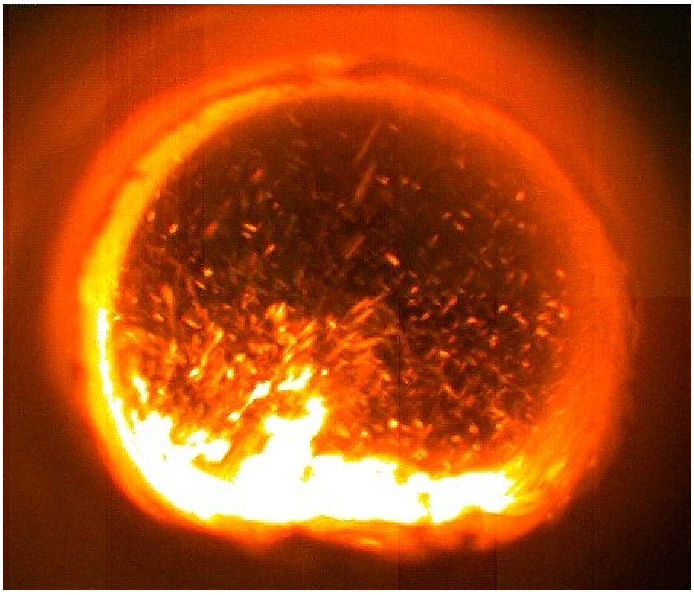
Joint Project on Transient Multiphase Flows (TMF3)

PROSPECTUS

By

Geoffrey F. Hewitt, Programme Director (Imperial College)



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Contents:

Executive Summary

JOINT PROJECT ON TRANSIENT MULTIPHASE FLOWS (TMF3)

Since 1996, industry and the UK Government have funded research into Transient Multiphase Flow (The TMF projects) with the stated aim of improving the oil and gas industry's tools for the prediction, design and optimisation of pipeline transportation and process plant. This work has been pursued by a group of UK University Centres under the management of Imperial College, London. The industrial participants include organisations active internationally in hydrocarbon exploration and production, their design consultants and experts in the development and marketing of sophisticated transient multiphase computer programs.

The TMF projects have been successful in their central aim of advancing the modelling bases for both two-phase (gas-liquid) and three-phase (gas-liquid-liquid) pipeline flows. Such flows are highly complex in nature because of the combination of turbulence and interfacial interactions. The interfacial structure is often classified into categories known as *flow regimes* (or *flow patterns*) and the work in the TMF projects has concentrated on two of these regimes, namely *stratified flow* and *slug flow*. The modelling work has been based around the *one-dimensional multi-fluid model* in which equations are solved for each of the fluids taking account of the interactions between them. This model has classically been used for stratified flow but the work in the TMF projects has shown that it can also perform remarkably well in predicting slug flow provided that a fine enough numerical grid is used.

In order to use the one-dimensional model, a number of sub-models or "closure laws" are required to account for such multi-dimensional phenomena as gas entrainment in slugs, liquid-liquid mixing and phase inversion in three phase flows and interfacial friction in stratified flows. Models for these phenomena and many others have been developed with encouraging results. The TMF projects have also embodied a wide range of experiments on two- and three-phase flows aimed not only at validating the overall models but also at aiding the development of better closure laws.

In order to make meaningful calculations of slug flows, therefore, numerical grids at least one order of magnitude finer than those used in present commercial codes are required. For a typical pipeline system, the computing time needed using the required fine grid may be large with present-day computers. There are several ways in which this problem may be ameliorated. The first is, of course, the fact that computers are continually getting faster and cheaper. The second is that improved numerical methods such as adaptive gridding can be used and extensive work on such methodologies has already been carried out in the TMF projects. A further alternative is to treat the slugs as individual entities and to track their motion along the pipe system (*slug tracking*); this is much more economical in computing.

In this Prospectus, we present plans for a further programme of work (TMF3). In the central area of modelling, the aim is to exploit the work on the multi-fluid models (for two-phase flows in Sub-Project I and for three phase flows in Sub-Project V). Building on work already done in other programmes at Imperial college, it is proposed to develop a modelling strategy which combines the slug tracking approach with the multi-fluid model approach (Sub-Project II). In all of these Sub-Projects, work is proposed on closure laws and numerical algorithms.

It should be stressed that, though the principal focus of TMF has been on multi-phase flow modelling as discussed above, the programme has also (at the instigation of the industrial partners) included many other associated topics. For the TMF1 and TMF2 projects, summaries of this work are given in what follows in the main text and in Appendices D and C respectively. For TMF3, work is proposed on large diameter risers (where existing models may fail) (Sub-Project III), on thermal management (controlling product fluid temperature to minimise deposition of wax and other solids) (Sub-Project IV) and on junction flows (interaction between joining flows and flow splits) (Sub-Project VI). It is proposed to extend the work on flexible risers with emphasis on three-phase flows (Sub-Project VII). Assessment studies are also proposed on non-Newtonian flows of produced fluids (Sub-Project VIII) and active control of slug flows (Sub-Project IX). Full details are given in the main part of this Prospectus and summaries in the industry-standard CTR Form presentation are given in the following pages.

In preparing proposals for TMF3, special attention has been given to technology transfer aspects. In addition to the existing technology transfer mechanisms involving the issue of simple spreadsheet solvers, progress and topical reports (usually via the TMF Web Site), and provision of CD-ROM'S containing the large range of high quality experimental data, there will be increased focus on technology transfer via software. This will include spreadsheet software tools for specific applications and also a test bed code (EMAPS). The provision of software interfaces will facilitate up-take of the results of the Project by the companies involved, including the commercial code-development companies.

The total cost of the TMF1 Programme was estimated at £1.6M, and that of TMF2 as £1.4M. The cost of the TMF3 programme is proposed as £1.6M. These figures exclude the value of extensive in-kind contributions from the participating companies.

Fourteen companies (including oil companies, design houses and code development companies) are already sponsors of the TMF Programme. Additional organisations involved in the hydrocarbon production industry are invited to participate in the project. New participants will benefit from the TMF1 and TMF2 Programmes (and receive all the deliverables from them) for a single payment of £18k, provided they agree to participate in the TMF3 Programme for which the ticket price is £20k per annum for three years.

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CTR Forms for the Proposed TMF3 Sub-Projects

The Cost Time Resource (CTR) Form has become the standard method in the petroleum and other industries for summarising and transmitting information about projects etc. At the request of existing TMF Sponsors, such forms have been prepared for the proposed TMF3 Sub-Projects. These CTR forms are given in the following pages as follows:

Sub-Project I: Multifluid Modelling
Sub-Project II: Slug Tracking
Sub-Project III: Large Diameter Risers
Sub-Project IV: Thermal Management
Sub-Project V: Three-Phase Flows
Sub-Project VI: Junction flows
Sub-Project VII: Flexible Risers
Sub-Project VIII: Non-Newtonian Flows
Sub-Project IX: Active Control of Slug Flows

For convenience, and to allow ready separation and/or photocopying, each form is given on a separate page.

<table>
<tr><td colspan="3">Project Title: Joint Project on Transient Multiphase Flows</td></tr>
<tr><td>Cost Time Resource</td><td colspan="2">Cost Time Resource Title</td></tr>
<tr><td>TMF3
Sub-Project I</td><td colspan="2">Multi-Fluid Modelling</td></tr>
<tr><td>Start Date</td><td>Duration</td><td>Cost</td></tr>
<tr><td>Autumn 2002</td><td>Three years</td><td>£244k</td></tr>
<tr><td colspan="3">Objectives
(1) To continue the development of numerical algorithms with the objective of bringing forward the time when one-dimensional multifluid model slug capturing methods can be used economically in calculations in real systems having hydrodynamic slug flow.
(2) To develop more accurate closure laws for multifluid models including work on the use of drift flux equations within the models and the use of multi-dimensional modelling to gain better understanding of the phenomena, also leading to improved one-dimensional closure laws.</td></tr>
<tr><td colspan="3">Description of Work
The work will be done on a collaborative basis between Cranfield University and Imperial College (Mechanical Engineering). At Cranfield University, the work will concentrate on the development of numerical algorithms with further improvements in speed and robustness and with the capability of handling variations in topography/geometry and flow regime transition. At Imperial College, the work will address the closure law problem. This will include developing valid adjustments to models to take account of such important problems as the effect of slug length on slug velocity. This work will include CFD studies to evaluate the key multi-dimensional effects not captured in the one-dimensional model.</td></tr>
<tr><td colspan="3">Input to Activity
(1) Many years of experience in Professor C.P.Thompson’s group at Cranfield on the development of adaptive gridding and other numerical techniques.
(2) The many years experience in Dr. R.I.Issa’s group at Imperial College on multifluid modelling and CFD for multi-phase flow systems.
(3) The background development work in the TMF1 and TMF2 projects which is already beginning to be applied in commercial codes.
(4) Available software packages which can serve as a basis for the further development work.</td></tr>
<tr><td colspan="3">Output from Activity
(1) New and appropriate closure laws for inclusion in the one-dimensional multifluid framework.
(2) New algorithms for economic and realistic calculation of multiphase flows, and in particular for the hydrodynamic slug flow regime.
(3) Detailed reports and computer sub-routines describing and embodying the developments.
(4) Delivery of a source code version of the EMAPS (Eulerian Multiphase Adaptive Pipeline Solver) Code which incorporates all the developments.</td></tr>
<tr><td>Revision No.</td><td>CTR Managers</td><td>Approved</td></tr>
<tr><td>0</td><td>Professor C.P.Thompson
(Cranfield)
Dr.R.I.Issa (Imperial, ME)</td><td>Professor G.F.Hewitt
(Project Director)</td></tr>
</table>

Project Title: Joint Project on Transient Multiphase Flows		
Cost Time Resource	Cost Time Resource Title	
TMF3 **Sub-Project II**	**Slug Tracking**	
Start Date	Duration	Cost
Autumn 2002	**Three years**	**£206k**

Objectives

(1) To develop efficient and self-consistent models for slug flows in which the evolution and movement of individual slugs (both in the hydrodynamic and severe slugging regions) would be tracked and the appropriate flow properties determined both on local instantaneous and averaged bases.

(2) To develop improved models for slug initiation for use in conjunction with slug tracking models.

(3) To produce new experimental data on slug initiation and slug development which can aid in developing and validating the slug tracking models. Emphasis would be placed on obtaining data on gas entrainment in slugs for oil-gas flows and on evaluating the effects of complex terrain (V and Λ configurations).

Description of Work

This Sub-Project would be carried out at Imperial College (Chemical Engineering). The advantages of slug tracking are that complex three-dimensional effects (such as the effect of velocity distribution within the slug and the effect of slug length on slug tail velocity) can be included and that a great increase in computing efficiency is possible, allowing correct description of the local and global flow. Building on previous work in the TMF and other projects, modelling methodologies would be developed which combine the best features of multi-fluid and slug tracking models with “seamless” junctions between the regions in which the respective models are applied. A particular focus would be on slug initiation. In parallel, experimental work would be carried out on the Imperial College high pressure multiphase flow facility (WASP). New data would be obtained on gas-oil flows, including studies on complex terrain. This data would be used to improve the constituent components of the slug tracking scheme.

Input to Activity

(1) Previous work at Imperial College on slug tracking (theses by Manfield and Hale (2000) and subsequent work by Ujang (current PhD) and Hu Bin (pilot study under TMF2)) gives a sound basis for the TMF3 study.

(2) Experienced supervision from Dr.C.J.Lawrence (analytical) and Professor G.F.Hewitt (experimental) who have jointly had several decades of work in the area.

(3) Availability of the WASP facility and in particular the wide range of gamma and X-ray methods which became available during the TMF1 and TMF2 projects. This equipment makes it feasible to perform detailed studies of oil-gas flows in order to extend the data base on which the models are based and to provide overall validation data.

Output from Activity

(1) A consistent base-line model for slug tracking, satisfying the constraints of mass and momentum balances and containing closures taking account of complex effects such as gas entrainment in slugs, the effect of slug length on tail velocity etc. The model would include a robust model for slug initiation.

(2) New data on slug properties in gas-oil flows, including initiation and development of slugs and gas entrainment in slugs.

(3) A computer code for slug tracking which would be deposited in the test-bed EMAPS – (see Section 5 and CTR form on technology transfer below) and would therefore be available for in-house use by Sponsors.

Revision No.	CTR Managers	Approved
0	Dr. C.J.Lawrence (Imperial, CE) Professor G.F.Hewitt (Imperial CE)	Professor G.F.Hewitt (Project Director)

Project Title: Joint Project on Transient Multiphase Flows		
Cost Time Resource	Cost Time Resource Title	
TMF3 **Sub-Project III**	**Large Diameter Risers**	
Start Date	Duration	Cost
Autumn 2002	**Three years**	**£140k**

Objectives

(1) To carry out experiments on flows in large diameter risers with the specific objective of establishing where current methodologies (based mainly on data for small pipes) fail to predict flow pattern and associated parameters such as pressure drop and holdup.

(2) To upgrade the existing models to take account of the specific effects associated with large diameters and to transfer the improved models to sponsors through technical reports, spreadsheets and other means as appropriate.

Description of Work

The work will be done at Nottingham University. The increasing water depths at which fields are being developed implies the use of larger diameter vertical and steeply inclined risers. Flow regimes (and hence other parameters) may be very different in large diameter vertical pipes. For instance, classical slug flow may disappear for pipes with diameters greater than 100 mm unless the slugs are introduced upstream of the riser. The main focus of the work will be experimental and will be aimed at observing flows in 76 and 125 mm vertical pipes for a wide variety of fluids. Higher gas densities will be achieved by using sulphur hexafluoride as the gaseous phase. An existing facility at Nottingham will be upgraded for this purpose. The results will be used as a basis for the development of improved models which will be transferred to the sponsors via reports, spreadsheets etc. (see CTR form on Technology Transfer).

Input to Activity

(1) Professor B.J.Azzopardi's extensive knowhow on multiphase flow in general and large diameter pipes in particular.

(2) A major large diameter vertical pipe facility at Nottingham suitable for upgrading to work with a larger range of flow rates (covering the full gamut of flow patterns from bubbly to annular flow) and fluid physical properties.

Output from Activity

(1) Experimental data allowing the existing flow regime, holdup and pressure drop models to be evaluated for the case of large diameter risers.

(2) Improved versions of predictive methods which take account of the effects of having large diameter pipes.

(3) Reports, spreadsheets etc transferring the outputs to the Sponsors.

Revision No.	CTR Managers	Approved
0	Professor B.J.Azzopardi (Nottingham University)	Professor G.F.Hewitt (Project Director)

Project Title: Joint Project on Transient Multiphase Flows

Cost Time Resource	Cost Time Resource Title	
TMF3 Sub-Project IV	**Thermal Management**	
Start Date	Duration	Cost
Autumn 2002	**22 Months**	**£145k**

Objectives

(1) To extend the software (spreadsheet) package for calculating the performance of a specified bundle configuration (developed in the TMF2 Project) to cover a wider range of cases including more sophisticated representations of insulation and partial insulation, representations of manifold systems and partially buried pipes.

(2) To carry out CFD and experimental studies on the thermal behaviour of a wider range of systems (more complex tube bundles, manifolds, partially buried pipes) and to use the results to develop new equations which can be used within the spreadsheet package ((1) above).

(3) To develop a *design* methodology which allows the user to make a rational choice between the many options available.

Description of Work

This work will be carried out as a collaboration between Bristol University and Imperial College (Chemical Engineering). *Thermal management* of pipeline systems has become increasingly important as distances for pipeline transport of produced fluids, and the water depth at which such pipelines are operated, increase. The aim of such thermal management is to prevent deposition of solid phases such as waxes, hydrates and ashphaltenes. In TMF2, the emphasis has been on pipeline bundles and the proposed TMF3 work will extend this but also deal with other geometries such as manifolds. The use of CFD (and its validation using specially designed experiments) allows the development of correlations for heat transfer in the (often complex) geometries used in bundles and other systems. These correlations can be subsumed into more convenient tools such as the spreadsheet programme for rating. These activities will continue but, in addition, work will proceed on the provision of a software tool for design which is analogous to the HTFS program DEVISE which allows rapid selection of heat exchanger geometries. Thus, the designer would be able to use this tool to select between the very large number of options now available for thermal management. Preliminary work has already been carried out on this concept as part of TMF2.

Input to Activity

(1) Existing software packages for rating developed as part of TMF2.

(2) Existing general expertise in CFD by Professor G.L.Quarini's group at Bristol University which has already been used for predicting bundle systems and the developing the associated heat transfer correlations.

(3) At Imperial College (Chemical Engineering), existing expertise and an apparatus for heat transfer measurements in bundles which is being constructed as part of the TMF2 programme.

Output from Activity

(1) The provision of software tools for the design and performance evaluation of thermal management systems.

(2) The provision of data and equations for heat transfer rates from the components of thermally managed systems which, in addition to their inclusion in the software tools mentioned in (1) above may also be used directly or absorbed into the commercial codes.

Revision No.	CTR Managers	Approved
0	Professor G.L.Quarini (Bristol University) Professor S.M.Richardson Professor G.F.Hewitt (Imperial College, Chemical Engineering)	Professor G.F.Hewitt (Project Director)

<table>
<tr><td colspan="3">Project Title: Joint Project on Transient Multiphase Flows</td></tr>
<tr><td>Cost Time Resource</td><td colspan="2">Cost Time Resource Title</td></tr>
<tr><td>TMF3
Sub-Project V</td><td colspan="2">Three-Phase Flows</td></tr>
<tr><td>Start Date</td><td>Duration</td><td>Cost</td></tr>
<tr><td>Autumn 2002</td><td>Three years</td><td>£293k</td></tr>
<tr><td colspan="3">Objectives
(1) Using advanced instrumentation developed in the TMF2 and other programmes, to measure the properties of three phase flows in the Imperial College WASP facility. These measurements would include slug composition, flow patterns in transients and average and time-varying pressure drop and holdup, thus providing important new information supplementing that already obtained in the TMF1 and TMF2 programmes.
(2) To further develop the application of multi-fluid models to three-phase flows with particular emphasis on transient flows, phase inversion and liquid phase mixing.</td></tr>
<tr><td colspan="3">Description of Work
This work will be carried out as a collaboration between Imperial College (Chemical Engineering and Mechanical Engineering) and Cranfield University. Three-phase (gas-water-oil) flows present a formidable challenge and, though a much more extensive data base and physical understanding of these flows has evolved from the work in the TMF1 and TMF2 programmes, it cannot realistically be asserted that the situation on prediction is anywhere near satisfactory. A central issue is that of phase inversion in which (in dispersed flows) the system changes from oil-continuous to water-continuous with the discontinuous phase being dispersed as droplets in the continuous one. The phase inversion process is associated with a very large increase in the effective viscosity of the mixture. The work proposed for TMF3 includes exploitation of the large range of new instrumentation for the Imperial College (Chemical Engineering) WASP facility developed as part of the TMF and other programmes. This includes a wide range of gamma densitometers (single and multi-beam, dual and single energy, traversing and fixed) and an X-ray tomography system. The studies will concentrate on investigating slug composition, flow regimes and transients. The work at Imperial College (Mechanical Engineering) and Cranfield University will be focussed on the application of multi-fluid modelling; at Imperial College (Mechanical Engineering), the TMF2 work on drift flux modelling will be extended and validated against the new steady state and transient data. At Cranfield University, work will continue on mixing models, again being benchmarked with the experimental data base. The software developed will be made available through the EMAPS test bed code (see Section 5 and the CTR form for Technology Transfer below).</td></tr>
<tr><td colspan="3">Input to Activity
(1) Existing modelling expertise and software developed as part of TMF1 and TMF2 both at Imperial College (Mechanical Engineering) (Dr.R.I.Issa) and Cranfield University (Professor C.P.Thompson).
(2) The Imperial College (Chemical Engineering) WASP facility, its advanced instrumentation and skilled experimental staff.</td></tr>
<tr><td colspan="3">Output from Activity
(1) New experimental and analytical information on three-phase flows include further data on flow parameters (flow pattern, liquid phase mixing, slug characteristics and composition, pressure drop, holdup etc) for both steady state and transient flows.
(2) New software methods for three-phase flow transferred through the medium of the EMAPS test bed code (see Section 5 and CTR form for Technology Transfer below) and through technical reports and presentations.</td></tr>
<tr><td>Revision No.</td><td>CTR Managers</td><td>Approved</td></tr>
<tr><td>0</td><td>Dr. R.I.Issa
(Imperial College, Mechanical Engineering
Professor G.F.Hewitt
(Imperial College, Chemical Engineering)
Professor C.P.Thompson
(Cranfield University)</td><td>Professor G.F.Hewitt
(Project Director)</td></tr>
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Project Title: Joint Project on Transient Multiphase Flows

Cost Time Resource	Cost Time Resource Title
TMF3 Sub-Project VI	**Junction Flows**

Start Date	Duration	Cost
Autumn 2002	**Three years**	**£85k**

Objectives

(1) Using the existing air-water facility at Nottingham, and exploiting new instrumentation procured in the TMF2 programme, to obtain experimental data on two phase flows at combining junctions, with particular reference to pressure drop and flow pattern interaction effects.

(2) To modify the existing combining junction facility to make it part of a closed loop rig which can operate with heavy gas (SF_6) and with a variety of liquids. To obtain further data on combining flows using this modified facility to cover a much wider range of fluid physical properties.

(3) Using an existing air-kerosene rig at Nottingham, to obtain data on *dividing* flows at a horizontal T-junction.

(4) To develop equations for junction phenomena based on this new data and to interact with the modelling teams, and particularly the team at Cranfield.

Description of Work

The work will be done at Nottingham University. Hydrocarbon recovery pipeline systems commonly include combining and/or dividing junctions. For combining junctions, the downstream flow patterns may be influenced by those in the flows entering the junction and may not be the same as those which would naturally occur at the combined flow rate. For dividing junctions, it is rare that the respective flows downstream of the junction have the same quality (gas flow fraction). The emphasis in the short TMF2 Sub-Project was on combining flows and this work indicated that more instrumentation and a wider range of fluid physical properties were needed to develop generic models. Obtaining such wider information on combining flows will be the main emphasis of the TMF3 work, though there is also considerable interest from industry in dividing flows. This has been responded to by including a more limited programme on dividing air-kerosene flows.

Input to Activity

(1) The internationally-recognised expertise of Professor B.J.Azzopardi and his team at Nottingham University in the area of two-phase junction flows.

(2) The existence of a number of facilities and associated instrumentation at Nottingham University which can be brought to bear on obtaining the data needed.

Output from Activity

(1) Experimental data for combining junctions in which key parameters of pressure changes, holdup and flow patterns are determined.

(2) Experimental data on dividing junction flow which complement the existing data.

(3) Validated equations for the additional pressure drops occurring in combining junctions and provision of calculation methods for junctions either as spreadsheets or embodied into the EMAPS test bed code (see Section 5 and the CTR form on Technology Transfer below).

Revision No.	CTR Managers	Approved
0	Professor B.J.Azzopardi (Nottingham University)	Professor G.F.Hewitt (Project Director)

Project Title: Joint Project on Transient Multiphase Flows		
Cost Time Resource	Cost Time Resource Title	
TMF3 Sub-Project VII	**Flexible Risers**	
Start Date	Duration	Cost
Autumn 2002	**Two years**	**£97k**

Objectives

(1) To investigate more closely the phenomena occurring at the bottom of the riser in an S-shaped riser, and in particular the way in which the gas enters the riser.

(2) To investigate the interaction of riser systems with associated systems (and in particular the separator and the well) for both two- and three-phase flows.

(3) To provide new test data on three-phase flows in an S-shaped riser including local measurements of time varying phase fraction.

Description of Work

The work will be done at Cranfield University. Flexible riser systems continue to be of vital importance in hydrocarbon recovery. These systems link the well-manifold system on the ocean floor with surface facilities (for instance floating processing units). The risers are typically configured in catenary or S-shaped form and are of increasing importance as reserves in deeper water are developed. Such risers are particularly susceptible to severe slugging instabilities. As part of the TMF1 and TMF2 projects, a large amount of data has been and is being generated at Cranfield University on air-water and oil-water flow in catenary and S-shaped flexible risers. Preliminary work is also being carried out on three-phase flows. The work proposed for TMF3 is aimed at extending this data base to include more detailed measurements on three-phase flow (probably using dual-energy gamma densitometer systems borrowed from Imperial College) and on gaining a better understanding of the manner in which the gas phase first enters the riser during the severe slugging cycle. Work on simulation of the system will continue with emphasis on system effects, i.e. the effects of upstream and downstream parts of the flow system such as the well and the separator.

Input to Activity

(1) The availability of a large scale flexible riser simulation facility at Cranfield University which has a wide range of instrumentation and a proven record of producing useful data for comparison with code predictions.

(2) An experienced team at Cranfield led by Dr. Hoi Yeung with a good track record in producing and analysing flexible riser data.

Output from Activity

(1) New and unique data on two- and three-phase flows in flexible risers. This will include measurements of local phase fractions and flow rates.

(2) Comparisons of the experiments with the predictions of the commercial computer codes and other software tools.

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Revision No.	CTR Managers	Approved
0	Dr. Hoi Yeung (Cranfield University)	Professor G.F.Hewitt (Project Director)

Project Title: Joint Project on Transient Multiphase Flows		
Cost Time Resource	Cost Time Resource Title	
TMF3 Sub-Project VIII	**Non-Newtonian Flows (Assessment Study)**	
Start Date	Duration	Cost
Autumn 2002	**Six months**	**£25k**

Objectives

(1) To ascertain, through communications and discussions with sponsors and other oil industry companies, the likely range of situations and conditions for the existence of non-Newtonian flows.

(2) To evaluate fluid models used in the commercial computer codes, and assess their applicability in the context of the study.

(3) To assess the adequacy of current models and property measurement methods. If there were notable inadequacies, then proposals for research would be prepared.

(4) To prepare an Assessment Report giving details of the findings.

Description of Work

Following the successful experience with Assessment Studies in TMF2, this Sub-Project will start with such a study which will be carried out through Imperial College Consultants (ICON) with inputs from Imperial College (Chemical Engineering) and Cranfield University staff. Many of the fluids encountered in hydrocarbon pipeline flows are significantly non-Newtonian in nature. For instance, waxy crudes exhibit important non-Newtonian behaviour with the existence of a yield stress. If the wall shear stress is less than this yield stress, then the fluid will not flow. Such behaviour is manifested as the temperature falls (hence the interest in thermal management reflected in the selection of Sub-Project IV as described above). Non-Newtonian fluid flow is a topic of wide interest and is being studied at a number of centres throughout the world. The topic is, however, a new one for TMF (though both Imperial College Chemical Engineering and Cranfield University have experience in the area). It is for this reason that the Assessment Study route has been chosen. The steps in the work will be as given under Objectives above.

Input to Activity

(1) Experience with non-Newtonian flows at both Imperial College and Cranfield University.

(2) Inputs from Sponsors and other industrial sources on types of fluid encountered.

Output from Activity

(1) A report which would act as a reference source for the subject, giving guidance on the likely departures from Newtonian behaviour in characteristic crudes and on the ways of mitigating the problems. The report would also state the principal relevant models and their solutions.

(2) An evaluation of the needs for specific research in the area and, if appropriate, the preparation of research proposals for future submission.

Revision No.	CTR Managers	Approved
0	Professor S.M.Richardson Professor G.F.Hewitt (Imperial College Consultants)	Professor G.F.Hewitt (Project Director)

Project Title: Joint Project on Transient Multiphase Flows

Cost Time Resource	Cost Time Resource Title	
TMF3 **Sub-Project IX**	**Active Control of Slug Flows (Assessment Study)**	
Start Date	Duration	Cost
Autumn 2002	**One year**	**£25k**

Objectives

(1) By investigation of the published information and by correspondence and meetings with those people and organisations involved, to prepare a taxonomy of methods for slug control which have been used in the industry.
(2) To study possible alternative methods and to assess their potential.
(3) If appropriate, to make recommendations for further work in the area.

Description of Work

Following the successful experience with Assessment Studies in TMF2, this Sub-Project will start with such a study which will be carried out through Imperial College Consultants (ICON) with inputs from Imperial College (Chemical Engineering) staff. Severe slugging represents an important limiting factor in the operation of sub-sea pipeline systems. The design and construction of large slug catchers can represent a very significant element in the overall capital cost of an installation. The search for a way of avoiding the formation of large slugs is a natural consequence. There is increasing interest in the use of active control systems for the control of slug flows. The objective is to constrain the size of slugs to acceptable limits. A number of organisations are pursuing active control systems for slug length control. For instance, Shell has been developing a system and this was described at the BHR Multiphase Flow Conference in Cannes in June 2001. However, the area is a new one for the groups involved in the TMF programme. Since this area is a new one for TMF, it is proposed that an Assessment Study be carried out on it. This work will be centred at Imperial College, Chemical Engineering (where there is a large activity in the control area) but with inputs from other University centres as appropriate. The steps in the work will be as given under Objectives above.

Input to Activity

(1) Experience with slug flows within the TMF projects.
(2) Inputs from Sponsors and other industrial sources on types of system encountered.
(3) Experience in control systems in the Centre for Process Systems Engineering at Imperial college (Chemical Engineering).

Output from Activity

(1) A report that would act as a reference source for the subject, giving information on the existing systems and on possible alternative systems.
(2) An evaluation of the needs for specific research in the area and, if appropriate, the preparation of research proposals for future submission.

Revision No.	CTR Managers	Approved
0	Professor G.F.Hewitt (Imperial College Consultants)	Professor G.F.Hewitt (Project Director)

Project Title: Joint Project on Transient Multiphase Flows

Cost Time Resource	Cost Time Resource Title	
TMF3 Technology transfer	**TECHNOLOGY TRANSFER**	
Start Date	Duration	Cost
Autumn 2002	**Three years**	**£130k**

Objectives

(1) To transfer to sponsors the technology developed in the programme by means of technical reports, provision of experimental data in machine readable form, presentations at meetings of sponsors and by staff attachments to Sponsor companies. The Project Web Site would be continued and enhanced.

(2) To transfer to sponsors specific items of technology through the medium of spreadsheet programs which can be used by sponsors to carry out specific calculations.

(3) To provide (in source code form) a test bed code in which software developments in the TMF program will be deposited so as to promote uptake of these developments by sponsors or for sponsors by the code development companies.

Description of Work

A key part of any industrially oriented research project is the mechanism for transferring the technology to the industrial sponsors. The normal methods of transmitting the results of the Project (presentations, reports, CD ROMs with data, the Project web page etc.) will continue. However, for TMF3, two complementary approaches are proposed as follows:

Simple Software Tools. Engineers need tools to allow them to quickly assess a specific aspect (e.g. thermal modelling for steady state, cool down and warm-up of bundles, pipe-in-pipe and buried insulated pipe; likely size ranges of slugs, flow regime prediction etc). Under TMF2, such tools are already being provided in the form of EXCEL spreadsheets. It is proposed to greatly increase this type of provision in the TMF3 programme.

Test Bed Code. One of the difficulties in transferring modelling methods is that there is a considerable cost incurred when merging new methodologies into an existing program. What is proposed is that a single test bed code will be made available in source form. The modelling developments will be carried out using this code as a test bed and developed versions of each model will be deposited in the code. It is proposed that the starting point for this test bed code will be the EMAPS code developed at Cranfield University.

In order to facilitate the above methods of technology transfer, a small software company will be appointed with experience in software management. This company will interact with both research Groups and with Sponsor Companies.

Input to Activity

(1) Existing experience in transferring technology to industry obtained in the TMF and other projects.

(2) Existing software bases, and in particular the EMAPS code.

(3) Experience in software management both in the research groups and through the external contract with a small software company.

Output from Activity

(1) Research outputs in the form of reports, data and presentations.

(2) Simple software tool in the form of EXCEL spreadsheets.

(3) Access to the EMAPS-based test bed code.

Revision No.	CTR Managers	Approved
0	Professor C.P.Thompson (Cranfield University)	Professor G.F.Hewitt (Project Director)

1.INTRODUCTION

The oil and natural gas production industry has an ongoing need to improve the understanding of multiphase flows. Such flows occur widely in hydrocarbon recovery and the industry needs to design and operate multiphase flow systems to achieve optimum economy whilst ensuring safety and protecting the environment. In support of these aims, Imperial College have managed, since 1996, a series of successful collaborative research and development projects targeting multiphase flow topics that have been chosen by the industry. This Prospectus presents the proposals for the third phase of this work – a Joint Project on Transient Multiphase Flows (TMF3).

Multiphase fluid flows are encountered widely in the oil and gas industry. The flows encountered include *two-phase flows* (oil-gas, oil-water) and *three-phase flows* (oil-gas-water). Such multiphase flows are fundamentally *time-varying* in nature with local phase content and velocity varying with time and position due to turbulence and the passage of interfaces. An extreme case of such time variations is that of slug flow where alternating liquid- and gas-continuous zones pass along the pipe. Superimposed on these variations in nominally *steady state* flows, various transients occur in which the flows entering or leaving pipeline systems change with time. Such *transient* flows occur for a variety of reasons which include start-up and shut-down, controlled blow-down, equipment malfunction and loss of integrity in piping or equipment.

The prediction of both steady state and transient multiphase flows is of vital importance in the design and operation of hydrocarbon recovery systems but also represents a formidable technical challenge. The importance of the area led to the setting up, under the auspices of the Marine Technology Directorate (MTD), of a Managed Programme in the area. This programme started in 1996: it was managed by Imperial College, London but also included projects at Cranfield University.

Following the successful implementation of the MTD (later Centre for Marine and Petroleum Technology, CMPT) Managed Programme on Transient Multiphase Flows (TMF1), a new Co-ordinated Project on Transient Multiphase Flows (TMF2) was set up and came into operation in late 1999. This further project included sub-projects at Nottingham, Bristol and Cambridge Universities in addition to Imperial College and Cranfield University. The project was managed by Imperial College. A key facet of both TMF1 and TMF2 was the involvement of the suppliers of the main transient prediction computer codes (OLGA, PLAC and TACITE). This gave the program developers a direct insight into the research and allowed them to incorporate the technological advances into the codes.

The phasing of TMF1 and TMF2 was such that there was overlap between the schedules of the two programmes; the last of the TMF1 Sub-Projects was completed in early 2001 and the last of the TMF2 Sub-Projects is due for completion in the autumn of 2002. Following discussions at the TMF2 Sponsors Meeting in April 2001, it was decided to begin preliminary considerations of future work to be started after the completion of TMF2. A list of potential topics was developed by the sponsors, who then voted for their preferred sub-projects. The proposals given in this Prospectus have been developed from the results of this voting procedure. Appendix A to this Prospectus gives further details of these consultations with industrial sponsors.

This Prospectus presents the proposed new project (Joint Project on Transient Multiphase Flows, TMF3) that will address issues of wide and fundamental importance revealed in these consultations to be of high priority. The following University Groups would carry out the work jointly:

Imperial College (Chemical Engineering):
Professor Geoff Hewitt (Project Director)
Dr. Chris Lawrence (Deputy Project Director)
Professor Stephen Richardson
Mr. Colin Weil (Project Manager)

Imperial College (Mechanical Engineering)
Dr. Raad Issa (Deputy Project Director)

Cranfield University
Professor Chris Thompson
Dr. Hoi Yeung

Bristol University
Professor Joe Quarini

Nottingham University
Professor Barry Azzopardi

A full description of the proposed Project is given below in Section 4. Briefly, the main objectives of the project are to advance the modelling of multiphase flow and to deal with a number of new problems such as non-Newtonian flows and large diameter risers. Specific attention will be paid to technology transfer aspects; spreadsheet-type programs will be prepared and issued to sponsors and a common code (EMAPS) will be used as a test bed for new methods and as a means of transferring these methods to industry. Further discussion of these technology transfer aspects is given in Section 5 below.

The Project is timed to start in the autumn of 2002 and will continue for 3 years. It is being proposed for joint funding by industry, the Department of Trade and Industry (DTI) and the Engineering and Physical Sciences Research Council (EPSRC).

In what follows, brief reviews will be given of the completed work under the TMF1 programme (Section 2) and of the completed and ongoing work under the TMF2 programme (Section 3). Further information on TMF1 and TMF2 is given in Appendices B and C respectively. A more detailed presentation of the work proposed for the TMF3 programme is then given in Section 4. With large and complex projects such as the TMF3 Project proposed here, it is essential to ensure efficient and comprehensive technology transfer; this aspect is discussed in Section 5. The methodology proposed for project management is presented in Section 6 and Section 7 deals with budgets and costs.

2. THE TMF1 PROGRAMME

The Managed Programme on Transient Multiphase Flows (TMF1) was a programme jointly funded by the oil industry and its contractors and by the UK Engineering and Physical Sciences Research Council (EPSRC). Contributing companies (either original members or companies who “bought in” to the project later) were as follows: BG International, ABB Corporate Research, Amerada Hess, BP Exploration, Chevron Petroleum Technology Co., Conoco, Elf Acquitaine Production, Enterprise Oil, Exxon Projection Research Co., Granherne, Marathon Oil, Mobil North Sea, Norsk Hydro, Texaco Britain and Total Exploration Production. Sponsors who (by encouragement and agreement of the contributing sponsors) provided a contractual "in-kind" contribution were AEA Technology, BHR Group Ltd, Institute for Energy Technology, Norway, Institut Francais du Petrole, France and Scandpower, Norway. In this latter group of companies, an important consideration was that they included the producers of the most important pipeline transient simulation codes, namely OLGA (IFE, Scandpower), PLAC (AEA Technology) and TACITE (IFP).

The overall aim of the research was to advance the knowledge of transient multiphase phenomena, improve the coding of the available computer models and thus directly benefit the industry in its quest to improve operability, safety and reduction in capital costs.

The TMF1 Programme was organised in six Projects as follows:

Project 1: Transient Three-Phase Flows (Imperial College, Chemical Engineering).

Project 2: Phase Interactions in Transient Stratified Flow (Imperial College, Chemical Engineering).

Project 3: Slug Growth and Collapse in the Flow of Gas Liquid Mixtures in Pipes (Imperial College, Chemical Engineering and Mechanical Engineering).

Project 4: Flexible Risers Severe Slugging (Cranfield University).

Project 5: Numerical Simulation of Multiphase Flow (Cranfield University).

Project 6: Transient Mass Transfer in Co-existing Hydrocarbon Liquid and Gas Phases in Flowing Systems (Imperial College, Chemical Engineering).

The TMF1 Programme ran from late 1996 through to January 2001. Over the period of the project, over 180 documents and a wide range of experimental data were issued to sponsors; the documents were made available to sponsors in both hard copy form and also through the programme Web Site. This represents a formidable amount of information. For each Project, a final summary report was written. The objectives and achievements of each of the constituent projects are summarised in Appendix B.

The overall investment in the TMF1 Project is estimated to have been. £2258k, comprising cash contributions of £442k and in-kind contributions of £625k from industry and a contribution of £1191k from CMPT/EPSRC.

The TMF1 Programme addressed priority issues in the all-important area of hydrocarbon recovery. The projects were selected on the basis of intensive initial discussions with industry and significant advances were made in all of the six projects. The success of the TMF1 Programme was reflected in the setting up of an even broader successor programme (TMF2).

3. THE TMF2 PROJECT

The Co-ordinated Project on Transient Multiphase Flows (TMF2) is a programme jointly funded by the oil industry and its contractors and by the UK Engineering and Physical Sciences Research

Council (EPSRC). Contributing companies are as follows: BG International, ABB Corporate Research, BP Exploration, Chevron Petroleum Technology, Conoco, Elf Acquitaine Production, Enterprise Oil, Granherne, Marathon Oil, Mobil North Sea Ltd, Norsk Hydro, and Total Exploration Production. Sponsors who provide a contractual "in-kind" contribution are AEA Technology, Institute for Energy Technology, Norway, Institut Francais du Petrole, France and Scandpower, Norway (i.e. the developers of commercial transient codes).

The objectives of the TMF2 Project were similar to those of TMF1, with an increased range of topics and University participation.

The TMF2 Project consists of 7 Sub-Projects as follows:

Sub-Project A: Modelling Bases (Cranfield University, Imperial College Mechanical Engineering, Nottingham University, Imperial College Chemical Engineering)

Sub-Project B: Three-Phase Flow (Imperial College Chemical Engineering, Cranfield University, Imperial College Mechanical Engineering).

Sub-Project C: Tube Bundles (Imperial College Chemical Engineering, Bristol University)

Sub-Project D: Transport Behaviour of Particulate Solid Constituents (Cambridge University)

Sub-Project E: Transient Hydrodynamic Loading (Cambridge University, Cranfield University)

Sub-Project F: Flexible Risers (Cranfield University)

Sub-Project G: Coupled Heat and Mass Transfer Effects (Imperial College Chemical Engineering)

The TMF2 Project commenced in 1999 and will continue until the autumn of 2002. Experimental data have been collected and made available to the participants on topics such as slugging in flexible risers, slug development in horizontal and inclined pipes and pipes with changes in inclination, flows with particulates, three-phase flows and hydrodynamic loading on elbows. Spreadsheets have also been issued covering basic design for hydrodynamic loading in bends and critical velocities for transportation of particles. An additional tool for approximate flowline bundle thermal modelling is also in development. Around 70 reports have already been issued in hard copy and are available on the Web Site . Further details of the objectives and existing achievements of the TMF2 Sub-Projects are given in Appendix C.

4. PROPOSED SUB-PROJECTS FOR THE TMF3 PROJECT

The methodology for designation and selection of the TMF3 Sub-Projects is described in more detail in Appendix A. The following topics are proposed for full research studies:

Sub-Project I: Multifluid Modelling
Sub-Project II: Slug Tracking
Sub-Project III: Large Diameter Risers
Sub-Project IV: Thermal Management
Sub-Project V: Three-Phase Flows

Sub-Project VI: Junction Flows
Sub-Project VII: Flexible Risers

In addition, it is proposed to perform Assessment Studies (aimed at evaluating current information and assessing the needs for research) in the following areas:

Sub-Project VIII: Non-Newtonian Flows
Sub-Project IX: Active Control of Slug Flows

The proposed work on each of these areas is presented in what follows; in each case, there is a brief introduction of the subject area followed by a summary of previous work. The proposed work is then described and the expected deliverables are listed. In the recognition that some sponsors may wish to have the proposed projects summarised in the Cost Time Resource (CTR) form format, a CTR form has been prepared for each Sub-Project and these are given in Appendix D.

Sub-Project I : Multifluid Modelling

Introduction. Modelling methods for multiphase flows (gas-liquid and gas-liquid-liquid) are at the core of the TMF projects. The *modus operandum* adopted in TMF is to develop modelling methods in close consultation with oil industry sponsors and with those developing software tools for use by these sponsors (the "code developers"). Within the TMF Projects, a key aim is to take an objective view of commercial software tools and to produce data and other test material against which these tools can be evaluated. Close collaboration with the code developers ensures that the comparisons are valid. However, it has so far been found that the agreement of the codes with much of the data is often, at best, qualitative. More serious, perhaps, are the large discrepancies in the predictions between the respective codes themselves. Real flowing systems and the code predictions of them are often very sensitive to small changes in boundary conditions and that care needs to be taken both in experiments and in representing experiments in the codes. Whilst this is certainly true, it cannot be the explanation for some of the discrepancies observed. Gross differences exist between the respective codes in the (crucial) closure relationships for interfacial friction etc.

The major commercial codes tend to use idealised representations of multiphase flow, most usually of the *multi-fluid model* type, but occasionally of the *drift-flux model* type. These models generally had their origin in nuclear safety codes produced in the 1960s-1980s. They do not, and indeed, cannot, produce *absolute* solutions. This is not surprising when it is borne in mind that even single phase turbulent flows cannot be solved in a fundamental way at normal engineering Reynolds numbers (though solutions are increasingly available at Reynolds numbers close to the transition from laminar flow – i.e., *direct numerical simulation*). When the complications of phase boundaries (interfaces) are introduced, then the multiphase flow situation is seen to be even more difficult. For both single phase and multiphase flows, therefore, additional heuristic or empirical relationships are required (*closure* relationships) in order to make the models functional.

Previous Work. As a result of the TMF1 and TMF2 Programmes, a number of observations can be made on the current state of modelling:

(1) Even in the simplest case of stratified flows, predictions from the models tend to differ from the experiments and from each other, mainly because the specification of the closure laws is different in the respective codes. Furthermore, evidence from the TMF Projects shows that the closure laws may be different during transients; it is not valid to assume that the same laws apply as for steady state flows (as is commonly assumed in the commercial codes). A factor influencing the comparison of codes and experiments

is the highly non-linear nature of the phenomena involved. Small changes in inlet conditions can exert a large influence on the phenomena. This means that additional care should be taken in assessing the accuracy of the measurements both of the independent variables (input flows etc) and of the dependant variables (holdups, pressure gradients etc.

(2) It is possible, by using very short grid intervals and time steps, to simulate *slug flow* using one-dimensional two-fluid models, as has been demonstrated in the TMF work in the Mechanical Engineering Department at Imperial College and, more recently, in the work at Cranfield. However, there are several difficulties in applying this approach:

a) The number of nodes per unit pipe length is typically one or two orders of magnitude greater than the number per unit length currently used in commercial calculations. There are two views of the use of such methods. Some feel that they are far from real applications and that other approaches are necessary (e.g. slug tracking – see below). Others feel that the advances in computer hardware will soon make these methods attractive and economic.

b) Many of the important features of slug flow cannot be represented by a one-dimensional model. Thus, the slug front and slug tail are three-dimensional in nature, and the one-dimensional predictions give different behaviour than that actually observed.

c) In a one-dimensional model, one possible approach is to assume that the phases are well-mixed within the slug body. Here, it is implicitly assumed that gas and liquid entering the slug front are mixed together and proceed to the tail of the slug as a homogeneous mixture. Measurements of gas void fraction in the slug and of the rates at which gas enters the slug show this assumption to be wrong. It is possible to correct for these effects by introducing local drift flux models; this approach is already being investigated in TMF2 for three-phase flows and shows promise.

d) A crucial factor in the development of slugs is the influence of slug length on slug tail velocity; as the slug gets shorter, then the tail velocity increases and this can cause the slug to collapse. This is a multi-dimensional effect which is simply not captured by the one-dimensional models. However, it should be noted that one-dimensional two-fluid models *can* predict slug collapse resulting from lower-than-equilibrium pickup rates at the slug front.

e) The number of nodes can be decreased by techniques such as adaptive gridding (as has been studied in the work at Cranfield University in the TMF projects) but even using these techniques, one-dimensional capturing of the slug flow may prove difficult (with current hardware) in predicting practical and very long pipelines. Even if such capturing were achieved, then there are the other difficulties mentioned above to contend with. It may be possible to reconcile entrainment rates and void fraction in slugs by using distribution parameters which take account of the cross sectional variations of velocity and void fraction which seem to be occurring. Generally, one may conclude that, as far as commercial code predictions are concerned, the region of hydrodynamic slugging is one in which the conventional multi-fluid model approach currently has some shortcomings. This may change at some point in the future in the light of advances in computer hardware and it is with this in mind that continued work in this area is strongly favoured by sponsors.

f) Liquid-liquid mixing processes in three-phase flows present a whole new dimension to the prediction of pipeline flows, that is currently inadequately dealt with. Hopefully, the work within the TMF2 Programme at Cranfield University will give rise to improved models for stratified flow, but the situation in slug flows is still largely unresolved

Proposed Work. Despite the recognised difficulties, there is a consensus amongst Sponsors that the multifluid modelling must continue to be actively pursued in TMF3. There is a feeling that many of the problems might be addressed by exercising ingenuity in developing methods to allow three-dimensional and other complex features to be approximately (but adequately) represented within the multifluid framework.

In response to this consensus view, the proposed TMF3 programme will have the following priorities:

(1) Continued development of numerical algorithms with the objective of bringing forward the time at which the methods can be used economically for slug-capturing calculations of real systems having hydrodynamic slug flow. The goals will be to develop algorithms with further improvements in speed and robustness, capable of handling variation in geometry/topography and flow regime transition. This work will be concentrated at Cranfield University.

(2) Continued studies of closure relationships. This work will be concentrated at Imperial College Mechanical Engineering and will include the following:

(a) Improvement of closure laws for one-dimensional models. In the TMF2 project, work was carried out on gas entrainment and on the use of drift flux relationships. Further work in this area will be focussed on improving these models to take account of the wider range of experimental data becoming available. Consideration will also be given to providing valid adjustments to the models for slug flows to take account of the effect of slug length on slug velocity.

(b) Multi-dimensional modelling studies. This will include advanced CFD studies in which the multi-dimensional features of the flow will be modelled with the objective of deriving more accurate closure laws for the one dimensional codes.

Deliverables. The main deliverables of the proposed work would be as follows:

(1) Improved numerical structures for one-dimensional multifluid codes which can be implemented into the commercial codes either directly or indirectly through the common test bed code EMAPS (Eulerian Multiphase Adaptive Pipeline Solver) – see Section 5 below. The new numerical structures would allow slug capturing in the codes, hopefully in a way which makes such slug capturing economic in design and assessment calculations.

(2) Improved closure relationships and other closure approximations (such as the partial use of drift flux relationships) which can be implemented directly or indirectly into the commercial codes.

Sub-Project II: Slug Tracking

Introduction. Though it is proposed that the multifluid modelling approach be actively pursued in the TMF3 work, the difficulties in that approach, as summarised above, make it worthwhile pursuing another approach for the prediction of slug flows in the short and medium term, namely *slug tracking.* In this alternative approach, the creation and behaviour of individual slugs are followed as they move down the pipe. Such an approach allows the natural introduction of relationships, derived from experiment and more detailed (e.g. CFD) modelling, into the prediction scheme.

Previous work. Recognising the difficulties of predicting hydrodynamic slug flow, at least one commercial code developer has introduced a so-called "slug tracking" model. Such models have also been pursued in associated work at Imperial College (by Colin Hale and Phil Manfield who completed their theses in 2000 and by Priscilla Ujang who is continuing the work in this area) and also at the University of Tel-Aviv (Prof. Yehuda Taitel) in association with the University of Tulsa. By including compressibility in slug tracking models, it is possible to treat both hydrodynamic slug flow and severe slugging. Features of the models developed at Imperial College also include:

(1) Look-up table solutions for the slug tail, these solutions being obtained by the two-fluid model for a variety of reference cases.

(2) Taking account of gas entrainment and the effect of slug length on tail velocity using empirical fits to measured data.

(3) Including accurate correlations for tail velocity for fully developed and developing slugs that take full account of the multi-dimensional nature of these slugs.

These models show some very interesting features; for instance, they suggest quite strongly that there is no unique solution for fully developed hydrodynamic slug flow. What is finally achieved seems to depend on the inlet conditions! The models also have recognised problems in application to transient flow.

Proposed Work. It is proposed that the slug tracking approach be pursued by Imperial College Chemical Engineering. Building on the work already done, it is proposed that modelling methodologies be developed which, essentially, combine the best features of the multi-fluid models and the slug tracking models, with an attempt to provide "seamless" junctions between regions in which the respective models are applied. Thus, for example, in a pipeline with a dip, the multi-fluid model could be used to describe a stratified flow regime upstream of the dip and a slug tracking model to describe a slug flow regime downstream of the dip. It is recognised that there are formidable challenges in this approach, not least the problems of dealing with transient flows and the problems of providing adequate descriptions of slug initiation, but it is believed that this suggested route offers a reasonable hope for progress in what has proved to be an intractable problem so far.

By following both the multifluid model and slug tracking routes, it should be possible to move fairly rapidly towards a medium term solution (slug tracking) whilst keeping the door open for adoption of one-dimensional slug capturing in the longer term. Many of the closure laws required are common to both routes. The links between the slug tracking work and the multifluid model work would be forged through the proposal to establish a benchmark/test bed code which will be the repository for developments in all areas of the TMF3 project (see Section 5 below).

To pursue the slug-tracking route, the following steps are proposed:

(1) The basic formulation of the slug tracking model would be derived from first principles, ensuring consistency in local and global mass and and momentum balances.

(2) Improved models will be developed for slug initiation which could be used in conjunction with the slug tracking models (and also, of course, with the one-dimensional multifluid model – see above). Here it will be necessary to build bridges between one-dimensional models for slug precursor formation and the multi-dimensional effects which subsequently occur and which are of vital importance in governing the development of the flow. New experimental data will be generated on slug initiation and gas entrainment in slugs in oil-gas flows using the Imperial College Chemical Engineering WASP facility.

(3) The slug tracking approach will be checked against data from the WASP facility and other sources. Where necessary, new data will be generated on a variety of geometries, and in particular on deviated geometries (vee-shaped test sections and lamda-shaped test sections) which, on the one hand, provide a significant challenge to the methodology but, on the other hand, demonstrate considerable advantages for the methodology if it is successful!

Deliverables. The main deliverables from Sub-Project II are expected to be:

(1) A useable methodology for slug tracking incorporating sub-models based on data and on detailed modelling.

(2) A code (embodied in the test bed code EMAPS – see Section 5 below) which can be used directly for predicting slug flows in complex geometries or which can be adopted into the commercial codes.

Sub-Project III: Large Diameter Risers

Introduction. With fields being developed in ever increasing water depths, the importance of large diameter vertical and steeply inclined riser systems is increasing. This provides severe challenges to the methodologies for predicting flow regime, phase fractions (holdups) and pressure gradient. This is because the flow regimes (and hence the other parameters) may be very different in large diameter pipes. Specifically, experiments at Nottingham, in Canada and elsewhere indicate that slug flow (as envisaged by the most commonly used flow pattern maps) *does not actually exist in large diameter vertical pipes* except where slugs are introduced, say, from a pipeline feeding the riser. The spherical cap bubbles which are characteristic of slug flow, become unstable at diameters greater than around 100 mm. We have been informed that intermittent flow has been observed in proprietary tests in the 200mm riser of the Tiller loop in Norway but is not clear whether this is for cases influenced by the upstream pipeline. There are also unsolved problems regarding the creation and behaviour of churn and annular flows, which are commonly found in such systems. As well as upflow, *downflow* in vertical or steeply downwardly inclined pipes is an increasingly important area. Gravitational pressure losses in upflow cannot be assumed to be recovered in the downflow regions. There is a need for much more information on flow regime differences between upflow and downflow.

Previous Work. There is very little work available in large diameter vertical pipes. Nottingham is one of the centres which has worked with such pipes. Cheng et al. studied the bubble/slug transition in 0.15 m diameter pipes. Over ranges of flow rates where slug flow would normally appear, no conventional large bubbles were seen. However, the void fraction was observed to fluctuate periodically. This was observed in the signals of cross-sectionally averaged void fraction and point void fraction probes. In earlier work on annular flow in a 0.125 m diameter vertical pipe, the characteristics of the very important disturbance waves on the film were studied. These were found to be essentially different to the waves in smaller diameter pipes.

Proposed Work. The proposed Sub-Project will be carried out at the University of Nottingham and will employ existing facilities which will be upgraded for the project. The rig will be converted to closed loop operation using a liquid ring compressor. Test sections of 0.076 and 0.125 m diameters will be configured so as to be able to operate in either upwards or downwards mode. The facility has been designed to operate from bubbly to annular flow. Test pipes will be manufactured from transparent materials.

The large scale closed loop facility will allow operation with fluids other than air/water. It is expected that sulphur hexafluoride will be employed as the gas and a silicon oil as the liquid. This will give a capability of gas densities up to 10 kg/m^3 and a surface tension about 25% that of water.

The facility will be used to observe flow patterns. Here, both axial and side views will be employed. In addition it is intended to implement a tomography technique. Either Electric Capacitance Tomography or Mesh Tomography will be applied.

Pressure drop and wall shear will be measured. In the annular flow pattern it is proposed to obtain film thickness, film flow rate and drop size information.

Deliverables. The research programme proposed will provide:

(1) Experimental data to allow the existing flow rate/pressure drop relationships for large diameter risers to be tested.

(2) A test of flow pattern prediction methods based on data gathered on the large diameter pipes.

(3) Improved versions of flow pattern and flow rate/pressure drop predictive methods suitable for large diameter pipes.

Sub-Project IV: Thermal Management

Introduction. With the increasing emphasis on deep water hydrocarbon recovery and with a wider variety of crude properties, *thermal management* of the pipeline systems has become increasingly important. The objective of such thermal management is to prevent solids phase deposition in pipelines carrying fluids from which solid phases (waxes, hydrates, asphaltenes) may be created if the temperatures are allowed to fall too low. There is also interest in heat transfer in partially buried pipelines and in heat transfer behaviour of manifold systems.

Previous Work. As a result of the work at Imperial College Chemical Engineering and Bristol University on Sub-Project C of TMF2, it is expected that a systematic methodology will have been established (including CFD and experimental validation) for predicting the behaviour of tube bundles for use in thermal management of pipelines. This work is summarised in Appendix C.

Proposed Work. What is proposed for TMF3 Sub-Project IV is that the joint activity between Imperial College Chemical Engineering and the University of Bristol be extended in the following ways:

(1) The software package arising from TMF2 will be extended to include a wider number of cases. This package allows performance calculation of tube bundle systems in which the tubes within the bundle are surrounded by an interstitial fluid phase. The extensions to the package will include more sophisticated representations of insulation and partial insulation, representations of manifold systems and modelling of partially buried pipes.

(2) CFD and experimental studies will be carried out to evaluate thermal behaviour of a wider range of systems (more complex tube bundles, manifolds and partially buried pipes) and the results used to develop new equations which can be used within the software package described in (1) above.

(3) Development of *design* (rather than performance) tools for thermal management systems. A wide range of configurations is available; which is the best for a particular task? The intention is to provide a software tool for thermal management system design which is analogous to the HTFS program DEVISE which allows rapid selection of heat exchanger geometries. Preliminary work on such a system has already been carried out at Bristol University and has been presented at a TMF sponsors meeting. There was unanimous agreement that the concept should be pursued.

Deliverables. The main deliverables from this Sub-Project are expected to be as follows:

(1) The provision of software tools for the design and performance evaluation of thermal management systems.

(2) The provision of data and equations for heat transfer rates from the components of thermally managed systems which, in addition to their inclusion in the software tools mentioned in (1) above may also be used directly or absorbed into the commercial codes.

Sub-Project V: Three-Phase Flows

Introduction. Three-phase (gas-water-oil) flows present a formidable challenge and, though a much more extensive data base and physical understanding of these flows has evolved from the work in the TMF1 and TMF2 programmes, it cannot realistically be asserted that the situation on prediction is anywhere near satisfactory. A central issue is that of *phase inversion* in which (in dispersed flows) the system changes from *oil-continuous* to *water-continuous* with the discontinuous phase being dispersed as droplets in the continuous one. The phase inversion process is associated with a very large increase in the effective viscosity of the mixture. This problem is difficult enough in steady state flow, but becomes even more intractable in the case of transient flows where the transient leads to a traversing of the phase inversion point. Work in the TMF1 and TMF2 programmes has shown many subtle and unexpected effects during such transients.

Previous Work. There are a number of approaches to prediction of three-phase flows which include:

(1) Application of two-phase flow empirical models with suitable adjustments of viscosity to take account of phase inversion. This approach has been followed, for instance, in

early work at Imperial College (Chemical Engineering) to analyse the first data arising from the WASP facility. The approach developed takes account of phase inter-mixing by developing an empirical relationship. In terms of prediction, it could be argued that this approach still gives the best results! However, it is not suitable for transients.

(2) Application of standard two-phase flow models (for instance, the multi-fluid model), treating the liquid phase as fully mixed and assigning to it a viscosity calculated from a liquid-liquid mixture viscosity model. This approach has been followed in the TMF2 Programme both for stratified flows (Cranfield University) and slug flows (Imperial College). The approach is less suitable for transients in which the input water cut is changed. It may be possible to deal with this latter case in terms of a drift flux model and this is currently being pursued by Imperial College (Mechanical Engineering). In this approach, rather than solving the full three-fluid model equations for the transient, the flow is represented in terms of a liquid phase velocity, a gas phase velocity and a drift velocity. The drift velocity is estimated from *steady state* solutions for the relevant flow regime.

(3) Detailed modelling of the phase mixing processes. This is the basis of the *five-layer* model being developed at Cranfield University where mixing processes are being modelled for both liquid-liquid and liquid-liquid-gas flows.

Proposed Work. For the TMF3 programme, there is a consensus that experimental work should continue. The Imperial College (Chemical Engineering) WASP facility has developed greatly during the TMF1/TMF2 project periods and a much wider range of instrumentation is now available which should help in validating and developing new models. The new instrumentation includes:

(1) New single-energy and dual-energy gamma densitometry systems. For three-phase flows, fixed single-beam, traversing single-beam and three-beam gamma densitometers are available and, for measurements of total liquid holdup, four fixed single-beam single-energy units have been constructed. This gives a total of 7 gamma densitometers on the facility which will allow much more detailed measurements to be made on slug evolution etc.

(2) Imperial College (Chemical Engineering) have acquired a two-hundred-detector X-ray tomography system which is being installed with finance from a European Programme. This unit will be available for tests under TMF3 and will give cross-sectional distributions of the three phases at reasonably high frequency (at least 11 Hz). This should prove a very powerful tool in developing understanding of phase mixing and separation effects in slug and other three-phase flows.

(3) A large amount of development work has been done on accurate measurement of pressure gradient. This has not yet been fully exploited in measuring three-phase flows but much more detailed information should be available on pressure gradients in slugs as a function of phase composition, etc.

What is proposed for the TMF3 Sub-Project in this area is as follows:

(1) Using the enhanced instrumentation described above, experimental work will be continued on the Imperial College Chemical Engineering WASP facility with the following main aims:

(a) Investigation of the homogeneity of slugs flowing along a pipe; do water-rich slugs and oil-rich slugs coexist in a given flow?

(b) Generation of a wider data base on flow patterns in three phase flow. Again, the enhanced instrumentation will be of great value in discriminating between the regimes and in particular the regimes occurring in transients.

(c) Measurements of average and time-varying pressure drop and phase holdups to provide a data base for validation of models. More data would be obtained for inclined and deviated pipes.

(2) Imperial College Mechanical Engineering would continue their work on the representation of the relative motion of the liquid phases using the drift flux concept. The work would be validated against transient as well as steady state data. This work will also address the phase inversion issue.

(3) Cranfield University would continue to develop mixing models. Again, these models should be validated in detail against the new data described in (1) above.

The modelling work would be transferred to industry both directly and through the medium of the EMAPS test bed (see Section 5 below). In addition to the modelling work on phase inversion to be carried out in Imperial College (Mechanical Engineering) under the proposed Sub-Project V, fundamental work on the topic of phase inversion is being pursued separately at Imperial College Chemical Engineering in association with other universities and it is planned that results of this work should be fed to industry via TMF3.

Sub-Project VI: Junction Flows

Introduction: Junctions, whether combining or dividing, are almost inevitable in pipeline systems. To be able to model operating systems or as a prediction tool in design, codes need to be able to handle systems with junctions. The physical processes, which need to be addressed, obviously differ according to the type of junction. For combining junctions important questions are the additional pressure drop across the junction, characteristics of the flow such as slugs before and after the junction and pressure fluctuations around the junction. The case of dividing junctions is made more complex by the inevitable maldistribution of the phases that occurs here. Though there is a significant amount of work in this area (see the extensive review by Azzopardi in Multiphase Science and Technology, 1999), there is a lack of knowledge on the division of slug flows. Moreover, the majority of available data have been taken with air/water flows.

Previous Work. In the case of combining junctions, a short (feasibility) study has been carried out under TMF2. This involved the design and construction of a flow facility (air/water). The project started with two initial aims: (i) characterisation of slugs upstream and downstream of the junction and (ii) examination of the possible persistence of slugs passing from the (smaller diameter) side pipe into the main pipe even when slugs would not have existed in the main pipe at the same total flow rate in the absence of the side pipe. The facility is now operational and data giving information under (i) have been successfully obtained using analysis of video films. The second objective was not achieved as another phenomenon was observed which interfered with the study. This involved waves travelling upstream from the junction at low flow rates. These waves caused an occasional slug to form when they reached the upstream mixer. Conditions for their occurrence were determined and a simple theory was developed to explain the phenomenon and quantify its boundaries. Information from an industrial company has indicated that analogous effects have been observed on one of their field systems. Cranfield University is developing a prototype code for modelling stratified flows in T-junctions.

Since the TMF1 project ended the instrumentation on the rig has been augmented. Eight pressure transducers and eight conductance void fraction probes have been installed in the pipes upstream and downstream of the junction. The work is being carried out in conjunction with a team from the University of Genoa (Professor Guglielmini, Dr Fossa) who have expertise in void fraction probes. Dr Fossa spent three weeks in Nottingham in September 2001 calibrating the void fraction probes.

Proposed Work. The work proposed for TMF3 Sub-Project VI will consist of three parts. The first two will consider combining junctions whilst the third will examine dividing slug flow. The first part will use the existing air-water facility and instrumentation to gather a comprehensive set of data. This will be made available to the modelling teams.

In the second part, the facility will be modified to make it part of an existing closed loop rig at Nottingham. This can operate with a heavy gas (SF_6, density = 20 kg/m^3 at 3.3 bar(a)) and a low surface tension liquid (silicon oil, surface tension= 0.02 N/m, viscosity = 0.005 Pa s). The above air-water experiments will be repeated with these different fluids.

The third phase will be to obtain information from a horizontal dividing T-junction mounted on an existing air/kerosene facility at Nottingham.

Deliverables. The research programme proposed will provide:

(1) The limits of the operational envelope for the occurrence of slugs which might appear unexpectedly and be caused by the secondary input equipment.

(2) Input to the modelling programmes carried out by other groups.

(3) Validated equations for the additional pressure drops across the junctions.

(4) Phase split information for dividing junctions.

Sub-Project VII: Flexible Risers

Introduction. Flexible riser systems continue to be of vital importance in hydrocarbon recovery. These systems link the well-manifold system on the ocean floor with surface facilities (for instance floating processing units). The risers are typically configured in catenary or S-shaped form. Such risers are particularly susceptible to severe slugging instabilities. There is strong interest in continuing the work on flexible risers reflecting the increasing importance of these systems as reserves in deeper water are developed.

Previous Work. As part of the TMF1 and TMF2 projects, a large amount of data have now been generated at Cranfield University on air-water flow in catenary and S-shaped flexible risers. This work is summarised in Appendices B and C. The TMF2 programme will finish with some tests on air-oil flows and air-oil-water three-phase flows. However, the range of instrumentation available for these latter systems will be much less than has been possible (using conductance devices, for instance) for the air-water flows.

Proposed Work. The proposed TMF3 Sub-Project VII work in this area would include experiments with both two-phase and three-phase flows and focus on:

(1) A closer look at the phenomena occurring at the bottom of the riser. The way in which the gas enters the riser seems to be an important factor in governing the system behaviour.

(2) Further investigations of the interaction of the riser system with the associated systems (and in particular the separator and the well). This would be done with both two-phase and three-phase flows.

(3) Improved instrumentation for three-phase flows allowing local phase flow rates and phase fractions to be determined. The only practicable way forward in this context appears to be the use of dual-energy gamma densitometry and, perhaps, some form of multiphase flow meter. Such systems may be provided on loan from Imperial College Chemical Engineering.

Deliverables. It is expected that the deliverables from this Sub-Project will include:

(1) New and unique data on two- and three-phase flows in flexible risers. This will include measurements of local phase fractions and flow rates.

(2) Comparisons of the experiments with the predictions of the commercial computer codes and other software tools.

Sub-Project VIII: Non-Newtonian Flows

Introduction. Many of the fluids encountered in hydrocarbon pipeline flows are significantly non-Newtonian in nature. For instance, waxy crudes exhibit important non-Newtonian behaviour with the existence of a yield stress. If the wall shear stress is less than this yield stress, then the fluid will not flow. Such behaviour is manifested as the temperature falls (hence the interest in thermal management reflected in the selection of Sub-Project IV as described above).

Previous Work. Non-Newtonian fluid flow is a topic of wide interest and is being studied at a number of centres throughout the world. The topic is, however, a new one for TMF (though both Imperial College Chemical Engineering and Cranfield University have experience in the area).

Proposed Work. The topic of non-Newtonian flow is very diverse in nature and it is proposed (following the successful practice used in TMF2) to carry out an Assessment Study to evaluate the current state of the art in the context of hydrocarbon pipeline flows and to ascertain what, if any, would be the most appropriate avenues for research. The following steps are proposed:

(1) Through communications and discussions with sponsors and other oil industry companies, the likely range of situations and conditions for the existence of non-Newtonian flows will be ascertained.

(2) An evaluation will be made of the appropriate fluid models used in the commercial computer codes, and of their applicability in the context of the study.

(3) An assessment would be made of the adequacy of current models and property measurement methods. If there were notable inadequacies, then proposals for research would be prepared.

(4) An Assessment Report would be prepared.

It is proposed that the work would be coordinated by Imperial College Chemical Engineering, though inputs would be sought from other academic and industrial experts in the area.

Deliverables. It is anticipated that the deliverables from the Sub-Project would be as follows:

(1) A report which would act as a reference source for the subject, giving guidance on the likely departures from Newtonian behaviour in characteristic crudes and on the ways of mitigating the problems. The report would also state the principal relevant models and their solutions.

(2) An evaluation of the needs for specific research in the area and, if appropriate, the preparation of research proposals for future submission.

Sub-Project IX: Active Control of Slug Flows

Introduction. Severe slugging represents an important limiting factor in the operation of sub-sea pipeline systems. The design and construction of large slug catchers can represent a very significant element in the overall capital cost of an installation. The search for a way of avoiding the formation of large slugs is a natural consequence. There is increasing interest in the use of active control systems for the control of slug flows. The objective is to constrain the size of slugs to acceptable limits.

Previous Work. A number of organisations are pursuing active control systems for slug length control. For instance, Shell has been developing a system and this was described at the BHR Multiphase Flow Conference in Cannes in June 2001. However, the area is a new one for the groups involved in the TMF programme.

Proposed Work. Since this area is a new one for TMF, it is proposed that an Assessment Study be carried out on it. This work will be centred at Imperial College, Chemical Engineering (where there is a large activity in the control area) but with inputs from other University centres as appropriate. The following steps are proposed:

(1) By investigation of the published information and by correspondence and meetings with those people and organisations involved, a taxonomy of methods for slug control will be developed.

(2) A study will be made of possible alternative methods.

(3) If appropriate, recommendations will be made for further work in the area.

Deliverables. It is anticipated that the following main deliverables will arise from this work:

(1) A report that would act as a reference source for the subject, giving information on the existing systems and on possible alternative systems.

(2) An evaluation of the needs for specific research in the area and, if appropriate, the preparation of research proposals for future submission.

5. TECHNOLOGY TRANSFER

A key part of any industrially oriented research project is the mechanism for transferring the technology to the industrial sponsors.

A primary assumption in TMF1 and TMF2 has been that the work would be exploited largely by its consumption within the major commercial software codes. The membership of the code vendor companies in the project has been aimed at facilitating this. This approach has certainly succeeded to some extent. The data have been used in code development and validation and contracts have been placed by one of the code developers to assist in the transfer of the adaptive gridding technology developed at Cranfield. However, there is an increasing feeling that technology transfer outside the commercial codes is not only useful but essential. For TMF3, two complementary approaches are proposed as follows:

Simple Software Tools. Companies feel that simple, focussed software tools would be useful to them in analysing specific problems. Engineers need tools to allow them to quickly assess a specific aspect (e.g. thermal modelling for steady state, cool down and warm-up of bundles, pipe-in-pipe and buried insulated pipe; likely size ranges of slugs, flow regime prediction etc). Discussions at the July 2001 Sponsors Meeting suggested that such models might best be made available via EXCEL spreadsheets. As will be seen from the summary of the work under TMF2 given in Appendix C, packages of this type are already being developed and delivered to sponsors in a number of areas. It is proposed to greatly increase this type of provision in the TMF3 programme. Adequate documentation will be provided to allow sponsors (including the code developing companies) to subsume these packages into larger programs where appropriate.

Test Bed Code. One of the difficulties in transferring modelling methods is that there is a considerable cost incurred when merging new methodologies into an existing program. What is proposed is that a single test bed code will be made available in source form. The modelling developments will be carried out using this code as a test bed and developed versions of each model will be deposited in the code. It is proposed that the starting point for this test bed code will be the EMAPS code developed at Cranfield University under the TMF1 and TMF2 and other programmes. This code already contains advanced numerical methods which greatly reduce the running time and thus allow more ambitious calculations to be carried out. The advantages of this approach are as follows:

(1) The test bed code will serve as an efficient and unified framework within which all groups involved in the modelling work can deposit their developments.

(2) Versions of the code which contain developed models will be made available to Sponsors (including the participating code development companies) on an ongoing basis in source code form. Each Sponsor Company would have access to this code. The components of the code contributed by a given participating University Group would remain the property of that Group, as in the previous TMF programme. Since source code is provided, this should allow the uptake of developments by the code development companies to take place on a much more efficient and economic basis. It is not envisaged, however, that the code development companies would wish to make direct use of the source code. Though every effort would be made to ensure the accuracy and effectiveness of the Test Bed Code, there would not be sufficient resources available to bring it to the QA standards of commercial codes, rather, the intention is to provide a robust prototype code. In the event that a code development

company did wish to make direct use of components of the Test Bed Code, then such use could be arranged through a separate contractual agreement between the code development company and the University Group which had generated these code components

(3) Although it should be emphasised that the EMAPS test bed code will not be a commercial code, it will be made available to all sponsors for research use. It will be provided with a modest input/output system to facilitate such use.

The efforts on simple software tools and the test bed code will be co-ordinated though a contract with a small company specialising in technology transfer. This meets the requirements of the UK Department of Trade and Industry who will be approached for funding support. A suitable company has already been identified. The activity will be managed though Cranfield University.

The use of the above software vehicles for technology transfer will be in addition to the normal methods of transmitting the results of the Project (presentations, reports, CD ROMs with data, the Project web page etc.).

6. PROJECT MANAGEMENT

The management of the TMF3 project will follow the successful pattern developed for TMF1 and TMF2.

Project Steering Group

The Project Steering Group includes representatives from all sponsor companies (both those supporting the project in cash or in kind). It will meet quarterly and will give support to the Project Director and the Project Manager in the following areas:

- Developing the priorities for the research work

- Monitoring the progress of each research project. Under the TMF2 project, a system of "Mentors" was set up in which individual representatives from the sponsor companies acted as advisers on each sub-project area. This system will be continued in TMF3. The mentors are sent the minutes of the sub-project review meetings and attend these when possible.

- Providing comments and input on reports and presentations arising from the Project.

An informal Multiphase Club was introduced during TMF1 at the request of the sponsors. This has continued under TMF2 and has provided an annual informal discussion evening allowing a wide range of multiphase topics to be aired. The Club would also be continued under TMF3.

Management

Imperial College, London will manage the Project on behalf of the Sponsors. The Project Director will be Professor Geoff Hewitt with Drs. Raad Issa and Chris Lawrence acting as his Deputies. The Project Director will be assisted on detailed organisational matters by a Project Manager (Mr. Colin Weil).

The remit of the management team will include:

- Organising Steering Group meetings and producing and distributing minutes from these meetings.
- Receiving, reviewing, filing and distributing (in hard copy form and through the web) periodic and topical reports from the various research groups.
- Interfacing between Sponsors and researchers on an ongoing basis.
- Arranging Workshops and ad hoc meetings.
- Continually reviewing the progress of the research projects through the medium of informal contacts and formal (minuted) review meetings.
- Collating and issuing final reports on each sub-project.
- Monitoring the financial progress of the Project and arranging re-allocation of funds where necessary.

7. MANPOWER AND COSTS

The project will be a joint one between Imperial College, London and the Universities of Cranfield, Bristol and Nottingham. The industrial funding will be based on a "ticket price" of £20k per annum for three years (with new sponsors also paying £18k for access to previous TMF information). The following basic assumptions have been made regarding the financial structure:

(1) It is assumed that there will be 10 Sponsors making a contribution of £20k per annum for three years making a total cash contribution of £600k. Following the experience of the TMF1 and TMF2 projects, it is calculated that these sponsors will each make an additional "in-kind" contribution of at least £15k per annum (comprising internal work in absorbing the results of the project, attending meetings, acting as project mentors etc).

(2) It is assumed that there will be 3 code-developer company members providing a contracted in-kind contribution (attendance at in-depth technical review meetings, modelling of results, provision of software and associated training, mentoring etc) of at least £15k per annum over the three-year period.

(3) A bid will be made to the UK Engineering and Physical Sciences Research Council (EPSRC) for a contribution of £870k to support the research activities.

(4) A bid will be made to the UK Department of Trade and Industry (DTI) for a contribution of £130k to support technology transfer.

(5) It as assumed, in line with experience of TMF1 and TMF2, that the management costs of the Project will be £210k (approximately 13% of the cash fund).

Thus, it is anticipated that there will a cash fund of £1600k to support research and technology transfer. The total in-kind contribution is expected to be at least £585k making the total industry contribution at least £1185k with a Government contribution of £1000k.

The allocation of funds to sub-projects is shown in Table 1 (overleaf).

Table 1: Allocation of Funds to Sub-Projects

Sub-Projects	**Title**	**University**	**Effort Man months**	**Total costs £k**
I	Multi-fluid modelling	Cranfield	36	119
		Imperial (ME)	36	125
II	Slug Tracking	Imperial (CE)	50	206
III	Large diameter risers	Nottingham	36*	140
IV	Thermal Management	Imperial (CE)	22	90
		Bristol	18	55
V	Three phase flow	Imperial (CE)	29	133
		Cranfield	18	85
		Imperial (ME)	17	75
VI	Junction flows	Nottingham	36*	85
VII	Flexible risers	Cranfield	24	97
VIII	Non-Newtonian flows (Assessment study)	Imperial College Consultants		25
IX	Active control of slug flows (Assessment study)	Imperial College Consultants		25
	Technology transfer (software)	Cranfield	36	130
	Management	Imperial College		210
		TOTALS	358	1600

* Project student.

APPENDIX A

DEVELOPMENT OF THE PROPOSALS FOR THE TMF3 PROJECT

A1: THE SELECTION PROCESS

Following discussions at the TMF2 Sponsors Meeting in April, 2001, it was decided to begin preliminary considerations of future programme areas. A group consisting of Alastair Tait (Advantica on behalf of BG International), Paul Fairhurst (BP), Lloyd Brown (Conoco) and Ratnam Sathanathan (Halliburton) agreed to provide initial industrial input into the development of a TMF3 research project. Based on extensive discussions with this group and others, a preliminary paper was submitted at the TMF2 Sponsors Meeting on July 10th, 2001. Following discussions at that meeting, and subsequent written responses, a final draft set of 15 proposals (given designatory letters A-O) was identified as being of potential priority interest to industry. A document describing these short-listed areas research was circulated to TMF2 participants in August 2001. The sponsors were invited to express their individual priorities by allocating a total of 100 marks between the areas. The results of this ballot are shown in Table A1.

Table A1: Results of ballot in descending order of votes

Project	Project Title	% of votes
B	Slug Tracking	**14.3**
A	Multifluid Modelling	**11.7**
F	Three Phase Flows	**10.4**
D	Thermal Management	**8.8**
C	Large Diameter Risers	**8.5**
O	Active Control of Slug Flows	**8.3**
K	Non-Newtonian Flows	**7.5**
I	Flexible Risers	**6.8**
G	Junction Flows	**5.5**
N	Sand Transport	**3.5**
M	Fluid-Structure Interaction	**3.5**
H	Phase Mass Transfer/Thermodynamics	**3.4**
E	Flow Assurance	**3.1**
L	Waves in Inclined Pipes	**2.9**
J	Field Data and Artificial Intelligence	**1.9**
		100

As has always been apparent, it would not be possible to support all the projects (though as Table A1 shows, most projects have significant support from at least one sponsor).

Looking at Table 1, it will be seen that there is a natural break in the level of support between junction flows (5.5%) and sand transport (3.5%). It is suggested, therefore, that only those projects ranking above Project N (sand transport) should be considered for funding.

A2. PROJECTS NOT SELECTED FOR FUNDING

In reviewing those projects which are *not* suggested for funding, the following comments can be made:

Project N: Sand Transport. There is clearly much more work which could be done in this area. There has been a significant level of achievement in the TMF2 project which allows some key parameters to be calculated. However, there are very significant unknowns remaining. For instance, in gas-oil-water flows, the presence of the second liquid phase might have a significant effect in promoting adhesion of the particles to the wall. Prof. Thorpe (now at Surrey University) has indicated his interest in continuing with work in this area and will be seeking separate funding.

Project M: Fluid-Structure Interaction. Again, this project received significant support from some sponsors and Prof. Thorpe has indicated his wish to continue working in the area with separate funding.

Project H: Phase Mass Transfer/Thermodynamics. The current TMF2 Programme should provide some useful information about phase mass transfer but the level of support for continuing the work is insufficient to justify a further project. Again, it may be possible to develop this area with separate funding.

Project E: Flow Assurance. Though this is clearly a very important area for the oil industry, many companies felt that the area was already being covered in more detail by other projects (notably that at the University of Tulsa). Though it is suggested that the area should not be funded under the TMF3 Programme, proposals may be submitted separately for work in this area with a strong focus on rapid cooling and wax slurry transportation etc.

Project L: Waves in Inclined Pipes. In inclined pipes, a liquid transport mechanism may occur in which liquid is carried in large waves up the pipe with falling liquid zones between the waves. This is actually very similar to churn flow in vertical pipes where waves occur with intermediate falling film regions. In both cases, there is a net liquid transport in the upward direction. Although this area was supported strongly by at least one sponsor, it did not receive sufficient marks to justify inclusion in the TMF3 Programme. However, it should be noted that an important part of the proposed slug tracking work will be to understand the interaction between waves and slugs and it may be possible to subsume this mode of transport into this treatment.

Project J: Field Data and Artificial Intelligence. The idea behind this project was to use artificial intelligence in interpreting field data in order to tune the closure laws used in the one-dimensional models. There was little support for the proposal but it is felt that reliable field data would be extremely valuable in testing and validating models. One sponsor felt that the term "reliable field data" was an oxymoron.

A3. PROJECTS FOR WHICH ASSESSMENT STUDIES ARE PROPOSED

For two of the projects:

Project O: Active Control of Slug Flows
Project K: Non-Newtonian Flows

there was considerable support but some uncertainty about the directions which would need to be taken. It is suggested that, following the successful pattern adopted in TMF2 these areas should be subject to an initial Assessment Study which would provide industry with information and models already available. Both these Assessment Studies would be led by Imperial College. There is a major activity in Process Control in the Centre for Process Systems Engineering at the College and Prof. Stephen Richardson and others have had many decades of experience with non-Newtonian flows. The Assessment Study would cover an evaluation of the problem areas together with suggested approaches and identification of areas for further development. £25k has been allocated to each of these two Assessment Studies. Further information on these proposals for Assessment Studies is given in Section 4 of this Prospectus.

A4. PROJECTS PROPOSED FOR SUBSTANTIVE FUNDING

The following projects are proposed for substantial funding:

Project B: Slug Tracking.
Project A: Multi-Fluid Modelling
Project F: Three-Phase Flows.
Project D: Thermal Management
Project C: Large Diameter Risers.
Project I: Flexible Risers.
Project G: Junction Flows.

Details of the proposed work in each area are given in Section 4 of this Prospectus.

A5. RE-DESIGNATION OF SELECTED PROJECTS AS TMF3 SUB-PROJECTS

The selected projects have been re-designated with the following TMF3 Sub-Project numbers:

Main Projects

Sub-Project I: Multifluid Modelling (Proposed Project A)
Sub-Project II: Slug Tracking (Proposed Project B)
Sub-Project III: Large Diameter Risers (Proposed Project C)
Sub-Project IV: Thermal Management (Proposed Project D)
Sub-Project V: Three-Phase Flows (Proposed Project F)
Sub-Project VI: Junction Flows (Proposed Project G)
Sub-Project VII: Flexible Risers (Proposed Project I)

Assessment Studies

Sub-Project VIII: Non-Newtonian Flows (Proposed Project K)
Sub-Project IX: Active Control of Slug Flows (Proposed Project O)

A6. CONCLUDING REMARKS

The process of gathering important topics for projects and then subjecting them to industrial assessment has proved very successful in identifying the key priorities for the industry. In proceeding from this assessment stage to the final proposals outlined in Section 4, the distribution of resources has been matched reasonably closely to the distribution of votes allocated by the sponsors. However, detailed negotiations on costs with the respective research groups have been taken into account in the final proposed distribution of funds.

APPENDIX B

OBJECTIVES AND ACHIEVEMENTS OF THE TMF1 PROGRAMME

Project 1: Transient Three-Phase Flows

*Objectives***.** The main aim of this project was to collect high quality data on three-phase flows. The principal objectives of the project were as follows:

(1) To measure the characteristics of three-phase (oil-gas-water) flows in pipelines with various configurations through development of advanced instrumentation systems, and notably dual-energy gamma densitometers,

(2) To carry out a series of experiments on transient three-phase flows in which one of the phase flowrates was varied at the inlet and the response of the system was determined.

*Synopsis***.** The experimental work was carried out on the WASP high pressure facility at Imperial College. An important part of the work was the development of the dual-energy gamma system. New single beam and triple-beam gamma densitometer units were built, supplementing the existing traversing beam gamma densitometer on the WASP facility. A thorough investigation of the technique was needed leading to an evaluation of the limits in its accuracy. There is a trade-off between statistical accuracy of the measurements and the extent of saturation of the counting equipment. A new algorithm was also developed to interpret the transient data. A wide range of tests were performed on the WASP facility which had a 37 m long, 77.9 mm internal diameter tubular test section. Tests were carried out with the test section horizontal, inclined downwards at 1.5° and arranged in an uphill-downhill (Λ) configuration. A large range of data was produced and reduced to the form of phase hold-ups etc.

*Achievements***.** The most significant achievements of the Project were as follows:

(1) Important insights were gained into the nature of transients in three-phase flows. Remarkable effects occur as a result of phase inversion during the transients. In the phase inversion region, a large positive excursion in effective viscosity occurs and this leads to counter-intuitive trends in the data, for instance the existence of a temporary region of stratified flow between the initial and end slug flow states in a decreasing water flow rate transient.

(2) The production (and issue to sponsors in electronic form) of a wide range of data. In addition to a full parametric coverage of steady-state three-phase flows, a total of 120 transient tests were done for horizontal flow, a total of 102 transient tests for downhill flows and a total of 33 transient tests for the uphill/downhill (Λ) configuration.

(3) The development of solutions to the problems associated with the use of dual-energy gamma densitometry, leading to a clearer understanding of the limits of the method and the development of improved algorithms for data reduction.

Project 2: Phase Interactions in Transient Stratified Flow

*Objectives***.** The main aim of this project was to improve prediction methods. The principal objectives of the work in this project were as follows:

(1) To carry out extremely detailed measurements of the events occurring in transients in stratified flows in which the flow remained in the stratified region throughout the transient.

(2) To compare the results of the measured transients with the predictions of the main commercial transient codes.

(3) To develop new closure relationships for the codes and other models.

*Synopsis***.** The experiments were carried out using the WASP facility and an associated low pressure facility, the latter being used for instrument development work. Thus, the test spool was developed and tested in the low pressure facility before being transferred, for the main series of tests, to the WASP facility. The measurements made included local velocities in the gas and the liquid (using hot wire and hot film probes), wall shear stress in the gas and liquid regions (using hot film probes), interfacial structure (using multiple twin-wire probes), pressure drop using rapid response transducers, holdup using gamma densitometry and visualisation using special high pressure visualisation methods, including axial view video. Arguably, this set of experiments, even for steady state, represented the most intensively instrumented set of data ever obtained for stratified flow. For the transient tests, effort was concentrated on the important case of a transient in which the inlet gas flow is increased. Extensive data were obtained on the initial and final steady state conditions and a total of 14 transients were measured (each test being repeated 3 times with the hot wire and hot film anemometry being in different positions such that the instantaneous phase flow rates could be determined). Even with this limited number of transients, a vast amount of data was generated! The experiments were compared with the commercial codes (OLGA, PLAC and TACITE) and parameters such as interfacial friction (directly deducible from the data) were compared directly with literature values. A new correlation for interfacial friction was developed based on the measurements.

*Achievements***.** Amongst the achievements of the project were the following:

(1) Extremely detailed measurements of the parameters of stratified flows in both steady state and increasing gas flow transients were obtained and made available to sponsors in CD ROM form.

(2) Extensive comparisons were made with the predictions from the commercial codes. Typically, the code predictions predict much lower holdup than that observed; also, it should be noted that the codes differ amongst themselves in addition to differing with the data. In increasing gas flow rate transients, a surge in holdup occurred before the new (lower-holdup) steady state was reached.

(3) Comparisons with published correlations for wall and interface friction (which could be obtained from the measurements) indicated the great divergence between the various methods (probably also reflected in the spread of the code predictions). A new method was developed based on determination of the magnitude of the interfacial fluctuations. This new method gave better predictions in both the steady and transient states.

Project 3: Slug Growth and Collapse in the Flow of Gas-Liquid Mixtures in Pipes

*Objectives***.** The main aim of this project was to gain a better understanding of the phenomena involved in slug flow and, thus, to improve the prediction methods. The main objectives of this Project were as follows:

(1) To develop an understanding of the processes by which liquid slugs grow and collapse in pipeline systems.

(2) To generate new data on slug behaviour in both steady state and transient flows.

(3) To develop calculations methods for the prediction of slug growth and collapse in pipeline systems.

*Synopsis***.** This work was carried out as a joint project between the Departments of Mechanical Engineering and Chemical Engineering at Imperial College. The work in the Mechanical Engineering Department concentrated on investigating the application of the one-dimensional two-fluid model to the slug flow case using an in-house code (TRIOMPH) as a test bed. The work in the Department of Chemical Engineering was both experimental and analytical. The experimental studies included measurements of the effect of gas content on the rate at which liquid is shed from a slug, measurements on transient slug flow in downward inclined pipes and in a test section in which the flow was successively downwards and upwards (a "V"-section). The analytical work was focussed on studying the details of slug initiation.

*Achievements***.** The main achievements of the work under this Project were as follows:

(1) It was shown that, given a small enough mesh size, the one-dimensional two-fluid model *could* predict the formation and translation of slugs. It is believed that this work demonstrated for the first time that such predictions were feasible. Previously, an insufficient number of mesh points had been used and the capturing of the slug behaviour was not feasible.

(2) Establishment of the limits of prediction of slug flow using the one-dimensional model; below the *viscous* Kelvin-Helmholtz instability condition, stratified flow is stable and slugs do not grow. Between the viscous Kelvin-Helmholtz limit and that for *inviscid* Kelvin-Helmholtz instability, the flow is *unstable* but the equations are *well-posed.* This means that wave growth is occurring but the rate of growth becomes independent of mesh size as the mesh size is reduced to very low values. Above the inviscid Kelvin-Helmholtz instability limit, the problem is *ill-posed* and converged solutions were not obtained by reducing the mesh size. In normal commercial codes, the mesh sizes are much larger than those used in these numerical experiments and the effects of ill-posedness are not apparent due to the introduction of numerical damping of the solutions. The work under Project 3 has led to a better understanding of these effects. Where commercial codes are relying on numerical damping to produce solutions, these solutions may not be real solutions of the problem!

(3) Large sets of new experimental data were produced for both steady state and transient flows in 1.5° downhill inclined and downhill-uphill (V-section) configurations, both sets of data being obtained on the WASP facility. A limited set of comparisons was carried out between these data and the predictions using the one-dimensional two-fluid model (again employing the TRIOMPH code as a test bed) and encouraging agreement was obtained

with various aspects of the data. The data have been made available in the form of CD ROMS which have been issued to sponsors

(4) A special form of experiment (the "gassy push-out experiment") was used to evaluate the effect of slug gas content on slug tail translational velocity. At a given total superficial velocity, it was found that the presence of gas in the slug could either increase or decrease the translational velocity. A new theory for the translational velocity was derived which is consistent with these results.

(5) It has been noticed that, near the entrance of the pipe, short high frequency slugs ("slug precursors") are formed. Slug frequency decreases rapidly downstream of the entrance, producing long slugs at much lower frequency. A model was developed for slug initiation, showing that the position of the first formation of the slug could vary from one slug to the next. This theory (consistent with the experimental observations) produces very different results than earlier theories which were not consistent with the physical mechanism. In contrast to the one-dimensional model, the theory takes account of complex three-dimensional effects

Project 4: Flexible Risers Severe Slugging

*Objectives***.** The main aim of this project was to study and understand the phenomena occurring in flexible risers. The principal objectives of Project 4 were as follows:

(1) To develop a better understanding of multiphase flows with severe slugging.

(2) To produce validated data for a typical riser geometry.

(3) To check the results both globally and in detail against predictions from the commercial transient codes.

(4) To develop alternative prediction methods to identify regions of severe slugging etc.

*Synopsis***.** A wide-ranging series of experiments were carried out in a 10 m high S-shaped riser over a range of pressures (2, 4 and 7 bara) and a range of buffer vessel volumes. A total of 250 tests were conducted and a very large data base (made available electronically to sponsors) was generated comprising information on liquid delivery rates, holdup at the riser base, pressure and pressure difference measurements and visual observations. Calculations were also performed for six selected test cases using the three main transient codes (ProFES Transient (the successor to PLAC), OLGA and TACITE). Independent theoretical studies were also carried out.

*Achievements***.** The main achievements of the work under this Project were as follows:

(1) A very large new data base was generated giving information on the slugging behaviour of the S-shaped riser configuration. These data have been made available in electronic form to sponsors.

(2) Comparisons were made between six data sets selected to typify various conditions and the predictions from commercial codes. The results were compared in terms of flow patterns, cycle times and production rates respectively. These comparisons showed that the range of predictions did occasionally cover the experimental measurements but the

general indication is that the agreement is not good and, perhaps equally significant, the agreement between the selected codes is also not good.

(3) A new criterion for large scale unstable flows (including the severe slugging) has been developed which fits both the new data obtained in the Project and also other published data.

Project 5: Numerical Simulation of Multiphase Flow: Speed, Error Control and Robustness

*Objectives***.** The main aim of this work was to develop enhanced numerical methods to increase speed and accuracy of multiphase code calculations. The main objectives of Project 5 were as follows:

(1) The development of mathematical and physical models for transient two and three phase flow in pipelines.

(2) The development of efficient and robust solvers, applicable to a wide variety of industrially relevant problems.

(3) The use of accurate discretisations with second-order accuracy in space and time in order to reduce mathematical diffusion and hence take as full an account of the physics as possible.

(4) The design of intelligent algorithms which will automatically and locally adapt the computing effort to the accuracy required.

(5) The validation of models against experimental data and the identification of critical aspects of these models.

*Synopsis***.** The Project has embodied developments of existing forms of model for two-phase flow (drift flux and two-fluid models) and has developed extensions of the latter for three-phase flow. For three-phase flow, the models developed can operate at various levels of sophistication (liquid phase having liquid mixture properties, separate layers of oil, water and gas and a "five-layer" model in which layers of oil drops in water and water drops in oil respectively exist between the single phase water and single phase oil layers). A strong focus of the programme has been on numerical methods with the aim of developing methods which can deal with discontinuities in the flow (shocks, rarefraction waves etc) whilst using adaptive gridding to obtain efficient solutions. A new code framework was developed and used for a wide range of numerical experiments.

*Achievements***.** The main achievements of the work under this Project were as follows:

(1) New mathematical models have been developed for stratified three-phase flow, these models taking account of intermixing of the phases and the phenomena associated with phase inversion.

(2) An explicit solver for one-dimensional hyperbolic conversation laws has been developed whose key feature is the use of adaptive grids to resolve regions where greater accuracy is sought or is necessary. Under contract with one of the code developer companies, this work has been introduced into one of the commercial codes

(3) The new solver has been assessed with various types of multiphase model embodied in it (drift flux, two-fluid and three-fluid) and performs well. For a typical transient (increasing gas flow), investigations were carried out with three types of grid, namely 8 cells, 64 cells and 8 cells with adaptivity. Though the transient is "smoothed out" with 8 non-adaptive cells, the 8 cells with adaptivity perform in a very similar manner to the 64-cell non-adaptive case. This implies enormous savings in computing resources or, more likely, an ability to calculate at more detail with the same resources

Project 6: Transient Mass Transfer in Co-Existing Hydrocarbon Liquid and Gas Phases in Flowing Systems

*Objectives***.** The main objective of this project was to gain better information on mass transfer phenomena in hydrocarbon pipeline transport systems. In computer codes for predicting both steady state and transient flows in pipelines, it is the common practice to assume *local equilibrium* between the respective phases. However, mass transfer would occur at a finite rate between the phases and, thus, the assumption of instantaneous local equilibrium can never be absolutely true. The question is whether this equilibrium assumption is good enough for normal calculations; otherwise, an order of magnitude more complex calculations would be required taking account of the phase mass transfer processes. The aim of the work carried out in Project 6 of TMF1 was to try to obtain an upper bound for the time taken to reach equilibration. Thus, the objectives were:

(1) To design, build, commission and operate a new facility in which equilibration times could be determined for a stratified flow of representative fluids (a liquid consisting mainly of propane and a gas consisting mainly of methane).

(2) To carry out transient experiments in which pressure of the circulating gas phase is increased, the compositional response of the liquid phase determined and equilibration times estimated from the data.

(3) To use the data to estimate typical upper limit equilibration times in pipeline systems.

*Synopsis***.** A new test facility was constructed in which stratified propane/methane mixture flows were set up in a 25.4 mm (1 inch) diameter, 2.4 m long horizontal tube. The concentrations of propane in the liquid phase were measured near the inlet and near the outlet of the test section using a special Fourier-Transform Infra-Red Spectrometer (FTIR) system. After a period in which equilibration of the methane-rich gas and the propane-rich liquid was achieved by recirculation through the system, the pressure was increased (typically from 20 to 40 bar or from 40 to 60 bar). This caused methane to be transferred into the circulating liquid and the change of concentration over the test section could be determined. The time to reach a new equilibrium condition could be measured; the gaseous phase concentration was simultaneously measured using a gas chromatograph (GC) system.

*Achievements***.** The principal achievements of the Project were as follows:

(1) The successful development (including preliminary tests on instrumentation) and commissioning of the mass transfer rig. This was quite a complex system, operating at high pressure with highly inflammable materials. Nevertheless, consistent results were obtained over a range of conditions.

(2) A series of transient tests were carried out with various changes of pressure level in the gas phase, with a constant liquid flow rate and with a range of gas flow rates. The

variation of inlet and exit concentrations of propane in the liquid phase was determined as a function of "elapsed time", i.e. the time a given element of fluid has spent in the test section. Eventually, a new equilibrium is reached as the two fluids pass repeatedly around the circuit. The results can be interpreted to give approximate equilibration times. For the experiments conducted, the equilibrium times were of the order of 45 s and did not vary significantly with gas flow rate or pressure levels.

(3) The data for equilibration time were interpreted to predict approximate upper limits for flows in the largest pipes. The latter were estimated to be of the order of 30 minutes, implying that equilibrium would require several kilometres to be achieved in such a pipeline. This may not be too significant in steady flows in very long (tens of kilometres) pipelines but departures from equilibrium may affect local phenomena in crucial regions. Also, in transient flows, these departures from equilibrium could be significant in predicting the detailed course of the transient

APPENDIX C

OBJECTIVES AND ACHIEVEMENTS SO FAR OF THE TMF2 PROGRAMME

Sub-Project A: Modelling Bases

General Objectives: The overall objective of this Sub-Project is to improve the modelling bases for multiphase flows in pipelines, with particular reference to the one-dimensional multifluid modelling approach. Specific objectives of the work include:

(1) To improve the numerical performance of codes based on the one-dimensional multifluid approach, i.e. speed and accuracy.

(2) To develop closure laws and procedures for use with the multifluid models with the objective of taking account of multidimensional phenomena within the framework of the one-dimensional approach.

(3) To generate experimental data on straight pipes, on pipes with changes of slope and on T-junctions in order to provide information against which the models can be tested and improved.

Work at Cranfield University (C.Omgba-Essama and C.P.Thompson)(Ongoing)

Objectives: The main objectives of the work at Cranfield are:

- The development of mathematical and physical models for transient two-phase flow in pipelines, which accurately describe the complexity of the flow features involved.
- The development of efficient and robust numerical solvers, applicable to a wide variety of industrially relevant problems.
- The use of accurate discretisations: second-order accuracy in space and time so that the physics can be represented on practical numbers of grid points.
- The design and implementation of intelligent algorithms that will automatically and locally adapt the computing effort to the accuracy required. Here the main tool will be adaptive mesh refinement (AMR).

Because of the numerous research topics covered by two-phase flow modelling, a particular focus is given to junction flows for two specific flow regimes, namely stratified and slug flows.

Achievements. The work is still ongoing; the developments so far have led to:

- The implementation of a robust AMR solver with increase in speed of almost a factor of 10 (Table C1) compared to uniform grids.
- A better understanding of slug flow modelling features (initiation, growth and propagation) in horizontal pipes (Figure C1) and the conditioning of this phenomenon.
- Preliminary results for two-phase stratified flows in T-junctions (Figure C2).
- The design and implementation of EMAPS (Eulerian Multiphase Adaptive Pipeline Solver) code, a unified and modular framework for one-dimensional multi-fluid models, which contains several advanced numerical methods (and supports automatic adaptivity); which

can be applied to several different equation systems; and which enables easy inclusion of accurate closure laws for the implemented mathematical models.

Finest grid level	Timings(s)		Speed-up
	Uniform	Adaptive	
1	14	-	-
2	45	31	1.45
3	163	65	2.51
4	635	162	3.92
5	2367	249	9.51

Table C1: Two-Phase Adaptive Gridding Performance

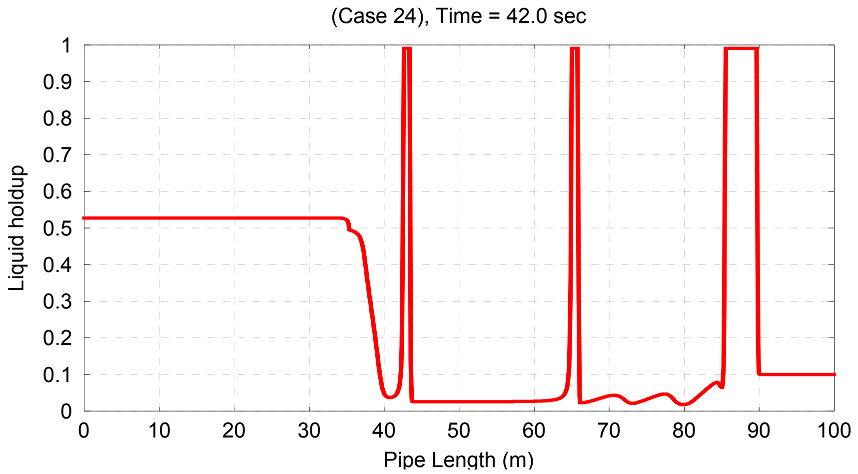


Figure C1: Slug Flow Profile (Initiation, Growth & Propagation)

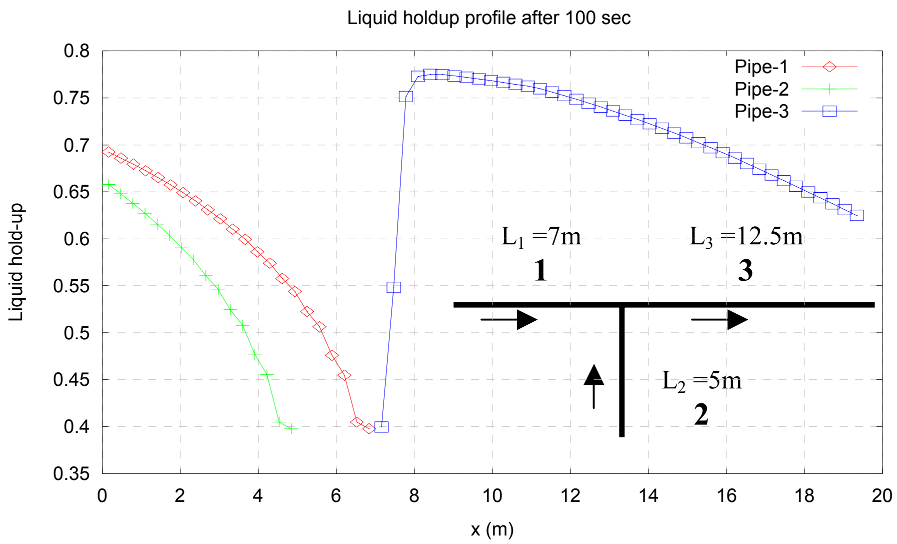


Figure C2: Stratified Flow Profile in a Combining T-Junction

Further Work. The next stage of the project includes further validation of:

- Two-fluid pressure based mathematical model for horizontal slug flows in pipes.
- The prediction of slug flows in combining T-junctions.

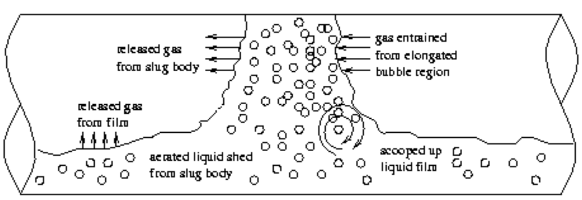
Work at Imperial College (Mechanical Engineering) (M.Bonizzi and R.I.Issa) (Ongoing)

The principal objective pursued was the development of a mathematical model to account for the entrainment of small gas bubbles into liquid slugs in horizontal slug flow. The model is cast in the framework of the one-dimensional transient two-fluid model and is incorporated in a numerical procedure, which is applied to the prediction of slug flow in horizontal pipes.

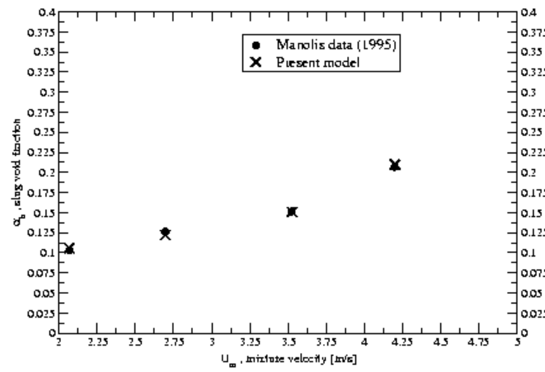
It is well known that in slug flow, considerable amount of gas is entrained from the large elongated gas bubbles into the slug in the form of small bubbles (Fig C3a). The gas entrained in this way can often account for 25% of the phase fraction in the liquid slug if not more. This would therefore have significant effect on the slug behaviour as well as on the pressure drop in the system. It is therefore highly desirable to model this phenomenon in order to predict slug flow with any reasonable accuracy.

Previous work in TMF1 demonstrated that the one-dimensional transient two-fluid model is capable of capturing slug initiation and development automatically. Their numerical simulations showed that that phenomenon can be simulated by the model, and that continuous trains of slugs could be generated automatically. However, the model ignored the phenomenon of small-bubble entrainment from the large elongated bubbles preceding the liquid slug. This was thought to be the reason behind some of the observed discrepancies in the prediction of overall hold-up.

The model developed here is based on the formulation of a scalar-transport equation for the volume-fraction of entrained-bubbles in the liquid. This equation yields the distribution of entrained gas within the liquid slug. The transport-equations for the liquid-phase in the two-fluid model are replaced by ones in terms of the mixture of liquid and small entrained gas bubbles. Thus the resulting model is attractive for its simplicity and similarity to the standard two-fluid model which enable direct incorporation into standard two-fluid model codes.



(a) Schematic of slug entrainment into a liquid slug



(b) Entrained gas hold-up

Figure C3: Gas entrainment in slugs

The model is applied to the prediction of slugging in air/water flow in horizontal pipes where entrainment effects are known to be significant. The results are compared against experimental data as well as against previous predictions ignoring the entrainment effect. One such comparison is shown in Fig 3b, where the predicted global gas hold-up in the liquid slugs shows excellent agreement with measurements for different flow rates.

Work at Nottingham University (B.J.Azzopardi) (Completed)

Objectives: The main objectives of the work at Nottingham University were to construct a new rig for studying combining flows at horizontal T-junctions, to obtain a range of data for slug and stratified flows and to collaborate with Cranfield University in the interpretation of this data.

Achievements. The work focussed on multiphase flow (particularly gas/liquid slug flow) as it passed through a junction with two inlets and one outlet. Data was gathered on an adapted air/water facility with small diameter pipes (0.038, 0.025 m) but of reasonable lengths (7, 5 and 12 m). Slug frequencies and velocities were measured in the three legs of the junctions. An initial target was to establish whether slugs from a small diameter side inlet would persist under nominally non-slug flow conditions in the main pipe. It was not possible to determine this because the flows were masked by a hitherto unsuspected phenomenon (see Figure C4). Waves were seen travelling upstream from the junction to the main pipe inlet and causing slugs to form at non-slug flow conditions. This in spite of carefully designed gas/liquid mixers. Our observations tie in with field experience. A simple theory has been developed to explain this phenomenon.

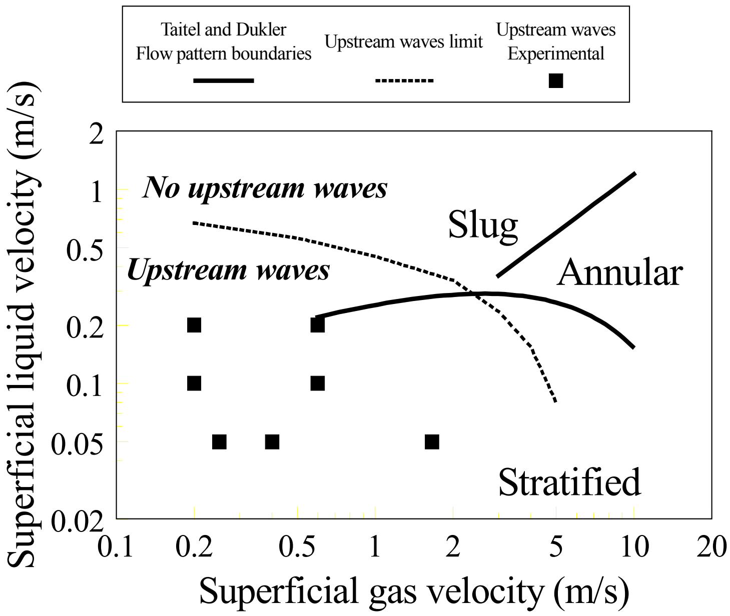


Figure C4: Flow regimes in combining flows at a T-junction

Work at Imperial College (Chemical Engineering) (C.P.Hale and G.F.Hewitt) (Ongoing)

Objectives: The specific objectives of the work in Imperial College (Chemical Engineering) are to generate experimental data on straight pipes in order to provide information against which the existing computer models may be tested and improved and to develop independent analytical and empirical interpretations of these data. These objectives are consistent with the original plan. However, plans for more extensive work using the WASP facility with complex geometries such as

V-sections and T-junctions are unlikely to come to fruition in the TMF2 programme; this is because it was decided to concentrate on much more detailed experiments on slug initiation, a major uncertainty area in prediction methods. Data is available from Nottingham on T-junctions and from the TMF1 programme on V-Sections.

Achievements: The experimental work on the Imperial College (Chemical Engineering) high pressure WASP facility has focussed on the initial development of the interface in both slug flow and stratified flow in a horizontal test-section. In order to examine this process a series of closely spaced conductivity probes have been installed at 16 distinct locations along the testline. Close to the inlet, where the flow is developing most, the probes are spaced at 0.6m
intervals whereas further downstream they are spaced approximately 7m apart. By producing a time trace of the liquid holdup at each probe location the interface development process, both as a function of time and position along the testline, may therefore be examined in detail.

An extensive database on interfacial development in steady state and transient two-phase stratified and slug flows. The data for stratified flow illustrate the extreme complexity of the interfacial development processes, explaining the large discrepancies in models for this apparently simple type of flow. The data for slug flow confirm the existence of high frequency "slug precursors" close to the inlet. As may be seen from Figure C5 below these short, high frequency, "slug precursors" interact and develop into longer lower frequency slugs within a relatively short distance from the test-section inlet. For the particular case illustrated below it can be seen that within 15m the slug frequency has decreased by a factor of three and that by 35m it has decreased by a factor of approximately 5. Since it was considered that a detailed knowledge of the boundary conditions is extremely important for any numerical simulation of this type of flow great care has been taken to control the experimental boundary conditions as closely as possible. In the figure illustrated below tests are shown for an experiment starting at predetermined steady-state gas and liquid feedrates and one in which the same final flowrate conditions are achieved by allowing the test-section to fill from an initially

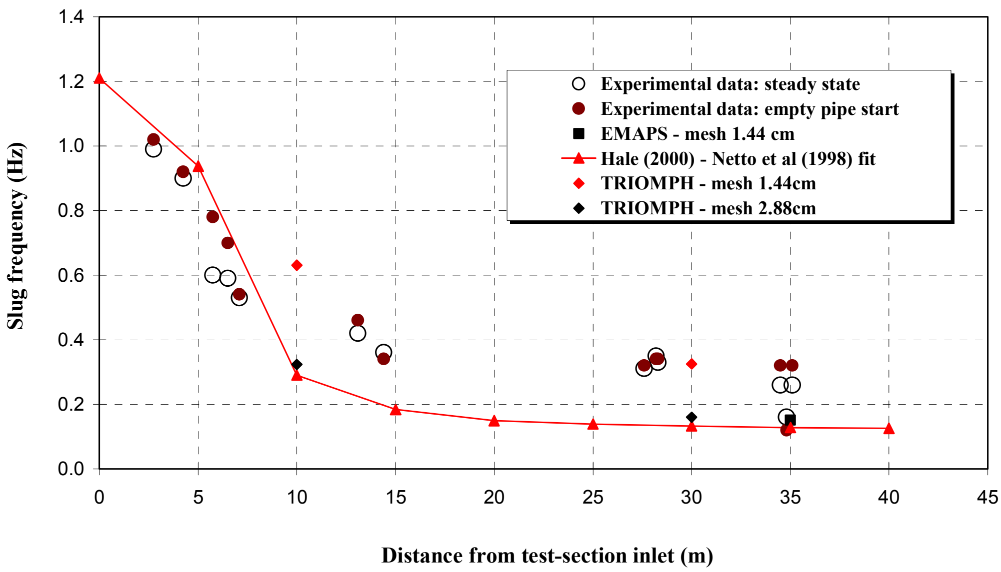


Figure C5: Data for slug frequency obtained in the WASP facility

empty pipe. After an initial transient period the flow development process is found to be similar for both cases. This development process is consistent with the model developed in the TMF1 programme (Hale, 2000). Predictions from the EMAPS code developed at Cranfield and the

TRIOMPH code developed at Imperial College (Mechanical Engineering) are also shown on this plot.

Further work: The remaining task is to codify and analyse the vast amount of data obtained, concentrating on the developing region in steady state flow and on the transient data.

Sub-Project B: Three-Phase Flow

General Objectives: The main aim of this project is to obtain new high-quality data for three-phase flows and use this data to assist, in parallel, the development of improved prediction methods. The principal objectives of the work under this Sub-Project are as follows:

(1) To generate new experimental data on gas-oil-water flows for a variety of geometries with the aim of providing bases for the validation of code models and to assist in the development of new closure models for three-phase flow.

(2) To develop models for three-phase stratified flow which take account, in particular, of the mixing of the liquid phases (oil and water).

(3) To develop models for three-phase slug flow building on the models developed for two-phase slug flow in the TMF1 programme.

Work at Imperial College (Chemical Engineering)(C.P.Hale & G.F.Hewitt)(Ongoing)

Objectives. The specific objective of the work at Imperial College (Chemical Engineering) is to gather data for a wide range of conditions on three-phase (oil-gas-water) flows. The work is being carried out on the Imperial College Chemical Engineering WASP facility, a high pressure loop with a 40m long, 79mm internal diameter test section. The emphasis is on obtaining information on liquid phase mixing and on transients in the individual phase flowrates.

Achievements: The achievements so far have included the generation of new data for both steady state and transient three phase slug and stratified flow. By using conditional sampling of the output from dual energy gamma densitometers, it is possible to obtain the distribution of the three phases within the slugs. This shows that the gas phase is concentrated towards the top of the slugs rather than being well mixed as is often assumed.

Further wok: A major series of tests is just starting to extend the existing data base and to more closely investigate the phase distribution. In this context, the acquisition and implementation of a new 200-detector X-ray system will allow more detailed steady state and transient measurements of phase distribution across the pipe cross section.

Work at Cranfield University (L.Hanich & C.P.Thompson) (Ongoing)

Objectives: The main objectives of the work at Cranfield are as follows:

(1) Development of a new mathematical model for transient three-phase pipeline flows which includes the dynamic mixing processes through a model in which there are intermediate mixed layers.

(2) Design of an efficient, robust and flexible solver for this system based on the work performed in the TMF1 project.

(3) Validation of the model against the experimental data and identification of critical aspects.

Achievements: In many three-phase flows liquid-liquid mixing occurs and this can significantly affect the total pressure drop in the flows, the flow regime and the corrosion rates in the pipeline. A model developed at Cranfield as part of the TMF1 programme is able to predict accurately stratified unmixed flows. In the current work, this model is being extended to include a mixture layer. In a conceptual sense, the liquid region can be considered as consisting of four layers (starting from the bottom of the pipe) as follows (see Figure C6):

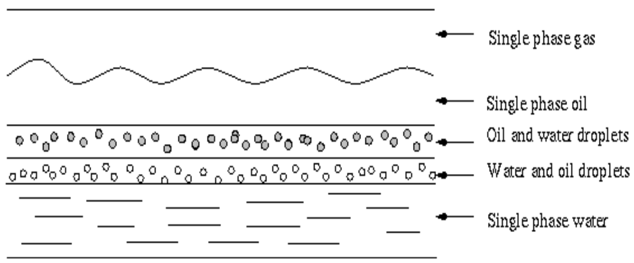


Figure C6: Conceptual view of inter-phase mixing

1. single phase water;
2. oil droplets in a continuum of water;
3. water droplets in a continuum of oil;
4. single phase oil;
5. single phase gas.

The approach followed is to develop a *four-layer* model (water, oil-water mixture, oil and gas, in ascending order from the bottom to the top of the pipe). The model assumes that entrainment into the mixed layer is driven by turbulence processes (approximated by the $k-\varepsilon$ model) and separation occurs due to buoyancy. All models of this kind rely on closure laws and new data produced on the WASP facility for three-phase stratified flow have been used to close the system. In this new data, the vertical distribution of the three phases in stratified flow is determined by traversing the dual-energy gamma densitometer across the tube with the beam horizontal.

The three-phase mixture equations have been incorporated into the framework of EMAPS (Eulerian Multi-phase Adaptive Pipeline Solver). This is the first multi-phase model capable of representing transient mixing processes. Initial validation is underway and so far a good agreement with the WASP data (from Imperial College) has been obtained (Figure C7) for a range of cases. The comparison is currently being extended.

Further work: The ongoing work will focus on further development of the mixing model with validation against the new data being generated at Imperial College (Chemical Engineering).

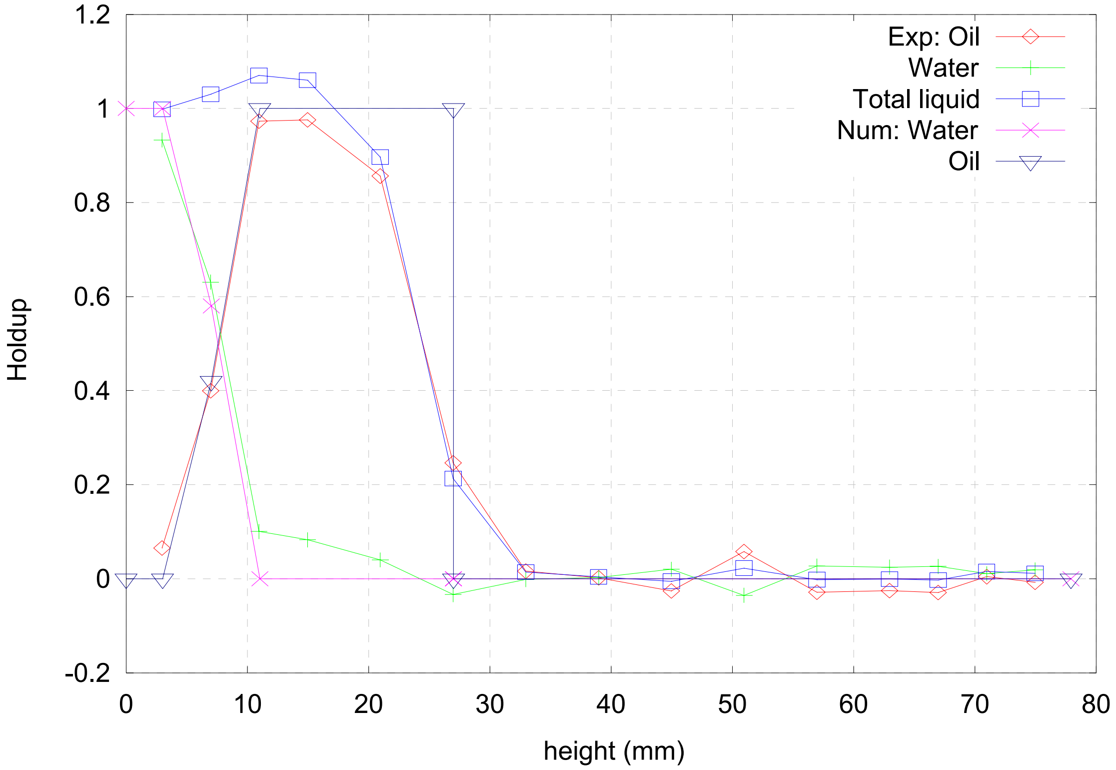


Figure C7: Comparison of numerical and experimental results showing good agreement in layer thickness.

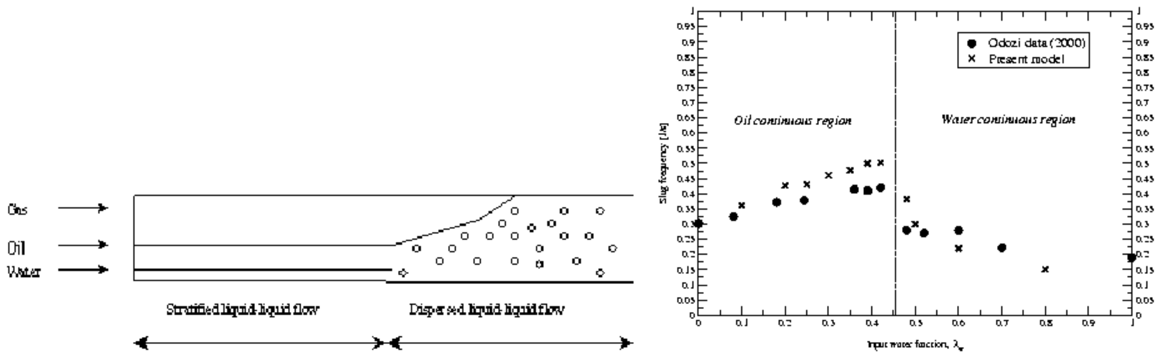
Work at Imperial College (Mechanical Engineering) (M.Bonizzi and R.I.Isaa)(Ongoing)

The objective of this task is to develop a computational model for the prediction of slug flow in three phase systems (oil/water/gas). The model is aimed at eventual incorporation into standard one dimensional transient codes.

The starting point for the development of the model, was the transport equations for momentum and mass for three phase flow. However, such a system of equations would impose high computational demands, and may not be practical. A novel approach was therefore followed to simplify the model into one that closely resembles the two-fluid model, yet enabling the prediction of three-phase flow. This is achieved by combining the two sets of equations for the two liquid phases into one set for both liquid components. In order to account for the relative motion of these liquid phases, a new scalar transport equation for the phase fraction of one liquid component in the liquid phase is formulated. The relative motion between the two liquid components is accounted for by specification of the relative velocities between in these components from a drift-flux of model. In this way, the framework for the standard two-fluid model is retained, while enabling true three-phase flow calculations.

In three-phase flow, the two liquid phases, depending on the flow conditions, can be stratified, or they may be dispersed into each other (Fig C8-a). In the latter case, (again depending on the flow conditions), one or the other of the liquid phases may be continuous (the other being dispersed in the form of droplets). The model developed therefore had to account for the occurrence of all these flow regimes on a local basis. To this end, a procedure has been introduced, based on the work of Fabre and Decarre, to determine locally whether the two liquids are in a stratified state, or are dispersed into each other, and if so then which liquid is the continuous one.

The new model was implemented in a research computer code and was applied to a large number of three-phase slug flow configurations. The predictions for a number of slug flow characteristics (such as slug frequency) have been compared against experimental data. An example of such comparison is shown in Fig C8-b where present calculations clearly capture the experimental trend, and show good agreement with the measurements.



(a) Schematic of three-phase slug flow (b) Slug frequency

Figure C8: Drift flux model for three-phase slug flow

Sub-Project C: Tube Bundles

General Objectives: This Sub-Project was set up to study the thermal behaviour of sub-sea tube bundles. Such bundles are used to minimise heat losses and therefore avoid solids (wax, hydrates or asphaltenes) formation in the product fluids flowing in sub-sea pipelines. The general objectives were as follows:

(1) To review and assess all available information on tube bundles and to make recommendations on best practice.

(2) To develop a spreadsheet type program to predict bundle performance on the basis of one-dimensional models.

(3) To carry out CFD predictions of local heat transfer coefficients in bundles leading to the development of suitable correlations for use in the one-dimensional models.

(4) To carry out basic experiments on systems simulating tube bundle geometries with the aim of validating the CFD methodology.

The project started with an Assessment Study which was carried out by Professors S.M.Richardson and G.F.Hewitt (Imperial College Chemical Engineering) and Professor G.L.Quarini (Bristol University). This report makes recommendations on current best practice. It also led to the definition of the research project in which Bristol University is carrying out the CFD studies, Bristol University and Imperial College Chemical Engineering are jointly developing the spreadsheet program and Imperial College Chemical Engineering are setting up experiments to validate the CFD results for realistic geometries.

Work at Bristol University (R.Salgado & G.L.Quarini) (Ongoing)

Objectives: The work at Bristol had the specific objectives of developing the first version of the spreadsheet programme and of developing and implementing the CFD calculations.

Achievements: The development of a preliminary version of the one-dimensional spreadsheet program which predicts temperature distribution in bundle systems was completed. Further development of this programme is being pursued at Imperial College (Chemical Engineering) – see below. Extensive CFD studies have been carried out and validated against the limited (somewhat idealised) experimental data available in the literature. Realistic geometries and boundary conditions, as specified by the sponsors, have been examined and a number of interesting and very important finding have been made which are of direct relevance to the sponsors Figure C9 shows the buoyancy induced flow distribution within the gaps between the

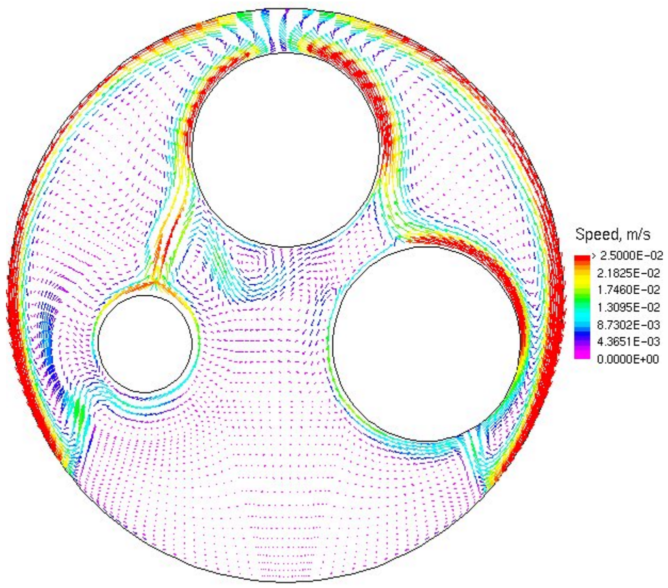


Figure C9: Natural convection patterns in a multi-tube bundle

tubes of a bundle. The challenge facing the hydrocarbon recovery engineers is to find the optimum layout of these tubes so as to achieve desired temperature distributions whilst minimising heating power requirements. For example, these studies have shown that there are simple topology changes which can be used to reduce heat losses from the bundle (just topology changes, without extra insulation or overall dimensional changes). The sponsors particularly value these findings, recommendations and the accompanying understanding. The methodology will be confirmed for more realistic geometries when the experimental data being produced within this Sub-Project (see below) become available.

Further work: An extensive series of calculations is under way covering a range of actual industrial geometries and also geometries closely matching the typical geometries being investigated in the experimental work (see below).

Work at Imperial College (Chemical Engineering)(T.Choudhury, J.A.Stoyel, G.F.Hewitt & S.M.Richardson) (Ongoing)

Objectives: The specific objectives of the work at Imperial College (Chemical Engineering) are to implement the spreadsheet programme (developed in a preliminary way by Bristol – see above) into a form useable by industry and to carry out experiments on model bundles in order to validate the CFD calculation methodology being developed by Bristol.

Achievements: A fully functioning version of the spreadsheet program is now in operation and is being tested by the industrial partners. Procurement is completed for the experimental study and construction of the test section is under way. The test section will consist of a 45cm internal diameter carrier pipe with three pipes within it. The carrier pipe and the internal pipes are maintained at constant (but different) temperatures and the heat transfer rates determined.

Further work: The experimental apparatus will be completed and data for heat transfer coefficient and compared with the CFD predictions.

Sub-Project D: Transport Behaviour of Particulate Solids

Work at Cambridge University (P.Stevenson & R.B.Thorpe)(Completed)

Objectives: This Sub-Project is concerned with the estimation of the fluid velocities necessary for the transport along a pipeline of sand particles present in the (multiphase) streams from wells. There was very little published information available on this topic as the majority of work relates to slurry transport. The focus of this project was to examine the conditions necessary to cause transport of single sand particles along a pipe carrying two-phase flows. The specific objectives were as follows:

(1) To measure critical velocity for initiation of transport of sand particles in single-phase water flow, two-phase stratified flow and two-phase slug flow over a range of flow rates.

(2) To develop equations for the prediction of critical velocity to initiate sand transport under various conditions.

(3) To produce stand-alone spreadsheet programs which will allow sponsors to calculate the conditions in which particulate material is transported.

Achievements: The work on this Sub-Project has been carried out in the Chemical Engineering Department at the University of Cambridge. A test rig was available for the performance of a wide range of tests on the velocity required to move a single sand particle sitting at the bottom of a pipe under single-phase and two-phase flow conditions and on the subsequent transport velocity of the particle once it began to move. The data were analysed to give equations for the various types of flow and these equations were embodied into spreadsheet programs. Outputs from the programme include:

(1) A very wide range of data for particle transport in single-phase flow, two-phase slug flow and two-phase stratified flow.

(2) Correlation of the data obtained using relationships that describe both the initiation of motion of the sand particles and their subsequent transport velocity.

(3) Preparation of three spreadsheet programs that predict sand particle transport in single-phase flow (hydraulic conveying), two-phase stratified flow and two-phase slug flow. These programs have been made available to sponsors via the Project web site.

(4) Issue of a comprehensive final report on the project to which CD-ROM's have been attached giving the data and the spreadsheet programs.

Sub-Project E: Transient Hydrodynamic Loading

Work at Cambridge University (B.L. Tay & R.B.Thorpe)(Ongoing)

Objectives: If slug flows occur in pipelines, then transient hydrodynamic loadings may be generated in fittings such as bends and junctions. The aim of this Sub-Project was to address the problem of predicting the magnitude and frequency of such transient (and potentially destructive) forces. The specific objectives were as follows:

(1) To assess the available information and to make *pro tem* recommendations for prediction of the forces pending the completion of the research work under the Sub-Project.

(2) To set up experiments in which the forces were measured for a range of flow conditions.

(3) To develop analytical tools which would allow the prediction of the transient forces in slug flow and to embody these into simple software tools (spreadsheet programs) for use by sponsors.

In a linked programme, work was planned, and is being executed (see discussion of Sub-Project F below) on making similar force measurements in the Cranfield flexible riser facilty.

Achievements: The work on this Sub-Project began with the preparation and issue to Sponsors of an Assessment Study that examined the available information and made tentative recommendations on the prediction of the forces on bends in slug flow. This study was carried out by the Department of Chemical Engineering at the University of Cambridge; it was an important precursor to the experimental work. It is difficult to make unambiguous measurements of the bend forces and a complex rig was designed, built and operated to carry out fundamental measurements in an air-water flow facility at Cambridge. The measurement principles used in the Cambridge tests are being applied in more realistic tests on the flexible riser test facility at Cranfield University (see below). In parallel with their experimental work, Cambridge University have been developing analytical models which are being compared with the data.

The outputs so far have included the following:

(1) The assessment of available information on transient hydrodynamic loading and the issue to sponsors of an Assessment Report which gives recommendations for design.

(2) The successful development of experimental methods for accurate measurement of bend forces and the obtaining of a wide range of fundamental data to test prediction methods.

(3) The development of analytical methods for the prediction of bend forces in slug flow and their validation against accurate experimental data.

(4) A draft spreadsheet program for prediction of hydrodynamic force magnitudes generated by slug flows.

Sub-Project F: Flexible Risers

Work at Cranfield University (H.Yeung & J.Montgomery)(Ongoing)

Objectives: Flexible riser systems are increasingly used in deep-water hydrocarbon recovery. Systems of this type are susceptible to severe slugging and the aim of this Sub-Project (expanded from that in the TMF1 programme) was to obtain more detailed data using the facility at Cranfield University. The main objectives of the Sub-Project are as follows:

(1) To extend the experimental work on two-phase flow in S-shaped flexible risers to cover a wider range of conditions and, thus, to provide a database for the assessment of prediction methods. To measure the forces induced by slugs on the bends in the riser.

(2) To compare the experimental results with the predictions of the commercial transient multiphase flow computer codes.

(3) To extend the experiments to three-phase (oil-water-gas flows).

Achievements so far: The tests on the Cranfield University flexible riser facility have continued, taking advantage of the enhanced instrumentation added to the rig at the end of the TMF1 programme. Detailed measurements of time-varying local holdups at four locations in the riser have been carried out as well as measurements of the production rates of the two fluids at the outlet of the riser. These data revealed there were significant differences between the experimental and computational holdups in the downcomer. A small, transparent test section was constructed to establish cause. Extensive comparisons have been made with the predictions of the commercial computer codes, paying particular attention to the modelling *system effects*. Tests have also been carried out using air and oil. The main results so far from the TMF2 work are as follows:

(1) The generation of a very large data base on flow pattern, phase production rates and local holdup at critical locations in a test configuration simulating an S-shaped flexible riser.

(2) Tests with available commercial predictive codes have shown their inability to adequately predict the bubble penetration mechanism at the base of the riser; the codes are also deficient in simulating the flow in the downcomer. This is not surprising as the air water interface was found very complicated and existing holdup correlations failed to predict the behaviour.

(3) Another important finding is that in order to simulate the behaviour of the riser, there is a need to model the whole system because of the non-linear interactions between the various components. The simulated results depend on how the inlet and outlet are represented. Based on the result so far, it is postulated that downstream conditions have bigger effects on the behaviour then upstream conditions.

(4) Comparison of air/water and air/oil experimental results revealed that fluid properties have a major effect on behaviour. The stability criteria developed in TMF1 also applies to the new data.

Further work: Work is proceeding on measurements on three-phase (oil-water-gas) flows and on measurements of forces on bends in the riser system. This latter work builds on the techniques described under Sub-Project E (see above).

Sub-Project G: Coupled Heat and Mass Transfer

Work at Imperial College (Chemical Engineering) (S.Richardson and G.Saville)(Ongoing)

Objectives: In predictions of pipeline multiphase flows of hydrocarbon mixtures, a common assumption is that the compositions of the liquid and vapour phases are in equilibrium. In the TMF1 programme, the validity of this assumption was explored using a new mass transfer facility in which the response of the system to changes of vapour phase pressure and composition was measured. The specific objectives of the continued work on this subject are as follows:

(1) To carry out new experiments with longer test sections in which the pressure is maintained constant and the inlet composition is changed.

(2) To assess the importance of equilibration effects based on the experimental results and associated analytical studies.

It had been planned to conduct studies on departures from phase equilibria in systems where solid phases (such as wax) are formed. This has not proved feasible within the resources of the project.

Synopsis: The rig used for the TMF1 experiments is being completely rebuilt with enhanced measurement devices. The experiments will again be with methane-propane mixtures. A flow will be set up and circulation continued until equilibrium is reached. The inlet gas composition will then be changed by diverting a second stream (at the same velocity and pressure) into the test section. The changes of composition in both the liquid and the gas will then be monitored until a new equilibrium situation is reached. The rates of mass transfer can be deduced from the change of composition with time.

Achievements so far: It should be stressed that the TMF1 project in this area was not completed until 2001. The TMF2 Sub-Project has only recently got underway. The achievements so far have included the following:

(1) The design of the new facility has been completed and procurement actions taken.

(2) The rig is under construction.

Further work: The rig will be commissioned and a range of data obtained. The data will be interpreted in terms of their relevance to pipeline prediction methods.