

Implementation of the empirical prescriptions conveyed by these maps varies between different algorithms but essentially the same core information is utilised (see Wallis, 1969): namely, first-cut classification of the pattern either as separated (annular/stratified) or distributed (bubbly/droplet) flow followed by the assignment of interphase transfer parameters. Most generally these factors provide measures of the mass, momentum and heat transfer coefficients relating to (for example) evaporation and condensation, separated flow friction or disperse flow slip, also entrainment or deposition of droplets and generation and disengagement of bubbles. In practice not all of these phenomena are usually distinguished explicitly which is probably sensible in view of the considerable uncertainties and gaps in present knowledge of the coefficients, indeed not just values of the coefficients but extending also to unidentified parametric sensitivities of the scalings themselves (viz trace contamination).

As to criteria for systematically discriminating which quantities should be included and which should be omitted, this has to be a matter of experience and interactive postdiction: ie using real data to heuristically enhance and extend calculation capabilities. The potted history of OLGA's evolution (Bendiksen *et al*, 1991) exemplifies this strategy with regard to the hierarchy of transport equations incorporated in the present release: namely, three for mass, two for momentum and one for energy. The five mass-momentum equations relate to the gas and the liquid as separated phases, plus another for 'possible droplets' included *a posteriori* to rectify earlier major discrepancies between calculated and measured values of pressure drop and voidage. On the other hand, using just one energy equation (ie incorporating both phases as a mixed fluid to estimate the temperature field) would seem to demand a more detailed justification and demonstration than is supplied in the published papers. Similarly, it is unclear to us why 'possible bubbles' were apparently deemed of lesser significance: no explanation is offered, not even in the paper (Rygg and Ellul, 1991) on rapid depressurisation transients when dissolution must usually make an important contribution to the gas mass transport.

Before closing this short background account of the modelling role played by empirical prescriptions for the interphase topology, we must also mention another innovatory

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aspect of the OLGA code. Instead of simply employing a parametric specification for the regime transitions (eg. in terms of superficial velocities), it seems that the major transitions can perhaps be adequately encompassed within a single hypothesis of minimum slip, as described by Bendiksen et al (1991). Any such unifying principle would be widely regarded as a striking advance but, unfortunately, only passing mention is made of this interesting notion and its credibility as a validated concept must remain unsure pending delivery of a comprehensive account and detailed assessment. It has been noted by Bendiksen and Espedal (1992) that a condition derived for the onset of slugging based on the existence of waves and a condition for slug growth is mathematically equivalent to the minimum slip principle.

2.3 TRANSPORT DYNAMICS

We have already indicated the main principles and shortcomings of two-fluid approaches, also remarked on one realisation as the driving equations in OLGA. Our discussion is developed here in the context of their practical implementation in viable computational schemes and more particularly with reference to candidate codes for the application of present interest. Probably the most important point is to recognise that, whilst the full equations in principle deliver an ensemble statistical description in terms of three-dimensional and unsteady flow, it is probably impracticable to consider their utilisation as other than sectionally averaged approximations: ie as an axially varying unsteady field. We say approximations because sectional averaging of the nonlinear advective fluxes introduces undetermined profile coefficients which require further closure modelling. In practice, ad hoc assignment of these coefficients is followed, usually as top-hat values (plug flow). Whilst this practice might be adequate for a first approximation with fully developed and gradually developing one phase turbulent flows, there must be considerable uncertainty about its suitability for dispersed elements in two-phase flow where vorticity focusing can enormously amplify their local concentrations within high shear zones of separated flows and wall turbulent boundary layers. Also debatable is the implicit assumption that the profile factors are invariant, or at least only gradually varying, in situations where there may be rapid axial adjustment of the system: ie as in the scenarios of present concern, especially in the vicinity of the rupture point. Careful attention should be paid to gauging the predictive uncertainties introduced by these aspects.

The sectional averaging transformation of stabilising transverse diffusive transport into boundary fluxes changes the mathematical character of the equations from essentially parabolic to essentially hyperbolic (ie axially non-diffusive) and this can have profound implications for their stability at critical conditions corresponding to the inception of Kelvin Helmholtz (KH) waves (see Taitel and Dukler, 1976; Wallis and Dobson, 1973) However, as may be discovered from the considerable literature generated by this issue, the apparent difficulty of complex characteristics disappears when the model is constrained by a sensible interphase topology closure - in particular, recognising that the transition from segregated to slug pattern in horizontal flow occurs subcritically with respect to the inception of KH waves. Whilst not a problem then with well worked-up codes for which there is satisfactory compatibility between the equations and their closures, this trap provides a salutary warning that the introduction of alternative topological closures into an established transport model must be conducted with due awareness of the physical and mathematical implications.

It is worth mentioning the underlying significance which attaches to the hyperbolic approximation in terms of sectionally averaged measures of the variables. This is perhaps best done by beginning with the simplest characterisation in terms of just two variables for the case of horizontal segregated flow: namely, the void fraction (head space) and liquid velocity. This system, simply the shallow water approximation (see Henderson, 1966) for surface waves, possesses two real mathematical characteristics which correspond physically to the celerities of upstream and downstream propagating waves. As is well known, because the celerity increases with local depth, any waves of elevation evolve to propagate with sharp frontal elevations and dispersive trailing faces such that they asymptotically approach so-called 'N-wave' profiles (see Lighthill, 1978). Although an artefact of the shallow water approximation which excludes dispersive behaviour due to pressure field departures from hydrostatic, the description serves well to characterise hydraulic criticality (Froude number unity) and bore/jump dynamics in supercritical flows; see Henderson (1966). Introducing the gas velocity as the third variable supplemented with a thermodynamic state property equation generates further mathematical characteristics corresponding physically to pressure wave speeds in the gas layer; see Wallis (1969). Providing the two sets of wave speeds are sufficiently disparate, these pressure waves would propagate as in quasi-steady geometry and so exhibit essentially the same behaviour as given by the classical equations of gradually varied gas dynamics (Liepman and Roshko, 1957): ie with frontal steepening in compression waves and flow criticality (choking) defined by sonic throat velocity (ie Mach number unity), here located at the travelling stations defined by the interfacial wave crests.

In many practical situations there is a strong dynamical coupling between the gas and liquid flows which derives from subpressures associated with gas-side accelerations over the wave crests and arises at sufficiently low Mach numbers that the gas flow can be regarded as sensibly incompressible. This effect, also the physical origin of KH interfacial instability mentioned earlier, is captured using just the two transport dynamical equations of the shallow water approximation supplemented with a kinematic constraint on continuity of the total flow which algebraically determines the local liquid velocity and depth. The resulting pair of characteristics, again physically representing the celerities of upstream and downstream propagating interfacial waves, now display a non-monotonic dependence on depth for Froude numbers exceeding a special value determined solely by the void fraction (Thomas, 1982). Specifically, the wave speed then exhibits a local maximum such that waves of elevation spanning this depth would exhibit both frontal and lee face sharpening, with the lee face wave speed exceeding that of the frontal face. This behaviour has a gas dynamic analogy in composite expansion-compression shocks which can arise with fluids possessing unusual thermodynamic state equations. More intriguingly, the Froude number formula describing the onset of this condition also furnishes an excellent correlation for the regime transition from segregated to slug pattern. It might well be worthwhile to pursue further this diagnostic interpretation as an alternative to the more empirical correlations employed in the candidate codes surveyed here. On the other hand, there are criteria for slugging inception derived directly from systematic analysis of the linearised disturbance equations (eg Lin and Hanratty, 1986; Prosperetti and Jones, 1988) which apparently capture the essential scalings without reference to nonlinear dynamical features. However, we mention this nonlinear interpretation especially in connection with the prospect of explicitly incorporating multicomponent exchanges (section 2.4) within the above framework of transport dynamics, a simplification that may well be necessary for realistic prospects of a PC-based code.

We close by recalling that the OLGA code has six transport dynamical equations, three for mass, two for momentum and one for energy. Presumably the characteristics here physically represent the pairs of wave speeds associated with pressure disturbances in the gas and with gas-in-liquid disturbances either as distributed void fraction or as interfacial motions, plus a single wave speed associated with liquid-in-gas disturbances (ie droplet kinematics) and another associated with thermal disturbances. This last one we suppose would have its one-phase gas dynamic counterpart in the contact surface which travels as a dissipative discontinuity behind travelling shocks (see Liepmann and Roshko, 1957). The PLAC code, as far as can be judged from the literature supplied,

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also employs six equations in its present release (two each for mass, momentum and energy), with two more apparently to be added in a future version. The physical significance of carrying two energy equations is obviously to distinguish the gas and liquid temperatures and so explicitly represent the interphase thermodynamics. Indeed, it is unclear how the OLGA code can properly address evaporation and condensation without distinguishing these temperatures; presumably they are not distinguished on the grounds that the heat capacity of the liquid overwhelmingly exceeds that of the gas. However, as the gas can be much colder than the liquid, distinguishing these temperatures can still be very important. For further development of these issues see section 2.4.

Lastly, we mention briefly that the BLOWDOWN code presently employs a homogeneous (zero slip) mixture model for its transport dynamical equations: ie one each for mass, momentum and energy, with the local gas fraction estimated assuming thermodynamic equilibrium. Whilst recognising the significant merits of its compactness (numerically undemanding, diagnostically digestible), moreover acknowledging its apparent success in following some main features of testcase multicomponent pipeline blowdowns, such a limited transport phenomenology is unlikely to adequately encompass many situations of practical interest - for example, the evolution of a travelling transition from distributed to separated pattern associated with sufficient depletion of the liquid fraction. Indeed the authors (Richardson and Saville, 1991) themselves have acknowledged such limitations in their present code and have indicated their intention to extend its versatility. At the same time BLOWDOWN's thermodynamic formulation incorporates a substantially more detailed prescription for multicomponent hydrocarbon exchanges than is apparently conveyed in either OLGA or PLAC. The underlying issues on this important aspect are now surveyed in the following section.

2.4 MULTI-COMPONENT EXCHANGES

In arriving at the rates of transfer of material between phases the assumption is usually made that the phases are in thermodynamic equilibrium (van Winkle, 1967). This implies that where compositions are constant no exchange will result. To proceed otherwise would require recourse to non-equilibrium thermodynamics to predict rates of transfer due to driving forces resulting from departures from equilibrium, as, for example, when flashing occurs. Such methods have not so far been applied to pipeline transients but, where rapid fluctuations can be expected as in the proposed application, they may well be required to achieve a satisfactory representation. Where equilibrium is assumed to be maintained, the equilibrium relationship is purely algebraic so that the dependent variables adjust instantaneously. The unsteady representation must strictly be obtained from differential relationships such that, for y(x) with x(t) prescribed, y(t) follows from the chain rule: viz $dy/dt = dy/dx \cdot dx/dt$.

Two main techniques are used within the chemical and oil industries to represent vapour-liquid equilibria (see Dubert, 1985): the use of liquid phase activity coefficients to model liquid non-idealities together with corrections for vapour non-ideality at low or moderate pressures or, at higher pressures, the use of an equation of state to represent both phases simultaneously.

Activity coefficients are used to account for liquid phase non-ideality at low pressures and as the pressure is increased, corrections such as the Poynting factor can be introduced (Dubert, 1985) to account for non-ideality of the vapour phase. Activity coefficient correlations vary from simple algebraic solutions of the Gibbs-Duhem equation

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such as the equations of Margules and van Laar (see Hougen et al, 1959) to physically based correlating equations such as that of Wilson, presented by Orye and Prausnitz (1965), and the NRTL (Nonrandom Two Liquid) equation developed by Renon and Prausnitz (1968) using the local composition concept. Engineering application of these and other correlations are discussed by Dubert (1985). Such applications require parameters generated from phase equilibrium data but, alternatively, purely predictive equations can be generated by means of group contribution methods such as UNIFAC proposed by Friedenslund et al (1975). This is also based on local composition methods but works in terms of molecular functional groups and uses a database of group interaction parameters to generate predicting equations for component activities. Both kinds of thermodynamic representation, that is equation-of-state and activity coefficient, are available in many Chemical Engineering steady state flowsheeting packages such as PRO/II (1990, from SIMSCI Ltd.). Such packages may be used for the simulation of pipeline depressurisation by representing the evolving pressure, composition profiles etc., within the line, as a series of steady state profiles. Some doubts remain over the physics, in particular thermodynamics and two-phase heat transfer, used in such packages, especially in connection with their application to pipeline transient calculations.

An advantage of equation-of-state methods over the activity coefficient approach is that representation of high pressure and near critical behaviour is improved. Departures from ideality of the liquid are less important at higher pressures than accurate representation of vapour phase non-ideality and this is why the equation-of-state method is adopted for most oil industry applications where pipelines are operated at raised pressures. All three candidate codes, that is BLOWDOWN, PLAC and OLGA use an equation of state to handle phase equilibrium calculations. Vartosis (1987) discusses convergence problems for equilibrium calculations using these approaches.

Associated with the thermodynamics is the possibility of composition variation along the pipe. This will occur when the liquid and vapour phases travel at different velocities within the pipe such as in the neighbourhood of a break. In order to take full account of this situation it is necessary to solve mass, momentum and energy balances and equilibrium equations for all of the individual components. The computational demands of this approach will obviously be heavy in dealing with oil flows where the number of components is large.

The problem of dealing with composition variation could be simplified by grouping of components to produce a manageable number of pseudo-components, much in the way that fractionation of oil is handled (see PROC/II, 1990). The components are grouped into two or three volatility levels and each group is then treated as a single component for the purposes of all, including equilibrium, calculations.

2.5 RECAPITULATION

We have seen that, although research in turbulent and two-phase flow is moving rapidly ahead, the topic is exceedingly complicated and choices and approximations must be made in mathematical modelling.

In particular classification of the flow is critically important, with improvements now possible as a result of moving away from the empirical pattern maps which are still widely used.

The form of the sectional averaging of quantities properly described in statistical terms materially affects the results of the simulation.

Finally, the choice of method by which thermodynamic equilibrium relationships are represented, whether by precomputed tables, on line evaluation or user supplied data, is seen to be important.

3. SPECIFIC REALIZATIONS

The attributes of the three candidate codes are summarised here. We begin by recalling the following outline of their main features and then reviewing their structure and capabilities under the descriptive headings of section 2, namely, with regard to interphase topology, transport dynamics and multi-component exchanges. Main driving equations and formulae appear in appendices B, C and D.

BLOWDOWN caters specifically for the blowdown of a pipeline which may be carrying a gas or a liquid condensate. Pure liquid (dead oil) is sufficiently simple to evaluate manually. The pipeline is modelled as a long horizontal line with a short vertical riser at one end at the top of which the escape or venting is assumed to take place (see figure 1a). The other end of the line remains intact.

PLAC is a general purpose code for the simulation of two-phase transient behaviour in pipeline networks, in particular with claimed capacity to handle start-up and shut-down, ruptures and severe slugging, and for which a typical geometry appears in figure 1b.

OLGA is also a general purpose code initially developed for the simulation of slow transients, such as production rate variations and start-up and shut-down associated with mass transport for the typical geometry shown in figure 1c. The code can handle gathering pipeline networks and components such as heat-exchangers, valves, compressors etc. Recently it has also been applied to rapid transient rupture problems.

3.1 INTERPHASE TOPOLOGY

BLOWDOWN. The assumption of homogeneous or non-slip flow is made, leading to the simplest code in this respect. Richardson and Saville (1991) claim the assumption to be justified by a study of flow regimes although details of the comparison are not presented. Whilst comparisons between predicted hold-up and calculated volumetric split look encouraging, no indication is given of how the occurrence of two-phase flow is identified or whether the flow is assumed to be separated or distributed.

PLAC. Empirical flow regime maps (figures 2a and 2b) are assigned for vertical and horizontal flow. For vertical flow this can be bubbly, slug, annular or annular mist with a further interpolated region as shown in figure 2a. Horizontal flow can be slug, churn, annular or stratified with a transition region also shown in figure 2b. Flow is assumed to be horizontal if the inclination of the pipe is less than 10 degrees. The flow maps used appear to be independent of the composition of the hydrocarbon. Interfacial shear and heat and mass transfer are calculated in conjunction with the separate flow regime maps and the predictions obtained depend upon the correlation used for interfacial friction.

OLGA. Two-phase flow regimes are considered to be either distributed, which includes bubble and slug flow or separated which includes stratified and annular mist flow. Flow pattern maps are not used in OLGA but the regime is selected according to the "minimum slip" concept, that is the flow regime yielding minimum gas velocity is chosen. Although only limited theoretical justification is given for the adoption of Wallis' (1969) observation as a general principle (Bendiksen and Espedal, 1992 for horizontal slugging inception), good agreement is demonstrated by the authors between prediction and experiment for a restricted range of pipe diameters. Figures 3 and 4 show the comparisons between experimentally determined pattern maps and OLGA prescriptions for two systems.

3.2 TRANSPORT DYNAMICS

BLOWDOWN. Mass, momentum and energy balances are posed as one-dimensional and solved using axial discretization. The equations used (Appendix B), though not presented, are described as set up using a quasi-steady approximation, that is the mass flow rate is assumed to be the same in every element at a given time. This would seem to imply that the fluids within the pipe are incompressible as flow transients must be transmitted instantaneously. This is clearly incompatible with the properties of gases generated from the thermodynamics package.

A logarithmic friction factor, equation (B1), is used within the momentum balance implying the assumption of turbulent conditions throughout although BLOWDOWN can also handle laminar flow within this same framework of Reynolds number dependent prescribed friction factor. Provision is made for choked flow at the pipeline exit, that is where sonic velocity is reached in the case of a gas so that no increase in flowrate results from a decrease in exit pressure, and critical flow in the case of a two phase escape. In the case where the fluid approaching the orifice is all volatile liquid, a flashing flow algorithm is used, based on the work of Abuaf et al (1983) but significantly modified to handle hydrocarbon mixtures.

PLAC. As listed in Appendix C, the mathematical model on which PLAC is based is formulated as a fully three-dimensional two-fluid representation allowing for friction and other dynamic interactions between the phases. However, in practice, it is utilised as the one-dimensional approximation discussed earlier. Moreover, it is stated that PLAC has, at present, no means of accommodating composition variation with time along the pipeline. As indicated above this limitation has implications regarding the capacity of the code to handle ruptures. Although a significant increase in complexity would be required to accommodate composition variations, a version of PLAC with this capacity is being developed (priv. comm.). PLAC, like BLOWDOWN has, at present, no means of accommodating composition variation between cells. Pipeline ruptures can be handled by PLAC but composition variations which result from the ensuing non-homogeneous flow, that is unequal liquid and vapour velocities, are not taken into account. The mass balance is carried out on "combined vapour" whose exact nature is not made clear but we understand it does not incorporate a droplet field.

OLGA. The equations used in OLGA are summarised in Appendix D. The fluid is assumed to consist of gas and liquid phases together with a droplet field travelling at approximately the gas velocity. Mass balances are carried out in one dimension on gas, liquid and droplets respectively and are given in equations D1 to D3. The momentum balance on the liquid phase is given in equations D4 and those on the gas and droplet phases are combined in equation D5 in which the gas/droplet drag terms cancel out. The energy equation is given in equation D6 and, to facilitate solution, equations D1 to D3 are expanded in terms of pressure, temperature and composition to give a single pressure equation D7.

According to Bendiksen et al (1991), "the total mixture composition is assumed to be constant in time along the pipeline." This would effectively rule out composition variation so OLGA, in common with PLAC, assumes that the total composition profile along the pipeline remains fixed during the simulation. As already noted, compositions can be expected to vary along the pipe in the vicinity of a rupture due to increased phase slip. A comparison by Rygg and Ellul (1991) on the results of a rupture calculation using OLGA with the assumptions of homogeneous and slip flow shows that constraining the gas and liquid phases to travel at the same velocity causes significant underestimation of the outflow of gas. The outflow of liquid is initially underestimated but thereafter overestimated. No information is available on how these flows would compare with real cases.

3.3 MULTI-COMPONENT EXCHANGES

BLOWDOWN. Rigorous thermodynamics are used within BLOWDOWN by means of the thermodynamics package PREPROP. This uses an extended principle of corresponding states to relate the properties of multicomponent mixtures to those of a single reference substance (methane). The principle of corresponding states assumes that the thermodynamic properties of the mixture are functions of the reduced temperature and pressure. In the opinion of Richardson and Saville (1991), accurate representation of the thermodynamics is of critical importance in the simulation of depressurisation and the use of PREPROP is a major factor in the success of their examples. A component physical property database is resident in PREPROP for the generation of fluid properties and the user can supply additional components if required.

PLAC. At present the thermodynamics used within PLAC are implemented by means of the package EQUIPHASE based on the Peng-Robinson equation of state (Walas, 1987). The limited nature of the package is acknowledged by the authors who have indicated that a more advanced PVT package is currently being implemented. It will then be possible to either pre-calculate a table of PVT data or to calculate this on a point-by-point basis. As with BLOWDOWN it is not clear how much user supplied information is needed for the execution of the PVT package.

OLGA. Interfacial mass transfer is calculated based on the assumption of equilibrium distribution of liquid and vapour. The gas/liquid split is calculated assuming thermodynamic equilibrium between the phases. The mass fraction is then differentiated with respect to pressure, temperature and position to yield equation D9 for the mass transfer rate. Mass transfer driven by non-equilibrium between phases is thus ignored.

The information available on the thermodynamics used within OLGA is similar to that available for PLAC. Any PVT package based on an equation of state can be used to generate tables of properties which are then used within the simulation. The degree of sophistication of the package is presumably dependent on the user and so, in the absence of further information, will be assumed to be equivalent to that used by PLAC. The comment of Richardson and Saville (1991) on the relative merits of the thermodynamic packages PREPROP and that used in PLAC is also applicable to the thermodynamics in OLGA.

The package used for the generation of phase equilibria is supplied by the user as will be the data used. This means that quality of any prediction is critically dependent on the quality of the user input.

3.4 SUMMARY

As listed above, the packages are in an approximate order of increasing complexity and refinement of transport dynamics and interphase topology and declining rigour of the thermodynamics or multi-component exchanges. The central issue would seem to be whether thermodynamic or fluid mechanical modelling makes the greater contribution to prediction quality. This point is re-examined in section 4 in the light of some of the validatory comparisons presented by the authors.

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4. PRACTICAL IMPLEMENTATIONS

4.1 BENCHMARK TESTS

Each candidate code has been subjected to testing by its authors against laboratory or industrial scale experimental data. The nature of the test cases used for each code is described below and the current capabilities are reviewed with reference to these published results.

BLOWDOWN. The BLOWDOWN code has been evaluated against two sets of experimental data, both at industrial scale. A third prediction, on a similar scale but not backed up experimentally, is not considered further here. The first set of data were reported by Cowley and Tam (1988) on full-scale experiments carried out at the Isle of Grain . These were performed on a 100m pipeline of 0.15m bore carrying commercial propane. The line was initially at 11 bar and 20 C and was vented through orifices ranging from 0.1m to full bore. The orifice size used in this case was full bore, 0.15m. Some main features of the facility are identified in Appendix E.

The measured and predicted pressure and temperature responses at the intact end of the line and the inventory of the line are shown in figures 5 to 7. These indicate that the pressure and temperature profiles during the blowdown are predicted with fair accuracy apart from an initial rapid pressure drop followed by a recovery which is attributed to approximation of the dynamics of the initial expansion wave. During the last stages of the blowdown the pressure is increasingly overestimated as is the inventory. Such an error in the prediction of liquid inventory, which is important for the assessment of safety and pollution hazards would clearly lead to an underestimation of the time required for full pipeline clearance. It is understood (Richardson, priv. comm.) that HSE funding has been provided for a full validation of BLOWDOWN against the Isle of Grain data.

The second set of data is that recorded during the Piper Alpha blowdown in July 1988 as reported by Richardson and Saville (1989). The subsea line length was 53804m with bore 0.4191m and the break was assumed to provide a full bore orifice. The initial pressure in the line was 117 bar and a typical summer sea temperature of 10 C was assumed, giving a line inventory of 51 million standard cubic feet (mmscf). The only data available is the recorded pressure at the intact end and this is compared with the prediction in figure 8. In contrast with data on the smaller scale experiment the agreement here is particularly good during the final stages of the blowdown. This could be because the higher flows and turbulent conditions existing in this case are better represented by the homogeneous flow friction factor used.

PLAC. Validation runs provided for PLAC include, amongst others, the prediction of severe slugging in a pipeline and riser system and transients during start-up and shut-down of a flow line. Only one comparison is provided relevant to the present purpose and this uses data obtained by Cunliffe (1978) on a production rate change in the Marlin gas condensate trunk-line near Melbourne. To meet increased demand, the line was subjected to an increase in flowrate from 155 mmscf per day (mmscfd) to 258 mmscfd. The topography of the line is shown in figure 9 and the comparison between observed and calculated condensate outflow is given in figure 10. The results show that excess condensate within the line is swept out over the first few hours. The initial surge representing this excess is seriously underestimated by PLAC and this is attributed to a correlation

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(Andritsos, 1986) for interfacial friction which overpredicts at high pressures. The authors suggest improved agreement with experiment could be obtained using a different model. The same problem would be likely to lead to serious error in liquid inventory prediction if PLAC was used for the simulation of pipeline blowdown. It should be appreciated, however, that the hydrocarbon composition is not given and the prediction is sensitive to the composition chosen.

The final condensate outflow from the pipeline is accurately predicted which is to be expected if the overall mass balance is to be satisfied. From a simple visual inspection it appears that the rate of approach to the final flowrate is rather overestimated in the simulation, although this is difficult to assess due to large fluctuations in the experimental data. The absence of such fluctuations in the simulation is surprising as these are likely to be terrain induced and one of the claimed strengths of PLAC is its capacity to represent such dynamic behaviour.

OLGA. The validations available for OLGA cover a wide range of pipe lengths and diameters both at steady state and under dynamic conditions. Principally, use is made of data from the SINTEF Two-Phase Flow Laboratory as described in detail by Bendiksen *et al* (1986; Bendiksen et al 1991). Their facility consists of a 334m pipe of which test sections of various lengths may be selected coupled with a 2 degree sloping section of length 64m terminating at a 54m riser. Some current facilities in the laboratory are summarized in Appendix E.

The SINTEF data was used for both steady state and dynamic experiments. The steady state experiments are of interest here because they allow validation of the minimum slip principle to locate flow regime transition boundaries; recall figures 3 and 4. Figures 11, 12, 13 and 14 show other steady state comparisons of pressure drop and liquid holdup which are dependent upon the selection of the correct flow regime. The predictions are clearly successful overall and should encourage a further analysis of the theoretical basis of the minimum slip principle.

The SINTEF Laboratory has also been used for dynamic experiments where the inlet flowrate was time varying as shown in figure 15. In this case the slope along the section of the pipe adjacent to the riser was removed. Variation of liquid holdup at points along the pipe are compared with OLGA predictions in figure 16 and in the riser in figure 17. Pressure variation at a point near the beginning of the pipe is given in figure 18. Again the results are encouraging and lead to the expectation of a similar performance for OLGA in a blowdown simulation.

4.2 DATABASE EXTENSION

According to the comparisons summarised in the previous section only BLOWDOWN has been validated against experimental blowdown data. Some capacity for systematic error on pipeline inventory is evident, probably arising from the simplifying assumptions in the representation of interphase topology and transport dynamics: for example, the assumption of homogeneous flow. The production rate change used to evaluate PLAC also shows deviations which could originate from the use of simple empirical flow regime maps or, as suggested by the authors, with the correlation used for interfacial friction. The shortcomings thus lie, principally, in the modelling of the interphase topology. OLGA seems to be strong in most areas except possibly multi-component exchanges. Again the validation of OLGA is encouraging but the immediate need is for validation against blowdown data.

In order to arrive at a fair assessment of the relative capabilities of the candidate codes, it is clear that a common set of experimental data needs to be used for the validation of each. Most satisfactory from the point of view of the present need, such an exercise would involve a pipeline blowdown rather than the production rate changes used to check PLAC and OLGA. It is suggested that the data used by Richardson and Saville (1991) to check BLOWDOWN's performance would serve this purpose as a first comparative benchmark.

The conditions under which the candidate codes have been validated above do not include those which are of interest in dealing with subsea conditions. Although no experimental investigations appear to have been carried out which would provide the necessary information, it would be useful to try to produce a suitable pipeline specification and rupture location on which the codes may be evaluated.

Clearly the conclusions which could be reached as a result of this exercise would be limited in that predictive quality could not be assessed. It would show, however, whether the codes could be modified to deal with this situation at all and, if so and useable simulations are produced, the relative plausibility of the results obtained.

It is suggested that one immediate way forward would be for all three codes to be run on an agreed trial set of data in which the external pressure at the break is made time varying. This would give an early indication of whether numerical instabilities might preclude the use of a particular code. As a situation which could also be realised experimentally, release via a time varying control valve would also provide a useful validation. This possibility is now the subject of preliminary discussion with our correspondents here.

4.3 CURRENT DEVELOPMENTS

The development of BLOWDOWN is continuing with further refinement of the thermodynamics to include composition variation. Information on how the increased computational load is to be accommodated is not yet available.

A future version of PLAC is also to include the capacity to handle composition variation. The computational demands are to be met in this case by introducing simplifications to the thermodynamics along the lines indicated in section 2.4 and research is currently in progress to identify the most efficient ways of combining and implementing such methods of approximation.

It is interesting that a new version of OLGA already exists, but is not yet generally available, which handles composition variation. Simplification of the thermodynamics may be involved but details are not yet available. The new version also provides for non-equilibrium between bulk fluid phases with equilibrium at the interface. Mass transfer then takes place between the bulk and interface such as to lead towards thermodynamic equilibrium. OLGA has also been recently enhanced (Straume *et al*, 1992) with the implementation of a Lagrangian slug tracker which eliminates the numerical dispersion errors introduced by Eulerian discretization schemes. Another development (Fuchs, 1992) particularly relevant to the present need is the emergence of a three-phase version (WOLGA) which accommodates the presence of water as a distinguished component of the liquid phase. Preliminary results show that water has a significant effect on the liquid inventory in the pipe which is not modelled satisfactorily using OLGA.

These modifications, proposed and in hand, for all the three codes materially improve the prospects for predicting the consequences of a subsea hydrocarbon release.

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5 CLOSING REMARKS

5.1 PROSPECTS FOR IMPROVED FUNDAMENTALS

Codes which are well supported at a fundamental level, such as the two-fluid flow model MELODIF developed at Laboratoire National d'Hydraulique (Simonin and Viollet, 1990), have not been applied to the simulation of transients in hydrocarbon pipelines. So far MELODIF has been used to assess the axial injection of a stream of liquid oxygen into turbulent flow of gaseous hydrogen with the object of investigating interactions between the phases, also dispersion of the liquid droplets and the droplet size distribution. Recent refinements to MELODIF's dynamical modelling of bubbly turbulent shear flows have been reported in, for example, Bel F'dhila (1991).

For the three candidate codes under consideration here, the immediate needs for improvement in interphase topology are clearly in hand with the OLGA code but detailed modelling of flow regime transitions is yet to be incorporated into BLOWDOWN. Flow regime prediction is an active research area and improvements on the empirical pattern maps used by PLAC should certainly be possible. Transport dynamical equations are one-dimensional in every case and there is no strong case for compounding existing uncertainties by introducing a radial component for the geometries involved in pipeline applications.

Recently, earlier doubts about the physical description afforded by PWR transient emulators, in particular COMMIX 2, RELAP 5 and TRAC PF1 have been reinforced in a detailed analysis by Drew in Arnold *et al* (1990) of the thermodynamic implications of two-fluid modelling for consistency with the second law of thermodynamics. They concede that the inconsistencies do not necessarily imply a large error. From our reading of this work the implication would be that any errors would become vanishingly small at low Mach numbers. More contentious is the physical plausibility of turbulence modelling for the continuous phase, especially in rapidly accelerated flows when the entropic inconsistencies would mainly arise. There may be a case for introducing the entropic constraints suggested by Arnold *et al* to correct for this shortcoming.

The obvious need for composition dependence in certain cases is being met in all three codes and the thermodynamics is currently being upgraded in PLAC and OLGA. The possibility of including a database of pure component or molecular group properties and interactions is attractive but this must be weighed against the advantages of using equilibrium data supplied by the user and in which he has confidence.

5.2 AVAILABILITY ON PC MACHINES

It would be useful in many applications to have a version of the code, possibly cut down, which could be run on a PC. We report briefly below on machine requirements of the three candid te codes surveyed here.

BLOWDOWN runs on an i860 enhanced PC-386, about 40 times faster than the basic processor. A calculation which requires more than a few minutes on the i860 would be impractical on an unenhanced PC.

PLAC currently runs on a SUN Sparc2 workstation with a typical run time of 0.25s per time step for a model using 100 cells and with fully optimised code. This suggests more than one second per step on a 486 PC which would mean run times of 1 to 5 hours for a blowdown simulation. A PC version of PLAC running under Microsoft Windows is, however, due for release in 1993. It is not clear to what extent this version will be cut down or whether the composition variation update will be included.

Fast UNIX workstations have been used for the development of OLGA but the final version may be implemented on a PC. A version of OLGA for simulation of the killing of blow-outs (Olga-Well-Kill) is now running on a PC. The specification of the PC used is not known and it is not clear whether the PC versions are the latest including composition variation or whether any code simplification is involved.

5.3 OTHER CODES

No other obvious options have been identified which can be regarded as significantly affecting the position reported above. A new product from SimSci (TRANSIM, due for release in 1992) apparently covers much of the same ground as PLAC and OLGA. We have no more details on this emerging product at present.

We have also been informed of the codes PEPIT (contact Dr J.P Bertoglio, Ecole Centrale de Lyon) and SPECTRUM (contact Prof. Fannelop, ETH Institut fur Fluid Dynamik).

5.4 BOTTOM LINE STATEMENT

In sum, there are no obvious candidates beyond the three codes surveyed here. Of these, PLAC's documentation is presently inadequate for detailed appraisal of its basis and prospects, especially in the scope and depth of its validation which has not yet been subjected to the scrutiny of peer review for public domain publications This situation may be remedied soon (Philbin and Butcher, priv. comm.) and we understand that a substantially enhanced version of PLAC is being developed for total system analysis of blowdown events involving valves and long pipelines with complex topography. Of the other two codes, BLOWDOWN's strength presently resides in its careful thermodynamic formulation and OLGA's in its comprehensive coverage of the flow dynamics. Although both ingredients are crucial, on balance we judge the latter to be the more challenging aspect for reliable characterisation and must therefore recommend OLGA ahead of BLOWDOWN. However, if PC-executable software is a crucial factor, then BLOWDOWN's thermodynamic formulation combined with an educated compromise on OLGA's flow dynamic modelling would undoubtedly be the appropriate way to proceed. This niche defines the best prospect for worthwhile future action.

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REFERENCES

Abuaf,N. Jones,O.C. and Wu,B.J.C. (1983)
"Critical Flashing Flow in Nozzles with Subcooled Inlet Conditions"
Trans ASME J.Heat Transfer 105 379.

Andritsos,N. (1986)
"Effect of Pipe Diameter and Liquid Viscosity on Horizontal Stratified Flow (Two-phase, Wave Generation)"
Ph.D. Thesis, University of Illinois at Urbana-Champaign.

Arnold,G.S. Drew,D.A. and Lahey,R.T. (1990)
"An Assessment of Multiphase Flow Models Using the Second Law of Thermodynamics"
Int.J.Multiphase Flow 16 No.3. 481.

Baker,A.C. (1988)
"Flow Simulation Model Used to Optimise Remote Production Systems"
Paper D2, BHRA: Offshore Multiphase Production. London Sept.

Barnea,D. (1980)
"Flow Pattern Transition for Gas-liquid Flow in Horizontal and Inclined Pipes"
Int.J.Multiphase Flow 6, 217.

Bel F'dhila, R. (1991)
"Analyse Experimentale et Modelisation d'un Ecoulement Vertical a Bulles dans un Elargissement Brusque"
Ph.D. Dissertation, INP Toulouse.

Bendiksen,K.H. and Espedal,M. (1992)
"Onset of Slugging in Horizontal Gas-Liquid Pipe Flow"
Int.J.Multiphase Flow 18 No.2. 237.

Bendiksen,K.H. Malnes,D. Moe,R. and Nuland,S. (1991)
"The Dynamic Two Fluid Model OLGA: Theory and Application"
Soc.Pet.Engrs. Production Engineering. Paper SPE 19451.

Brandt,I and Fuchs,P (1992)
"Multiphase Flow - an Update"
EXPRO '92 International Review of Hydrocarbon Exploration and Production Technology 153.

Cowley,L.T. and Tam,V.H.Y. (1988)
"Consequences of Pressurised LPG Releases: the Isle of Grain full-scale Experiments"
Presented at GASTECH 88, Kuala Lumpur.

Crouzier,O. (1978)
"Ecoulements diphasiques gaz-liquides dans les conduites faiblement inclinees par rapport a l'horizontale"
MS thesis, l'Universite Pierre et Marie Curie, Paris.

Contents

Crowley,C.J. Wallis,G.B. and Barry,J.J. (1992)
"Validation of the One-dimensional Wave Model for the Stratified to Slug Transition Boundaries"
Int.J.Multiphase Flow 18 No.2. 249.

Cullen,W.D. (1990)
The Public Enquiry into the Piper Alpha Disaster
HMSO. London 134.

Cunliffe,R.S. (1978)
"Condensate flow in a Wet-gas line can be Predicted"
Oil and Gas J. Oct 30.

Deutsch,E. and Simonin,O. (1991)
"Large eddy Simulation Applied to the Motion of Particles in Stationary Homogeneous Fluid Turbulence"
Turbulence Modification in Multiphase Flow: 1st ASME-JSME
Fluids Eng. Conf. 35.

Dubert,T.E. (1985)
"Chemical Engineering Thermodynamics"
McGraw-Hill.

Dukler,A.E. (1983)
"Flow Patterns"
Int. Symp. on Two-phase Gas-liquid Flow in Pipes. Cuernavaca, Mexico Aug 8-9 Paper 1.

Dukler,A.E. and Kelessidis,V.C. (1989)
"Modelling Flow Pattern Transitions for Upward Gas-liquid Flow in Vertical Concentric and Eccentric Annuli"
Int.J.Multiphase Flow 15 No.2 173.

Dukler,A.E. and Taitel,Y. (1982)
"Modelling Flow Pattern Transitions for Gas-liquid Flow"
Trans. Amer. Nuc. Soc. 41 666.

Fredenslund,A Jones,R.L. and Prausnitz,J.M. (1975)
"Group-contribution Estimation of Activity Coefficients in Nonideal Liquid Mixtures"
AIChE Journal 21 1086.

Fuchs,P. (1992)
"Three-phase Modelling is a Must"
Multiphase Transportation III (Rotrov, Norway; September).

Grolmes,A.M. and Leung,J.C. (1985)
"Code Method for Evaluating Integrated Relief Phenomena"
Chem.Eng.Prog. August 47.

Hamilton,T. Swanson,B. and Ward,P. (1992)
"Use of new Kick Simulation will Increase Wellsite Safety"
World Oil, September 71.

Harrison,P. (1988)
"Blowout and its Prevention"
Prof. Engng. 1 No.6 Nov. 50.

Contents

Henderson,F.M. (1966)
"Open Channel Flow"
N.Y. London MacMillan.

Hougen,O.A. Watson,K.M. and Ragatz,R.A. (1959)
"Chemical Process Principles, Part Two: Thermodynamics"
Wiley N.Y.

Hunt,J.C.R. (1990)
"Numerical Simulation of Unsteady Flows and Transitions to Turbulence"
Proc. ERCOFTAC Workshop at EPFC (Lausanne). CUP.

Hunt,J.C.R. Auton,T.R. Sene,K. Thomas, N.H. and Kowe,R. (1988)
"Bubble motions in Large Eddies and Turbulent Flows"
Transient Phenomena in Multiphase Flow Ed. N.H. Afghan p103 Hemisphere.

Ishii,M (1975)
"Thermo-fluid Dynamic Theory of Two Phase Flow"
Eyrolles, Paris.

IUTAM Symposium (1983)
"Measuring Techniques in Gas-liquid Two-phase Flows"
Abstracts of papers (INP Lorraine, Nancy).

Liepmann,H.W. and Roshko,A. (1957)
"Elements of Gas Dynamics"
Wiley N.Y. and London.

Lighthill,J. (1978)
"Waves in Fluids"
Camb. Univ. Press.

Lin,P.Y. and Hanratty,T.J. (1986)
"Prediction of the Initiation of Slugs with Linear Stability Theory"
Int.J. Multiphase Flow 12, 79-98

Lingelem,M. and Majeed,A. (1989)
"Challenges in Areas of Multiphase Transport and Hydrate Control for a Subsea Gas Condensate Production System."
Proceedings 68th Annual Convention of the Gas Processing Association Ch.33 19.

Orye,R.V. and Prausnitz,J.M. (1965)
"Multicomponent Equilibria with the Wilson Equation"
Ind. Eng. Chem. 57 No.5, 18.

Parry,C.F. (1991)
"Relief Systems Handbook"
Inst. Chem. Engrs. Rugby.

Peterson,C.E. Chexal,V.K. and Clements,T.B. (1985)
"Analysis of a Hot-leg Small Break LOCA in a Three Loop Westinghouse PWR Plant"
Nuc. Tech. 70 No.1 104.

Philbin,M.T. (1991)
"The Simulation of Transient Phenomena in Multiphase Production Systems"
AEA Harwell Report AEA-APS-0177.

Contents

PRO/II Users Manual (1990)
SIMSCI Ltd. Stockport.

Prosporetti,A. and Jones,A.V. (1987)
"The Linear Stability of General Two-phase Flow Models"
Int. J. Multiphase Flow 13 161

RELAP 5 (1978)
"A Computer Program for Transient Thermal Hydraulic Analysis of Nuclear Reactors and Related Systems"
Users Manual, CADP TR 003
Available as National Energy Software Centre Code NESC 0917.

Renon,H. and Prausnitz,J.M. (1968)
"Local Compositions in Thermodynamic Excess Functions for Liquid Mixtures"
AIChE Journal 14 No.1 135.

Reynolds,W.C. (1990)
"The Potential and Limitations of Direct and Large Eddy Simulations"
Whither Turbulence, Turbulence at the Crossroads 357 Ch.30 313.

Richardson,S.M. and Saville,G. (1989)
"Analysis of Flows in Piper Alpha Gas Import and Export Lines"
Transcript of Days 90/91 of Piper Alpha Public Inquiry.

Richardson,S.M. and Saville,G. (1991)
"Blowdown of Pipelines"
Soc.Pet.Engrs. Paper SPE 23070.

Rygg,O.B. and Ellul,I.R.(1991)
"The Dynamic Two-phase Modelling of Offshore Live Crude Lines"
Offshore Tech. Conf. Paper OTC 6747.

Simonin,O. and Viollet,P.L. (1990)
"Prediction of an Oxygen Droplet Pulverisation in a Compressible Subsonic Coflowing Hydrogen Flow"
1990 Spring Meeting of the Fluids Engineering Division of ASME June 4 - 7 .

Skouloudis,A.N. (1991)
"Benchmark Exercises on the Emergency Venting of Vessels"
J. Loss Prev. Process Ind. 5 No.2 89.

Straume,T Nordsveen,M and Bendiksen,K (1992)
"Numerical Simulations of Slugging in Pipelines"
ASME Int. Symp. on Multiphase Flow in Wells and Pipelines. Anaheim, November.

Taitel,Y. and Dukler,A.E. (1976)
"A Model for Predicting Flow Regime Transitions in Horizontal and Near Horizontal Gas-liquid Flow"
AIChE Journal 22 47.

Taitel,Y. and Dukler,A.E. (1987)
"Effect of Pipe Length on the Transition Boundaries for High Viscosity Liquids"
Int. J Multiphase Flow 13 No.4 577.

Contents

Tennekes,H. and Lumley,J.L. (1972)
"A First Course in Turbulence"
London M.I.T.Press.

Thomas,N.H. (1982)
"Horizontal Two-phase Flows: Transition from Stratified to Slugging"
Multiphasic Flows Meeting at EPS Clamart. Schlumberger (priv. comm.).

TRAC-PIA (1979)
"An advanced Best Estimate Computer Program for PWR LOCA Analysis"
NUREG/D - 0665-LA 7777 - MS March (1979)
TRAC-PF1 available as National Energy Software Centre Code No. NESC 0836.

van Winkle,M. (1967)
"Distillation"
McGraw-Hill, New York.

Vartosis,N. (1987)
"A Robust Prediction Method for Rapid Phase Behaviour Calculations"
Soc.Pet.Engrs. Paper SPE 16943.

Walas,S.M. (1987)
"Phase Equilibrium in Chemical Engineering"
Butterworth Publishers. Boston.

Wallis,G.B. (1969)
"One-dimensional Two-phase Flow"
McGraw Hill Book Co.Inc. New York City.

Wallis,G.B. (1980)
"Theoretical Models of Gas-liquid Flows"
Keynote address. ASME, Polyphase Flow and Technology Symposium, San Francisco.

Wallis,G.B. and Dobson,J.E. (1973)
"The Onset of Slugging in Horizontal Stratified Air-water Flow"
Int.J.Multiphase Flow 1 173.

White,D.B. (1991)
"Gas-rise Velocities During Kicks"
SPE Drilling Engineering 6 (4) 257.

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APPENDICES

Appendix A

TECHNICAL SPECIFICATION

A need has been identified for improved and extended capabilities in the characterisation of events following the rupture of subsea pipelines, particularly but not exclusively seabed risers to production platforms. This enhancement is to be achieved by building on information not only from public domain literature sources but also, so far as is possible, from databases held by industry sources. The scientific basis to existing software for multiphase pipeflow and depressurisation modelling is to be critically appraised, especially with regard to crucial omissions in going from on-shore to off-shore applications: eg. gas slugging against ingress water flows.

Specific attention will be given to shortlisting candidates for potential future enhancement and extension. A critical assessment will be provided of existing methods for predicting the outcome of subsea line failure with special reference to hazard evaluation in terms of the ensuing two-phase fluid escape and evolution dynamics. The survey will extend to validation against real data and the prospects for implementing extension benchmarks with new data from appropriate facilities. Special emphasis will be given to the current status of computational schemes and the prospects for PC-DOS software as hazard diagnostic tools. An important element here will be the formulation of physically secure and, so far as is possible, first principles ideas about the sequence of events following the fracture of submerged oil-gas and gas condensate pipelines. Soundness and generality are paramount needs at this stage, in order to retain best prospects for encompassing the wide variabilities in compositions and pressures encountered from field to field.

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Appendix B

SUMMARY FORMULATION OF THE BLOWDOWN CODE

The code is defined in the paper by Richardson and Saville (1991) . The mass, momentum and energy balance equations used are not reported, but the balances for each element are linked in an iterative scheme to satisfy the boundary conditions. These are specified pressure at the intact end and a pressure of 1 bar at the exit or choking conditions (see below).

The momentum balance uses the friction factor for single phase flow correlated by

$$\frac{1}{\sqrt{f}} = 2.28 - 4.0 \log \left[\frac{e}{D} + \frac{4.67}{Re\sqrt{f}} \right] \tag{B1}$$

where e is roughness, D is the pipe bore and Re = $4F/\pi\mu D$ where μ is fluid viscosity and F is the flowrate.

Choking: for a gas, the speed of sound, a, in the orifice is given by

$$a = \left[\frac{dp}{d\rho} \right]^{1/2} \tag{B2}$$

For a two phase mixture, the material approaching the orifice is assumed to be in "thermodynamic and phase" equilibrium and critical flow is imposed. Where the material approaching the orifice is all volatile liquid, a modified version of the flashing flow algorithm due to Abuaf *et al* (1983) is used.

Appendix C

SUMMARY FORMULATION OF THE PLAC CODE

No paper is available in the public domain specifying the basis for the PLAC code. The following is extracted from AEA Petroleum Services internal reports and publicity material provided by UKAEA.

The balance equations are:

Liquid mass

$$\frac{\partial(1-\alpha)\rho_l}{\partial t} + \nabla.\left[(1-\alpha)\rho_l\vec{V}_l\right] = -\Gamma + \textit{mass source terms} \qquad \text{(C1)}$$

Combined vapour mass

$$\frac{\partial(\alpha\rho_g)}{\partial t} + \nabla.[\alpha\rho_g\vec{V}_g] = \Gamma + \textit{mass source terms} \qquad \text{(C2)}$$

Liquid momentum

$$\begin{aligned}\frac{\partial\vec{V}_l}{\partial t} + \vec{V}_L\nabla\vec{V}_l &= -\frac{1}{\rho_l}\nabla p + \frac{c_i}{(1-\alpha)\rho_l}(\vec{V}_g-\vec{V}_l)|\vec{V}_g-\vec{V}_L| \\ &- \frac{\Gamma^-}{(1-\alpha)\rho_l}(\vec{V}_g-\vec{V}_l) - \frac{c_{wl}}{(1-\alpha)\rho_l}\vec{V}_l|\vec{V}_l| \\ &+ g + \textit{momentum source terms}\end{aligned} \qquad \text{(C3)}$$

Vapour momentum

$$\begin{aligned}\frac{\partial\vec{V}_g}{\partial t} + \vec{V}_g.\nabla\vec{V}_g &= -\frac{1}{\rho_g}\nabla p - \frac{c_i}{\alpha\rho_g}(\vec{V}_g-\vec{V}_l)|\vec{V}_g-\vec{V}_L| \\ &- \frac{\Gamma^+}{(1-\alpha)\rho_g}(\vec{V}_g-\vec{V}_L) - \frac{C_{wg}}{\alpha\rho_g}\vec{V}_g|\vec{V}_g| \\ &+ g + \textit{momentum source terms}\end{aligned} \qquad \text{(C4)}$$

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Vapour energy

$$\frac{\partial}{\partial t}(\alpha\rho_g e_g) + \nabla.(\alpha\rho_g e_g \vec{V}_g) = -p\frac{\partial \alpha}{\partial t} - p\nabla.(\alpha\vec{V}_g)$$ (C5)

$$+ q_{wg} + q_{ig} + \Gamma h_{sg} + \textit{energy source terms}$$

Total energy

$$\frac{\partial[(1-\alpha)\rho_l e_l + \alpha\rho_g e_g]}{\partial t} + \nabla.[(1-\alpha)\rho_l e_l \vec{V}_l + \alpha\rho_g e_g \vec{V}_g]$$

$$= -p\nabla.\left[(1-\alpha)\vec{V}_l + \alpha\vec{V}_g\right] + q_{wg} + q_{wl}$$ (C6)

$$+ \textit{energy source terms}$$

Implementation

The interfacial shear is calculated in conjunction with separate simple flow regime maps for vertical and horizontal flow given figure 2.

The pattern map for vertical flow is shown in figure 2a in terms of mass flux and vapour fraction and that for horizontal flow in figure 2b in terms of gas velocity and vapour fraction. The experimental basis for these is not stated nor is any validation given.

Validation of the code is currently under way by APS (AEA Technology, Harwell) against experimental data provided by BP and field data for 20 multiphase pipelines from the National Multiphase Flow Database. The results of this comparison are not yet available.

Note added in proof. A preprint article for submission to the open literature has just been issued by APS. Further commentary in the light of this paper (Philbin and Butcher, for Pipes and Pipelines Inter. J., September 1992) cannot be offered here.

Appendix D

SUMMARY FORMULATION OF THE OLGA CODE

The OLGA code is based on the extended two-fluid model. The defining equations are taken from the paper by Bendiksen *et al* (1991).

The balance equations are:

Liquid mass

$$\frac{\partial}{\partial t}(V_L\rho_L) = -\frac{1}{A}\frac{\partial}{\partial z}(AV_L\rho_L v_L) - \psi_g\frac{V_L}{V_L+V_D} - \psi_e + \psi_d + G_L \tag{D1}$$

Liquid droplets mass

$$\frac{\partial}{\partial t}(V_D\rho_L) = -\frac{1}{A}\frac{\partial}{\partial z}(AV_D\rho_L v_D) - \psi_g\frac{V_D}{V_L+V_D} + \psi_e - \psi_d + G_D \tag{D2}$$

Vapour mass

$$\frac{\partial}{\partial t}(V_g\rho_g) = -\frac{1}{A}\frac{\partial}{\partial z}(AV_g\rho_g v_g) + \psi_g + G_g \tag{D3}$$

Liquid (at wall) momentum

$$\begin{aligned}\frac{\partial}{\partial t}(V_L\rho_L v_L) &= -V_L\left(\frac{\partial p}{\partial z}\right) - \frac{1}{A}\frac{\partial}{\partial z}(AV_L\rho_L V_L^2) \\ &-\lambda_L\frac{1}{2}\rho_L|v_L|v_L\frac{S_L}{4A} + \lambda_i\frac{1}{2}\rho_g|v_r|v_r\frac{S_i}{4A} + V_L\rho_L g\cos\alpha \\ &-\psi_g\frac{V_L}{V_L+V_D}v_a - \psi_e v_i + \psi_d v_D - V_L d(\rho_L-\rho_g)g\frac{\partial V_L}{\partial z}\sin\alpha\end{aligned} \tag{D4}$$

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The momentum balances on gas and liquid droplets are combined to give

$$\frac{\partial}{\partial t}(V_g\rho_g v_g+V_D\rho_L v_D) = -(V_g+V_D)\left(\frac{\partial p}{\partial z}\right)$$
$$-\frac{1}{A}\frac{\partial}{\partial z}(AV_g\rho_g v_g^2+AV_D\rho_L v_D^2)-\lambda_g\frac{1}{2}\rho_g|v_g|v_g\frac{S_g}{4A}$$
$$-\lambda_i\frac{1}{2}\rho_g|v_r|v_r\frac{S_i}{4A}+(V_g\rho_g+V_D\rho_L)g\cos\alpha \tag{D5}$$
$$+\psi_g\frac{V_L}{V_L+V_D}v_a+\psi_e v_i-\psi_d v_D$$

A mixture energy-conservation equation is applied

$$\frac{\partial}{\partial t}m_g\left(E_g+\frac{1}{2}v_g^2+gh\right)+m_L\left(E_L+\frac{1}{2}v_L^2+gh\right)$$
$$+m_D\left(E_D+\frac{1}{2}v_D^2+gh\right)=-\frac{\partial}{\partial z}m_g v_g\left(H_g+\frac{1}{2}v_g^2+gh\right) \tag{D6}$$
$$+m_L v_L\left(H_L+\frac{1}{2}v_L^2+gh\right)+m_D v_D\left(H_D+\frac{1}{2}v_D^2+gh\right)+H_S+U$$

with the following pressure equation

$$\left[\frac{V_g}{\rho_g}\left(\frac{\partial\rho_g}{\partial p}\right)_{T,R_s}+\frac{1-V_g}{\rho_L}\left(\frac{\partial\rho_L}{\partial p}\right)_{T,R_s}\right]\frac{\partial p}{\partial t}=-\frac{1}{A\rho_g}\frac{\partial(AV_g\rho_g v_g)}{\partial z}$$
$$-\frac{1}{A\rho_L}\frac{\partial(AV_L\rho_L v_L)}{\partial z}-\frac{1}{A\rho_L}\frac{\partial(AV_D\rho_L v_D)}{\partial z}+\psi_g\left(\frac{1}{\rho_g}-\frac{1}{\rho_L}\right) \tag{D7}$$
$$+G_g\frac{1}{\rho_g}+G_L\frac{1}{\rho_L}+G_D\frac{1}{\rho_L}$$

Defining the gas mass fraction at equilibrium conditions as

$$R_s=\frac{m_g}{(m_g+m_L+m_D)} \tag{D8}$$

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the mass transfer rate is given by (see section 2.4)

$$\frac{\psi_g}{m_g+m_L+m_D} = \left(\frac{\partial R_s}{\partial p}\right)_T \frac{\partial p}{\partial t} + \left(\frac{\partial R_s}{\partial p}\right)_T \frac{\partial p}{\partial z}\frac{\partial z}{\partial t} + \left(\frac{\partial R_s}{\partial T}\right)_p \frac{\partial T}{\partial t} + \left(\frac{\partial R_s}{\partial T}\right)_p \frac{\partial T}{\partial z}\frac{\partial z}{\partial t} \tag{D9}$$

The wall friction factor for gas and liquid is the maximum of the turbulent and laminar values given by

$$\lambda_t = 0.0055\left[1 = \left(\frac{2\times10^4\epsilon}{d_h} + \frac{10^6}{N_{Re}}\right)^{\frac{1}{3}}\right] \tag{D10}$$

and

$$\lambda_l = \frac{64}{N_{Re}} \tag{D11}$$

The following are used for interfacial friction:

Annular flow

$$\lambda_i = 0.02\ [1 + 75\ (1-V_g)] \tag{D12}$$

Annular mist flow

$$\lambda_i = 0.02\ (1 + KV_L) \tag{D13}$$

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where K is an empirically determined coefficient of the form

$$K = K\left(\frac{h_f}{d}\,,\ \frac{\sigma}{g(\rho_L-\rho_g)}\right) \tag{D14}$$

For wavy flow, the minimum of equation (D13) and

$$\lambda_t = \frac{h_w}{d_{hl}} \tag{D15}$$

is used and for droplet deposition

$$\psi_d = \frac{4}{d}\frac{V_D\rho_L}{V_g}\,2.3\times10^{-4}\left(\frac{\rho_L}{\rho_g}\right)^{0.8}\left(1+\frac{1}{0.1+v_{sL}}\right) \tag{D16}$$

is used in the case of vertical flow.

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Appendix E

EXPERIMENTAL FACILITIES

BP ISLE OF GRAIN FACILITY

The test facility at the Isle of Grain, Kent occupies the site of a former BP refinery and covers a land area of about 40,000m^2. A large fan shaped zone downwind allows safe dispersal of the gases. The facility was designed and built by BP who also made in-pipe measurements. Shell provided instrumentation of the external field.

The equipment consists of a pressure vessel supplying two 100m pipelines of 0.05m and 0.15m diameter respectively. The pressure vessel has a volume of 2m^3 and is mounted on a weighbridge to monitor vessel inventory and flowrates during discharge.

The pipelines are two parallel and horizontal plant pipelines, each 100m long with roughness characterised by a scale length of 0.05mm. The line in use is suspended at 5m intervals on hangars connected to load cells used to measure the mass of fluid in their respective 5m sections and hence local liquid-vapour phase ratios.

Each pipeline is also provided with two 1m long transparent sections for direct video and high speed cine photography of the internal flow. Fluid temperatures are measured by 10 thermocouples positioned to minimise flow disturbances. 10 pressure sensors are at the same distances from the spill point as the thermocouples.

Further information and details of the full scale experiments are given by Cowley and Tam (1988).

SINTEF MULTIPHASE FLOW LABORATORY

The SINTEF laboratory has been in existence since 1983 having undergone several modifications since that time.

The laboratory has three pipes of 0.2m nominal diameter and length nearly 400m lying on a pipe rack at 0, 0.5 and 1 degrees inclination from the horizontal. Two of the pipes are connected through a 200m turning circle at the far end from the inlet to produce a total flow length of almost 1000m. By connecting different pipes and changing flow direction, a range of inclinations from -1 to 1 degrees can be covered. There is also a 54m riser pipe with a separate inlet for purely vertical flow.

The total volumetric circulation rates for liquid and gas are 450 and 1400m^3 /h respectively corresponding to maximum superficial velocities of 4.5 and 14m/s in the 0.2m pipes. The facility operates with naphtha, diesel or lube oil liquid and nitrogen gas at pressures of over 90 bar.

In 1991 Statoil and SINTEF-IFE installed additional pipes of 0.1 and 0.3m diameter to run at inclinations of 5 and 90 degrees from the horizontal. The pipe lengths involved are not provided.

Further information and detail of the OLGA base software used with the SINTEF laboratory are given by Brandt and Fuchs (1992).

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FIGURES

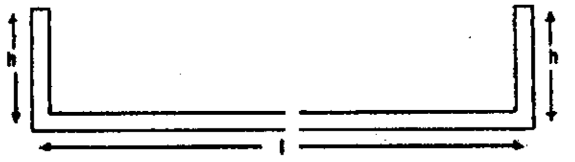

Fig 1a Pipeline Geometry used by BLOWDOWN
Reproduced from Fig 1 of Richardson and Saville (1991)

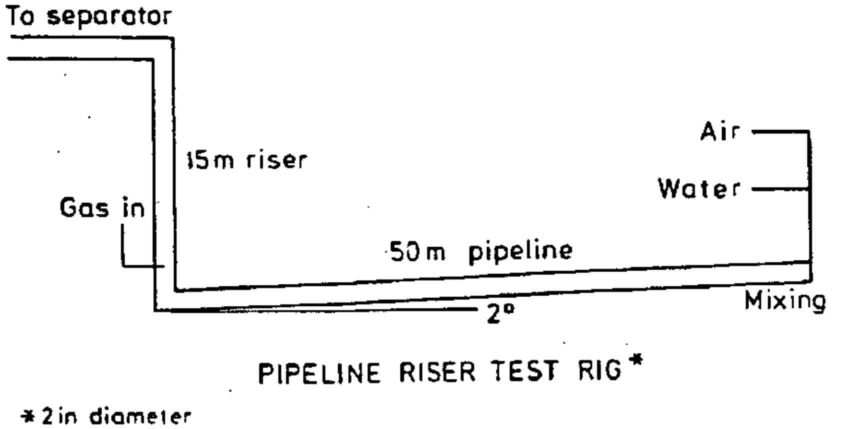

Fig 1b Pipeline Geometry used by PLAC
Reproduced from Fig 9 of Philbin (1991)

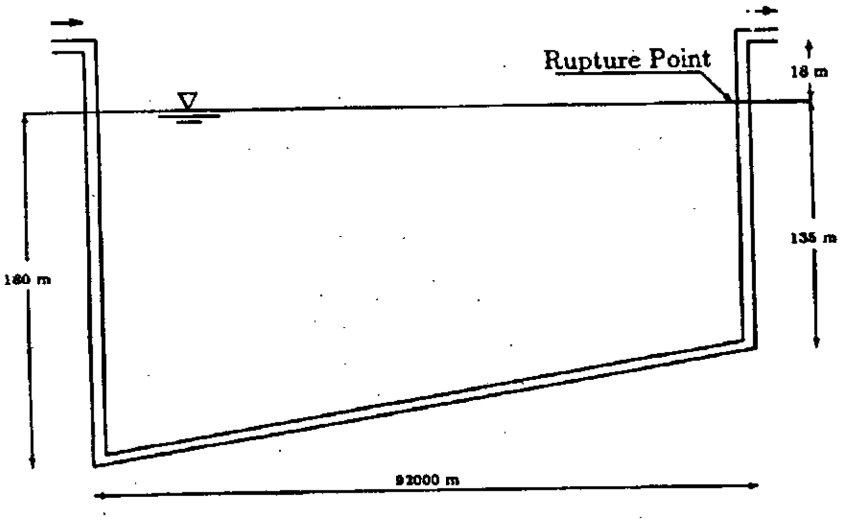

Fig 1c Pipeline Geometry used by OLGA
Reproduced from Fig 3 of Rygg and Ellul (1991)

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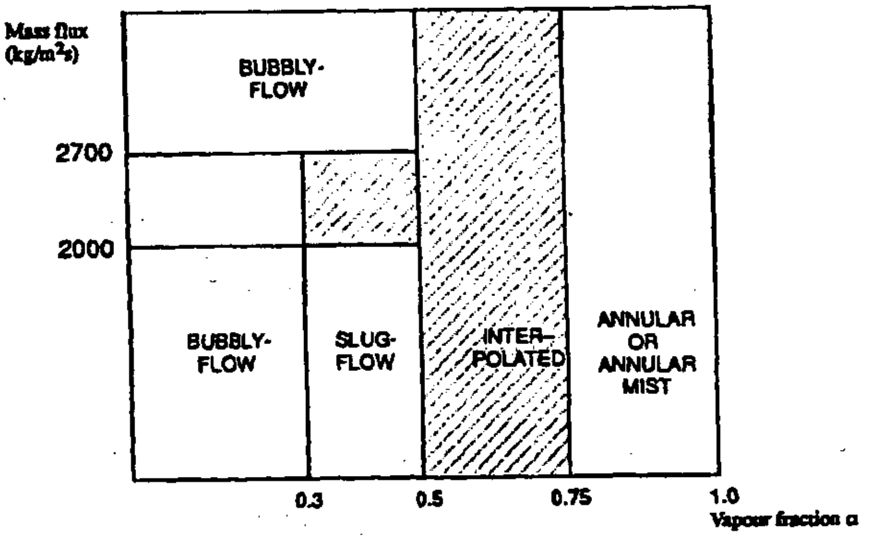

Fig.2a Flow regime map used by PLAC for vertical flow
Reproduced from Fig.3 of Philbin (1990)

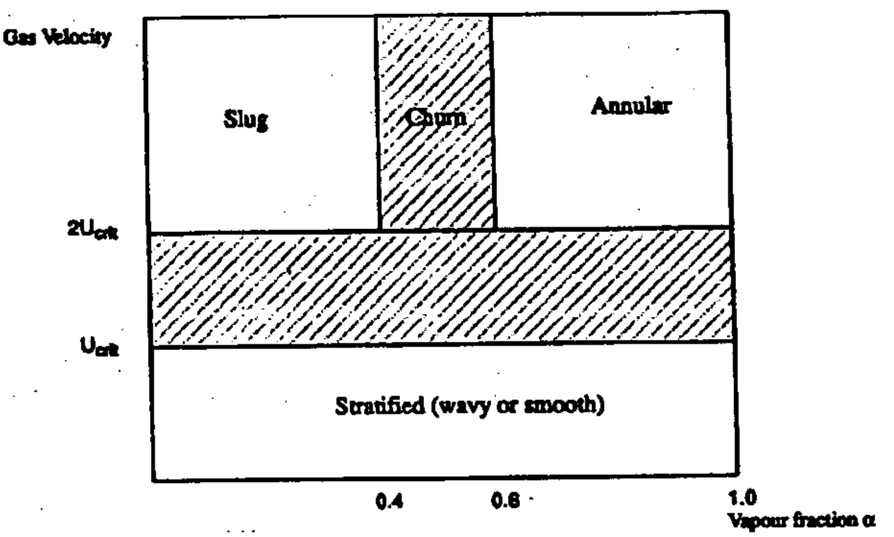

Fig.2b Flow regime map used by PLAC for horizontal flow
Reproduced from Fig.4 of Philbin (1990)

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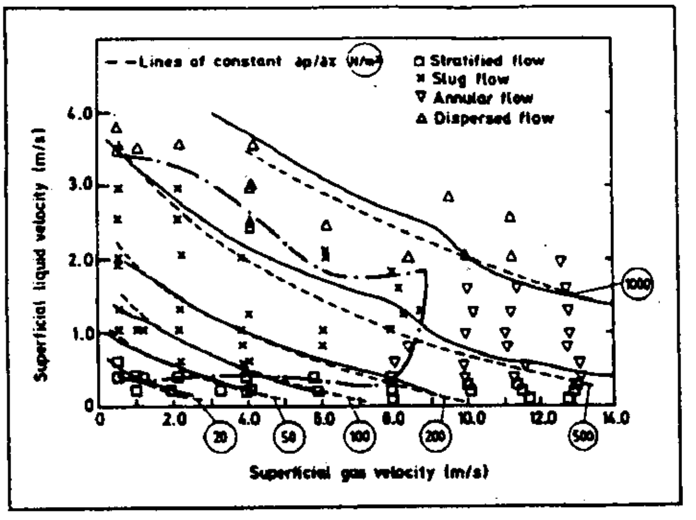

Fig.3 Pressure gradient (- -) and slug flow boundaries compared with OLGA predictions (–∂p/∂x ; –·– slug-flow boundaries) for horizontal flow. (Diesel and nitrogen at 3 MPa and 30 deg. C) Reproduced from Fig.5 of Bendiksen et al (1991).

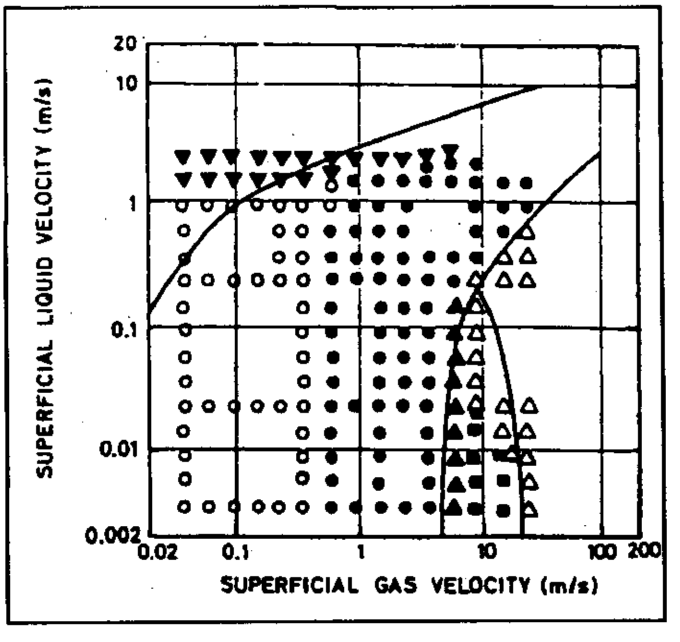

Fig.4 Flow-regime transitions from Barnea et al (1980) compared with OLGA [2 deg upward inclination, 2.5 cm ID; (—) OLGA flow-regime transition].
Reproduced from Fig.6 of Bendiksen et al (1991)

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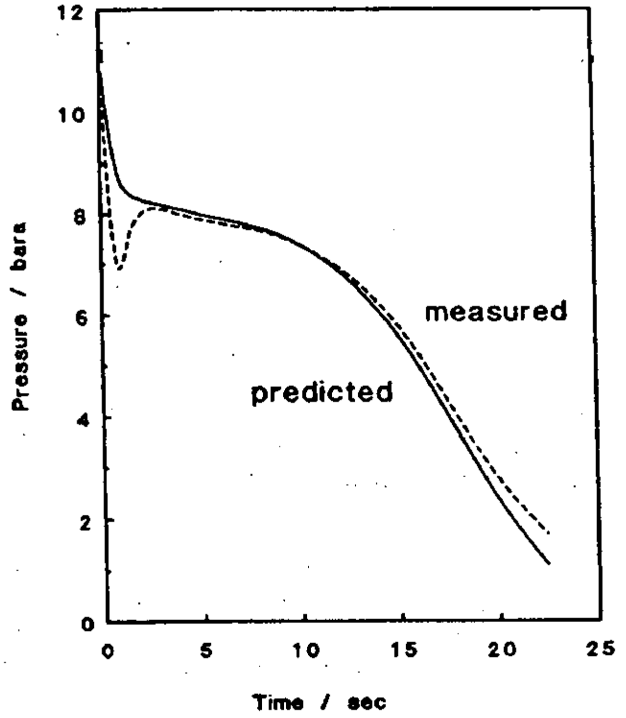

Fig.5 Variation of pressure at intact end with time and BLOWDOWN prediction.

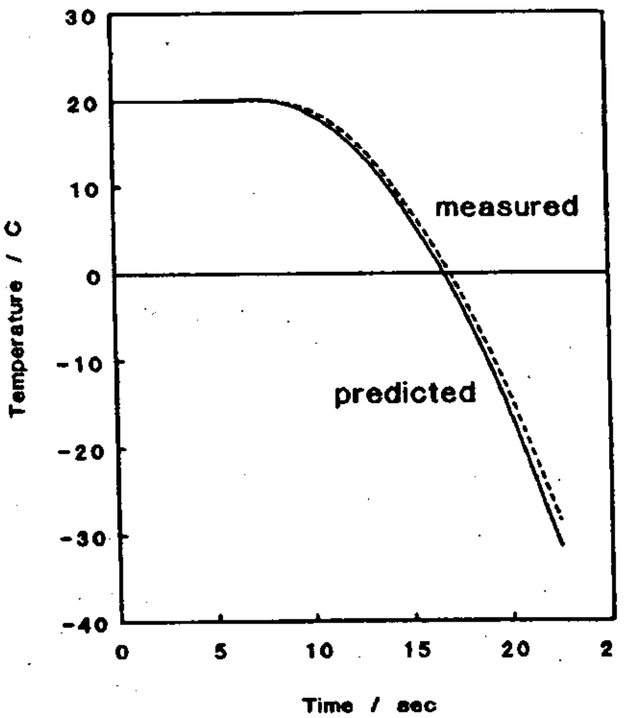

Fig.6 Variation of temperature at intact end with time and BLOWDOWN prediction.

Figures 5 and 6 are reproduced from figures 2 and 3 of Richardson and Saville (1991).

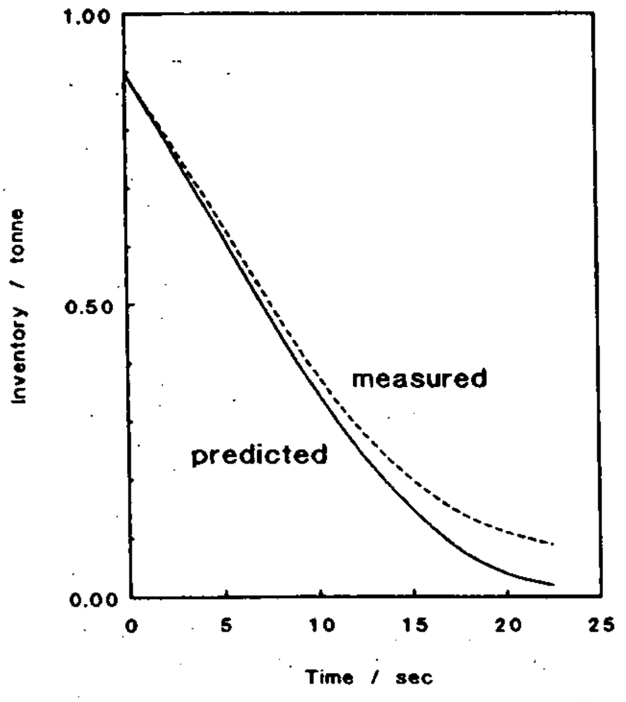

Fig.7 Variation of inventory of line with time and BLOWDOWN prediction.

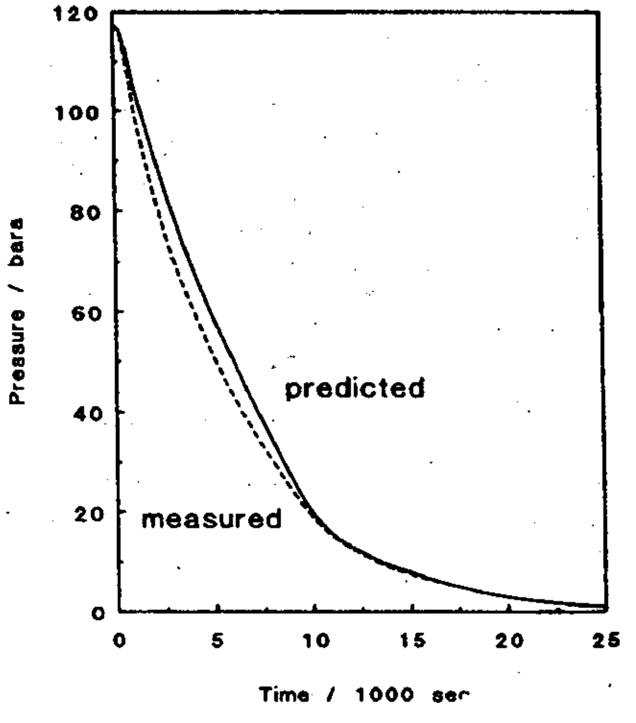

Fig.8 Variation of pressure at intact (MCP-01) end with time and BLOWDOWN prediction.

Figures 7 and 8 are reproduced from figures 4 and 5 of Richardson and Saville (1991).

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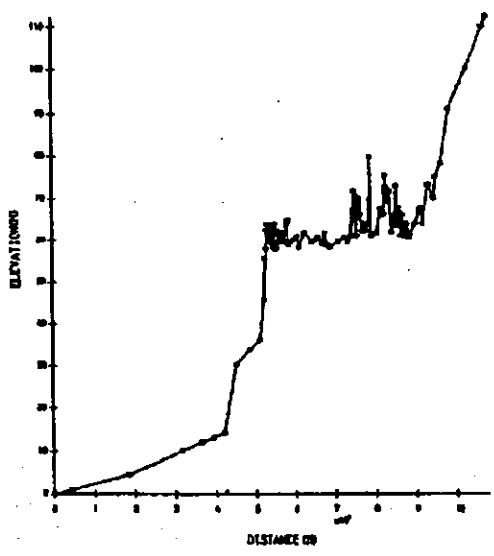

Fig.9 Topography of the Marlin Gas-condensate Trunkline
Reproduced from Fig.1 of Philbin (1991)

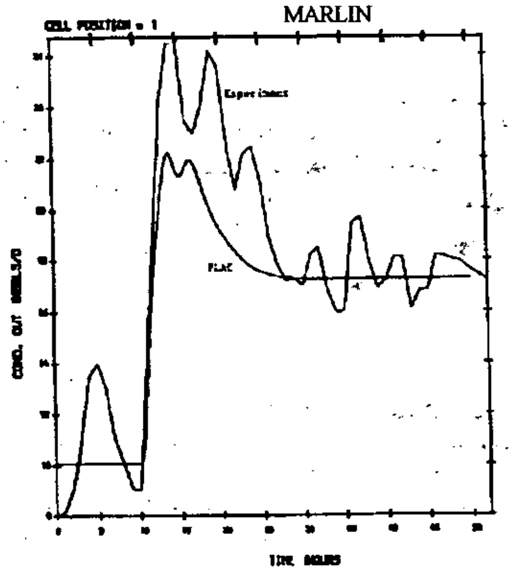

Fig.10 Condensate Flow Rate Out versus Time for the
Marlin Gas-condensate Trunkline
Reproduced from Fig.2 of Philbin (1991)

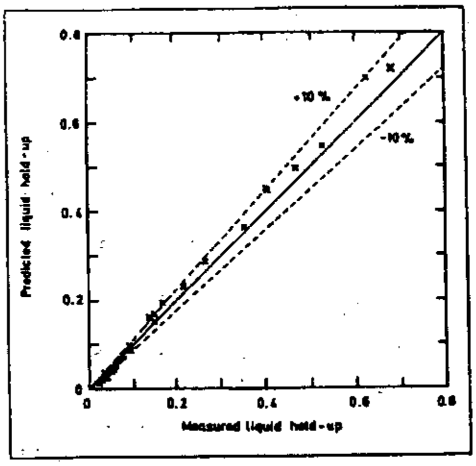

Fig.11 Comparison between measured and predicted liquid holdup [diesel and nitrogen horizontal stratified flow at 3.10[6] Pa and 30 deg C (×) OLGA].
Reproduced from Fig.4 of Bendiksen et al (1991)

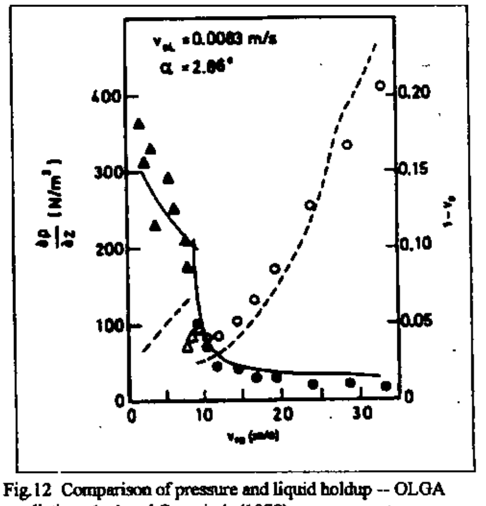

Fig.12 Comparison of pressure and liquid holdup -- OLGA predictions (—) and Crouzier's (1978) measurements (ID = 0.045 m ● stratified pressure drop ▲ slug pressure drop; o stratified holdup; △ slug holdup).
Reproduced from Fig.9 of Bendiksen et al (1991)

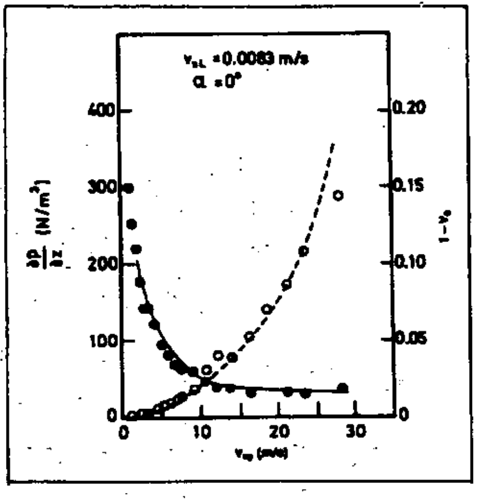

Fig.13 Comparison of pressure and liquid holdup -- OLGA predictions (—) and Crouzier's (1978) measurements (ID = 0.045 m ● stratified pressure drop ▲ slug pressure drop; o stratified holdup; △ slug holdup).
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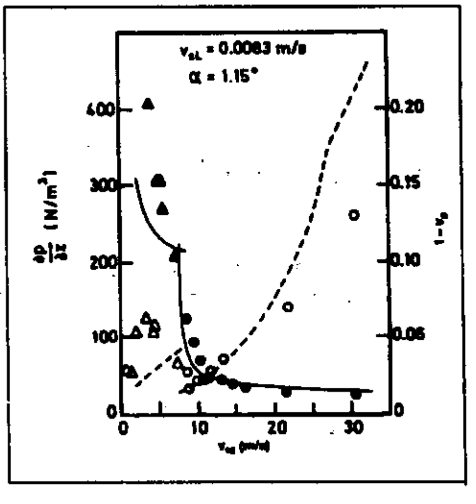

Fig.14 Comparison of pressure and liquid holdup -- OLGA predictions (—) and Crouzier's (1978) measurements (ID = 0.045 m ● stratified pressure drop ▲ slug pressure drop; o stratified holdup; △ slug holdup).
Reproduced from Fig.8 of Bendiksen et al (1991)

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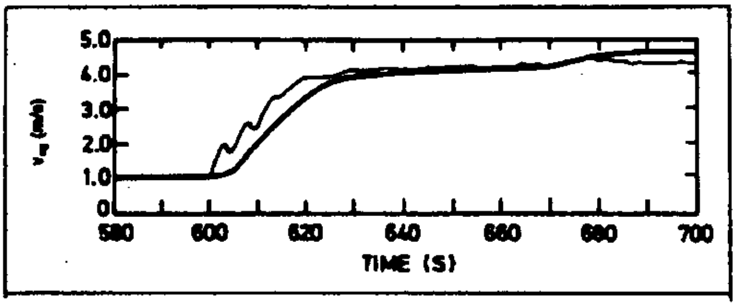

Fig.15 Superficial-gas-velocity recordings for the dynamic inlet-flow experiments at the SINTEF Two-phase Flow Laboratory (— applied in OLGA).
Reproduced from Fig.15 of Bendiksen et al (1991).

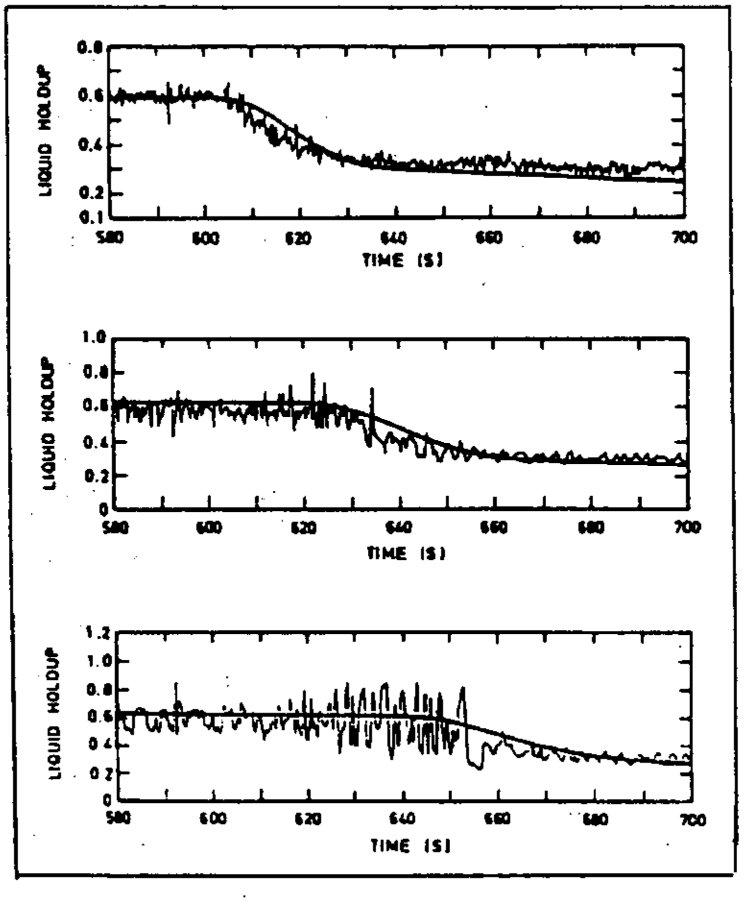

Fig.16 Liquid-holdup recordings in the horizontal compared with OLGA (---) at locations 49, 179 and 229 m from the mixing point.
Reproduced from Fig.16 of Bendiksen et al (1991)

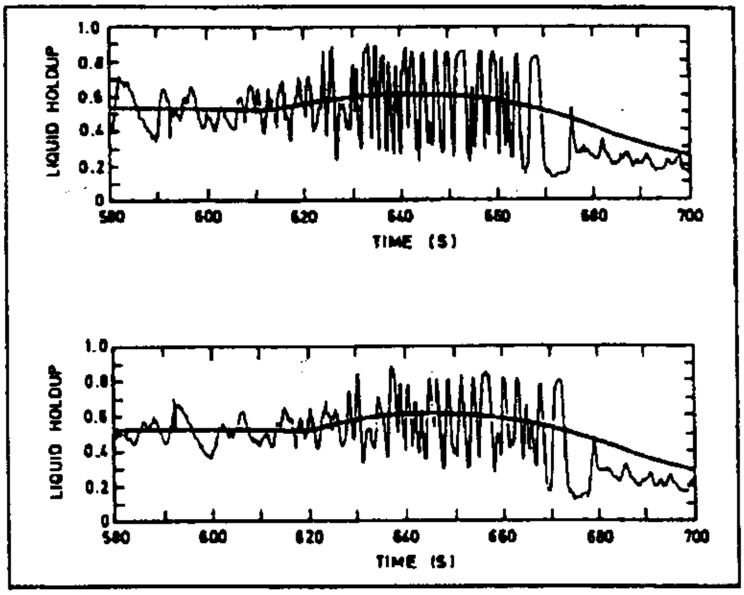

Fig. 17 Liquid-holdup recordings in the riser compared with OLGA (—) at locations 7 and 29 m from the riser bottom.
Reproduced from Fig. 17 of Bendiksen et al (1991)

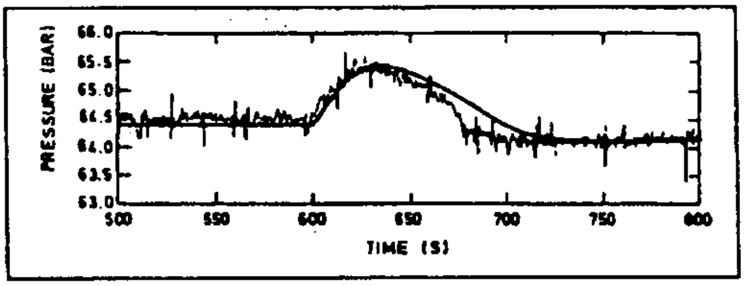

Fig. 18 Absolute pressure recorded 10 m from the mixing point compared with OLGA (—).
Reproduced from Fig.18 of Bendiksen et al (1991).