January 3rd, 2006

JOINT PROJECT ON TRANSIENT MULTIPHASE FLOW AND FLOW ASSURANCE

TMF4

PROSPECTUS

by

G.F.Hewitt, Imperial College London

1. BACKGROUND

This Prospectus for a Joint Project on Transient Multiphase Flow and Flow Assurance (TMF4) describes a proposed research programme which has its roots in the extensive discussions with, and suggestions from, the industrial Sponsors of the current Joint Project on Transient Multiphase Flows (TMF3). Discussions with TMF3 Sponsors on future programme directions took place at Sponsors' meetings in early 2005 and culminated in the distribution, in July 2005, of a paper (TMF3/P126(05)) which described the programme options arising from these discussions and invited TMF3 Sponsors to vote on these. The results of this voting process and the research directions which emerged from it were described in paper TMF3/P127(05) which was presented at a Sponsors' meeting on September 29th, 2005. The outline proposals described in this paper were accepted unanimously by the TMF3 Sponsors as a basis for a new project (TMF4) to start in June 2006. This Prospectus describes the elements of this new project.

To serve as a background to what follows, Section 2 summarises the current priorities of the industry, identified in discussions with TMF3 sponsors. In Section 3 below, the outcome of the selection process for the Sub-Projects in TMF4 is summarised and Section 4 describes the *modus operandum* for TMF4. Section 5 gives details of the content of the proposed TMF4 Sub-Projects. Finally, in Section 6, the financial details of participation in TMF4 are given.

2 THE NEEDS OF THE INDUSTRY

The current priorities of the oil industry are focused in four areas as follows:

(a) Optimum continued production from mature fields. It is vital that, subject to economic constraints, the maximum amount of hydrocarbon recovery is secured from currently operating fields. This means optimum operation of these fields for the remainder of their productive life and extending this life by avoiding problems such as the shut-down of wells due to liquid build-up giving high back pressures at the reservoir level. This leads to increased interest in technologies aimed at reducing these high well static heads. Other problems of mature fields include the often-increasing fraction of water in the liquid product (hence the importance of three-phase flows) and the consequences of lower flow rates in the associated pipeline systems.

(b) Development of small and marginal fields. The increasing oil price is obviously making it more economic to develop small and marginal fields. It is also leading to the revisiting of negative decisions about the viability of previously-identified fields in this category. Such developments inevitably involve multiphase transportation and require accurate assessments of the performance of recovery systems such as pipelines, separators, flowmeters etc.

(c) Development of deepwater fields. A significant proportion of the available reserves are in fields accessible only through deep water. Designing and operating recovery systems for deep water fields raises a number of special challenges. There are the usual problems of multiphase flows in flow lines but, in addition, there is the need to transport the fluids to the surface via large diameter riser systems. Data and prediction methods for such systems are sparse.

(d) Long-distance tie-backs. There is increasing need to transport product streams over long distances (for instance in the Barents Sea). This places increased emphasis on thermal management and the transport of solids (hydrates, wax) formed due to cooling down of the fluids. There are also, of course, the usual problems of slug formation and transport and of transient behaviour; the longer the pipe, the more significant these problems become.

(e) Deeply-buried reservoirs. It is now becoming more economic to exploit deeply buried reservoirs (i.e. reservoirs at >20,000 feet and typically at around 30,000 feet). This type of reservoir is often associated with very high temperatures and pressures and this can give new problems in hydrocarbon recovery processes.

As will be seen from the above, there are new priorities in addition to those previously addressed in the TMF series of projects. The general area of multiphase flows is central to current challenges and the need for targeted research in multiphase flow and related areas is well recognised. It is clear that the above priorities have strongly influenced the voting on the list of possible projects.

In the light of the above priorities, the broad overall objective of TMF4 can be stated as: *To provide information and methodologies which industry can use in extending its operational envelopes both in exploiting existing fields and developing new ones*. For each Sub-Project area, specific objectives (consistent with this broad objective) are stated below.

3. LIST OF TMF4 SUB-PROJECTS

There was an excellent response to the request to complete the voting sheets and the TMF management team would like to thank Sponsors for their efforts in this context. The process of selecting and voting on the alternative projects has provided excellent information on industry's priorities in this area which are reflected in the selection (see paper TMF3/P127(05) for details) of the following six Sub-Project areas:

Sub-Project 1: **Multiphase flow in vertical and deviated pipes** (Barry Azzopardi, Nottingham University)
Sub-Project 2: **Slug flow** (Chris Lawrence, Imperial College)
Sub-Project 3: **Interfacial development and behaviour in stratified flow** (Peter Spelt, Imperial College)
Sub-Project 4: **Modelling of complex flows** (Chris Thompson, Cranfield University)
Sub-Project 5: **Thermal management** (Joe Quarini, Bristol University)
Sub-Project 6: **Slug control** (Hoi Yeung, Cranfield University)

Each Sub-Project would have a Project Coordinator and the name and affiliation of the proposed Coordinator are given here for reference. The duties of a Project Coordinator are discussed in more detail in Section 4 below.

The Sub-Projects are described in more detail in Section 4.

4. SUGGESTED *MODUS OPERANDUM* FOR TMF4

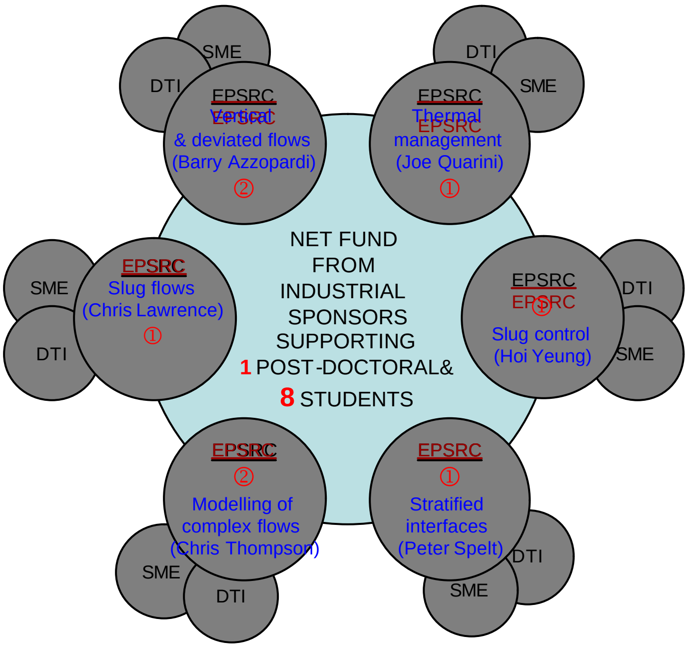
As in previous TMF projects it is suggested that funding for TMF4 be sought from industry and from UK Government sources. Broadly speaking, in previous TMF projects, the industrial funds supported research expenses (equipment, consumables, travel etc) and project management costs, with only a small proportion supporting research staff costs. The UK Government (EPSRC and DTI) funds were used to fund research staff, EPSRC and DTI funding being sought for the *whole* programme. This presented increasing difficulty as the size and complexity of the TMF projects grew. EPSRC proposals are mainly judged, in competition with many other proposals, on their *scientific merit.* The length of the Case for Support in an EPSRC proposal is restricted to 6 pages and it is difficult to make the scientific case in that space for programmes as large and complex as TMF. Though it is sometimes permitted to have annexes for further clarification, it is not clear that these have sufficient impact on the often-busy peer review community. In view of these considerations, a different approach is suggested for TMF4. This approach is illustrated schematically in Figure 1.

Though several new areas and many new topics within a given area are included in what is suggested below for TMF4, an important point to bear in mind is that the previous TMF projects have developed a wide range of capital equipment, measurement techniques and know-how which can be used effectively in TMF4. Large scale facilities include the WASP facility at Imperial College, the flexible riser and large diameter high gas density riser facilities at Cranfield University and the new large diameter riser facility at Nottingham. Available measurement techniques include X-ray and impedance tomography, axial view photography, laser induced fluorescence (LIF), optical drop sizing etc. The basic know-how is embodied in a number of computer codes (EMAPS, TRIOMPH, GRAMP2, a level set code, etc) and computational procedures. Thus, though what is proposed for TMF4 is certainly ambitious, it is based on a firm basis of investment and expertise.

The principal elements of the proposed scheme are as follows:

a) The payments received from sponsors would be collected into a central fund which, in contrast to the earlier TMF projects, would be used mainly to directly fund research staff. The staff supported would be one Post-Doc (Colin Hale) and eight research students. Thus, even before any funding from EPSRC and DTI funds, there would be a substantial cadre of full time research workers involved in TMF4. Colin Hale would lead the experimental work at Imperial College and thus participate in several Sub-Projects and the research students would be allocated to Sub-Projects as indicated in Figure 1. In establishing a cost for a student, an allowance has been made for some consumables, for student fees, for technician effort and for overheads. The allocation for a student over three years has been set at £90k. The suggestion is that four students be so funded at Imperial College, two at Cranfield and one each at Nottingham and Bristol. The calculations are based on having the 12 existing 'cash' sponsors each paying £29k per annum over three years. It is hoped that additional companies will join, thus increasing the number of staff who can be supported by this central fund.

Figure 1: Proposed structure for TMF4



b) In each of the Sub-Project areas, a proposal would be made to EPSRC for appropriate additional funding for additional staff and research support. These proposals would focus on the (very real) scientific challenges in each Sub-Project area. EPSRC proposals are evaluated by peer reviewers and then ranked for funding (based on the reviews) by an academic panel. It seems unlikely that *none* of the proposals made would succeed in attracting funding; however, it also seems unlikely (despite the good track record of the individual academics involved) that *all* of the proposals would receive funding on first submission. Nevertheless, one could reasonably expect that a substantial input of EPSRC funding could be achieved in the first round of submissions and, if a proposal was unsuccessful, then it could be resubmitted in a form taking account of the reviewers' comments after a statutory period of six months. The great advantage of using the industrial funds to support staff would be that the work on TMF4 could begin in all Sub-Project areas immediately after the end of TMF3 (i.e. on June 1st, 2006). A substantial stock of equipment and know-how has been accumulated in the TMF projects and could be brought to bear on a TMF4 Sub-Project area even in the absence of further EPSRC support in that area. It would be the intention to submit the proposals to EPSRC as soon as possible, giving time for the evaluation process to be complete around the start of TMF4.

c) The UK Department of Trade and Industry (DTI) have recently changed their policy on supporting research. In TMF3, they had given a grant to support the technology transfer activity at Cranfield University. Such a grant would not now be permissible under the new rules; rather, DTI wish to encourage (and financially support) collaborative research between industrial partners and between industry and academia. What is suggested, therefore, is that partnerships be set up between one or more of the groups participating in each Sub-Project area and an industrial partner for a joint development. The ideal type of company to enter into such a partnership would be the existing in-kind sponsors of the TMF projects and companies of similar type (i.e. "small and medium enterprises" – SME's). The natural activity in such collaborations would be software development. Informal discussions have been held with several such companies and a favourable industrial response to pursuing such schemes seems likely. Again, proposals for such collaborations would need to be submitted in response to the DTI call for proposals (launched in November, 2005 and at six monthly intervals thereafter). There would be no reason why such collaborative activities should not also take place with the oil companies. However, the trend in these companies has been away from in-house research and towards participation in JIP's; nevertheless if any of the oil company or contractor sponsors wishes to consider such collaborative schemes, then we would be very pleased to take this forward

What is also being proposed here is a significant change to the management structure of TMF. There would be a small central management effort consisting of the following:

Geoff Hewitt, Programme Director (4 days per month) whose main responsibility would be coordinating the whole activity and solving policy problems as and when they arose. Geoff Hewitt would also be a Co-Investigator in each of the TMF4 Sub-Projects.

Colin Weil, Project Manager (4 days per month) whose principal role would be maintaining contacts with sponsors, arranging meetings and liaising with Imperial College in setting up contracts etc.

Colin Hale, Assistant to the Programme Director, whose main roles would be to monitor the financial aspects and to solve day-to-day problems as and when they arose. It is envisaged that around 20% of Colin Hale's time would be spent on these activities. This time would be funded from the central fund for the whole three year period of the contract. For the first year, the remaining 80% would also be funded from the central fund and be devoted to research. The aim would be to fund the remaining time of Colin Hale for the second and third years from EPSRC and/or DTI funds.

Some funds would be set aside to cover secretarial effort, meeting costs etc.

An important functional responsibility for the central management team will be to organise the collation of the data and results obtained in TMF4 and in previous TMF projects into an easily accessible form so that it can be readily used by TMF sponsors. Obviously, the TMF web site will have an important role in this activity and continuous improvement and development of the site is envisaged. A key related aspect is that of *education*; it is important to keep industry informed of what is happening in the project but there is also a broader need to adopt an educational stance to promote the transfer of generic knowledge of multiphase flow and the related flow assurance issues. This educational activity would cover such aspects as multiphase flow patterns and their significance, the alternative modelling bases for multiphase flow, control and metering aspects etc. Again, the web site will have an important role in implementing this educational activity but consideration would also be given to arranging short courses, industrial management briefing sessions etc.

The reduction in the level of central management effort compared to TMF3 will be compensated for by *delegating* much of the detailed operational management to the Project Coordinators. Their duties would include:

a) Participating in detail in the initial project definition stages and taking the lead (in collaboration with colleagues both at their University and at other Universities and with industry) in preparing the EPSRC and DTI proposals for their Sub-Project.

b) Arranging regular meetings with other groups involved in their Sub-Project area to monitor progress and agree actions.

c) Monitoring progress against agreed objectives and preparing quarterly progress reports on their Sub-Project area for submission to TMF4 central management and, through them, to the industrial sponsors.

d) Taking the lead in presentations on their Sub-Project area at the main sponsors meetings.

e) Arranging periodic meetings of groups of sponsors (mentors) and academics to discuss the work in their area. The first of these meetings would be a "kick-off" meeting in which detailed plans for the experimental, analytical and computational work in the Sub-Project would be presented and discussed. This would assist in achieving the optimum deployment of resources, which is important bearing in mind the costs of large scale experiments.

f) Taking the lead in ensuring that the work in their Sub-Project area is published (where possible and appropriate) in archival journals and presented at both industrial and academic conferences.

g) Submitting appropriate reports to DTI and EPSRC.

5. TMF4 SUB-PROJECTS

In what follows, summaries of the six proposed Sub-Projects are given. For each technical area in the voting sheets, a list of possible topics forming the contents of the area was given. In the voting process on TMF4, Sponsors were invited to tick those topics which were of greatest interest to them. The selection of the technical elements in each Sub-Project is based on these responses from the sponsors. In what follows, the elements of technical work to be carried out using the central funds are specified as are the elements for which EPSRC funding will be sought. It should be stressed that, though convenient to present the proposed project in terms of these technical elements, there are strong links between many of them (for example they may share common experimental facilities or common theoretical bases); the intention will be to ensure a strong interconnection between the elements as appropriate.

Sub-Project 1: Multiphase Flow in Vertical and Deviated Pipes
Project Coordinator: Barry Azzopardi

Rationale: The area of flows in vertical and deviated pipes was strongly supported by sponsors in the voting exercise. This reflects the increasing use of large diameter risers in deep sea systems. There is a real dearth of data on large diameter vertical and deviated pipes and wells. Flow patterns, and therefore closure laws, may be very different in large diameter conduits and there are severe doubts about whether models based on the data for smaller diameter pipes can realistically be applied to these cases. The project aims to build on the work in this area started in TMF3, with particular reference to obtaining further data and addressing the modelling issues.

Investigators:
Nottingham: Principal Investigator: Barry Azzopardi
Imperial: Principal Investigator: Geoff Hewitt
Co-Investigator: Chris Lawrence
Co-Investigator: Omar Matar
Co-Investigator: Peter Spelt
Cranfield: Principal Investigator: Hoi Yeung

Allocation of centrally funded students: Nottingham (1), Imperial (1)

Elements of technical work to be supported by central (industrial) funds:

- *Studies of flow patterns and flow parameters in new vertical riser facility (Nottingham).* There are large uncertainties in the nature and behaviour of multiphase flow in large diameter vertical pipes; for instance, it seems likely that the conventional slug flow pattern may not exist at all in such pipes. In the TMF3 project, a large vertical riser facility has been constructed at Nottingham University in which measurements of flow pattern and flow parameters can be made over a wide range of flow rates and gas densities. It is proposed that the student supported from the central (industrial) fund should be deployed on obtaining a wide range of data (flow pattern, pressure gradient, holdup, phase distribution) using this new facility and to analyse these data to elucidate the flow behaviour in large diameter vertical pipes.
- *Modelling of flows in vertical and deviated pipes (Imperial).* Imperial College has developed a computer code for vertical flows (GRAMP2) which embodies flow-pattern-based phenomenological models. Recently, this code has been adapted to prediction of well and riser flows by linking it to a commercial physical properties package. Though encouraging results have been obtained, it has to be recognised that the models in the current code are (perforce!) based on observations and data for smaller diameter pipes. It is proposed, therefore, that the student supported from central funds in this area should develop improved phenomenological methods for large diameter pipes, both vertical and deviated. The data to be obtained from the Nottingham facility will be important not only in validating the coded models, but also in developing the conceptual basis for the new models.

Elements of technical work for which EPSRC funds are being sought:

- Experiments on a 10 inch air-water riser facility (Cranfield)
- Studies of flows in singularities (valves, chokes, bends etc) (Nottingham and Imperial)
- Studies of flows in deviated pipes (Nottingham and Imperial)
- Studies of entrainment phenomena, drop size etc in vertical and near-vertical flows (Nottingham and Imperial)

Sub-Project 2: Slug Flows
Project coordinator: Chris Lawrence

Rationale: Slug flows are of great importance and, despite many years of work in the area (including work in the TMF projects), there are still difficulties in prediction. The importance of this area was again reflected in the voting from the Sponsors. The direct calculation of slug behaviour by applying the two-fluid model at a high level of discretisation ("slug capturing") has been developed under the TMF projects and has proved very promising; however, there are still challenges in applying this to large systems because of the demands on computer resources (though these will be mitigated as computers improve and better solvers are developed). Following the motion of individual slugs ("slug tracking") allows potentially faster computing and also the opportunity of taking into account some of the multi-dimensional effects; this methodology has been pursued intensively in TMF3 and the methods developed should form a basis for a robust calculation route. More detailed experimental studies are required of the precise slug initiation mechanisms, coupled with advanced computational methods for interface behaviour, such as level sets (a start has been made on such methods in TMF3). It seems likely that no single method would be the optimum choice for all situations and there is scope for an integrated computing approach in which the appropriate level of sophistication is automatically chosen during the course of the calculations.

Investigators:

Imperial: Principal Investigator: Chris Lawrence
Co-Investigator: Geoff Hewitt
Co-Investigator: Peter Spelt
Co-Investigator: Raad Issa
Co-Investigator: Stephen Richardson

Cranfield: Principal Investigator: Chris Thompson

Allocation of centrally funded students: Imperial (1)

Element of technical work to be supported by central (industrial) funds:

- *Slug capturing methods (Imperial College, Mechanical Engineering).* The slug capturing methodology has been extensively investigated for both two-phase and three-phase flows, and the results have proved very interesting. Though limited tests of the methodology have been carried out for pipes with changes of inclination and for flow transients (and these results demonstrated the great potential of the approach), the work has been concentrated mainly on steady flows in horizontal pipes. In the centrally funded work in TMF4, the intention is to extend the limits of the methodology in terms of its applications to inclined pipes, networks and transients. Data on slug flow in inclined pipes have been generated in earlier TMF projects at Imperial College and will be used to validate the slug capturing methodology for such flows. Similarly, data have been generated at Nottingham on slug flow in dividing and combining junctions; such junctions are the essential ingredient of network systems and the data will be compared with predictions from slug capturing. Extensive TMF data also exist for flow transients and more detailed comparisons with these data will be carried out. A potential concern in the application of slug capturing methods is that of the large computer resources required to carry out calculations at this level of detail. However, recent work on improved computational algorithms pursued both within TMF3 and outside the TMF project has established that the large increases in speed required for the viability of the method can be achieved.

Elements of technical work for which EPSRC funds are being sought:

- Detailed experiments on slug initiation and evolution (Imperial)
- More advanced computing for prediction of initiation (level sets etc) (Imperial)
- Development of integrated computing approaches (automatic selection of appropriate level of sophistication in calculation) (Imperial and Cranfield)

Sub-Project 3: Complex Flows in Hydrocarbon Recovery
Project Coordinator: Chris Thompson

Rationale: So far, in the TMF projects, the emphasis has been on multiphase flows of relatively simple fluids; this has in itself been challenging enough. However, the reality has to be faced that real hydrocarbon production fluids are often very complex and difficult. They can have complex structures and extremely high viscosities (heavy oils), they can be non-Newtonian in nature (as exemplified by waxy crudes, which exhibit a yield stress behaviour, and by slurries). Furthermore, the actual structure of flows with two liquid phases (liquid-liquid and liquid-liquid-gas) is only poorly understood and this forms a barrier to better prediction. There was strong support from Sponsors for the TMF4 project to move firmly towards these more complex situations. An assessment study on non-Newtonian flows was carried out as part of TMF3 and established priorities for future work (namely on waxy crudes and slurries).

Investigators:

Cranfield: Principal Investigator: Chris Thompson

	Co-Investigator: Hoi Yeung
Imperial:	Principal Investigator: Geoff Hewitt
	Co-Investigator: Stephen Richardson
	Co-Investigator: Chris Lawrence
	Co-Investigator: Raad Issa
	Co-Investigator: Omar Matar

Allocation of centrally funded students: Cranfield (1), Imperial (1)

Elements of technical work to be supported by central (industrial) funds:

- *Experimental studies of flows with two liquid phases (Imperial College, Chemical Engineering).* The crucial and complicating factor in flows with two liquid phases is the way in which the two liquid phases interact to produce inter-entrainment (inter-dispersion). In TMF3, extensive gamma and X-ray tomography studies have been carried out on mixing in liquid-liquid flows and these data are being used in the Cranfield modelling studies. In the work in TMF4, the focus will be on two aspects, namely the extension of these mixing studies to three-phase slug flow and the investigation of the interfacial processes associated with phase inversion in liquid-liquid flows. The first study will be carried out using the WASP facility and in particular the X-ray tomography system. The second study would use laser induced fluorescence and would use the Imperial College TOWER (liquid-liquid) loop. An important part of this work will be to obtain a better understanding of flow regime transitions in these flows. The work will include studies on inclined tubes to match the work on modelling being done at Cranfield.
- *Modelling of three-phase flows in channels of varying inclinations (Cranfield).* So far, the work at Cranfield on modelling three-phase flows has concentrated on horizontal flows, whereas inclination of production pipelines is the norm rather than the exception. Even small inclinations may have a profound effect. Thus, the work proposed for Cranfield in TMF4 includes an extension of the models to inclined flow systems.

Elements of technical work for which EPSRC funds are being sought:

- Development of better computer algorithms including mixing processes (Cranfield)
- Basic studies of droplet break-up and coalescence in liquid-liquid flows. Anomalous viscosity effects (Imperial)
- Heavy oil systems – experimental studies of water/heavy oil and water/heavy oil/gas flows (Cranfield)
- Studies of slurry flows (representing wax, hydrate, sand slurries). Near wall phase distribution. Slurry /gas mixtures (Cranfield and Imperial))
- Studies of shear thinning behaviour (waxy crudes). Gels and yield stress (Imperial)

Sub-Project 4: Interfacial Behaviour in Stratified and Annular Flows
Project Coordinator: Peter Spelt

Rationale: Many of the multiphase flows encountered in production are in the stratified regime. This regime is in many ways even more complex than slug flow. The interface is usually covered by a complex pattern of waves which not only exerts a profound influence on the all-important interface friction but is also the source of droplet entrainment. In view of these complexities, it is perhaps not surprising that there are no satisfactory generic relationships for interface friction even in the steady state flow case. Another serious problem is that the steady state interface friction relationships, though used extensively in the transient flow prediction codes, are demonstrably inapplicable to the transient case. Further investigation of interface characteristics and friction is indicated, extending the work done in steady flows and obtaining more data on stratified flows. The phenomena associated with drop entrainment are notably poorly understood; droplet entrainment and deposition are crucial factors in governing pressure drop. Thus formation of a slowly draining film of oil at the top of the pipe as a result of droplet entrainment, transport and deposition can give huge increases in pressure drop. An important problem for the oil industry is "top of line corrosion"; this can take several forms and is often addressed by adding a corrosion inhibitor to the liquid phase. However, for such additives to be effective the liquid phase containing the additive must wet the upper surface of the tube; a liquid phase formed at this upper surface by condensation (for example water containing CO_2) would not be effective and may actually promote corrosion. Thus, entrainment and deposition processes are of paramount importance in this key problem. Furthermore, in the case of three-phase stratified/annular flow, the identity of the liquid which wets the top of the pipe is important in governing corrosion behaviour; there is practically no information available on this. Though work was carried out on stratified two-phase flows in the TMF1 project, and though some work on three-phase stratified flows has been done at Imperial College outside the TMF framework, the dearth of knowledge in this vital area prompted Sponsors to promote the inclusion of work in stratified flow in the list of possible topics for TMF4 and to vote strongly for such work in the voting process.

Investigators:

Imperial: Principal Investigator: Peter Spelt
Co-Investigator: Geoff Hewitt
Co-Investigator: Chris Lawrence
Co-Investigator: Omar Matar
Co-Investigator: Raad Issa

Allocation of centrally funded students: Imperial (1)

Element of technical work to be supported by central (industrial) funds:

- *Studies of two- and three-phase systems with low liquid content: behaviour of corrosion inhibitors (Imperial).* Corrosion inhibitors are routinely added to production pipeline flows to extend pipeline life, particularly where the production stream is especially corrosive. Typically, corrosion inhibitor is added to the aqueous phase in a three-phase flow case and this raises important questions about whether the inhibitor can be transported to the top of the pipe. In a two-phase stratifying annular flow, droplets are entrained from the interface and deposit on the upper surface of the pipe to form a film; clearly, in this case, any inhibitor added to the liquid phase can be effective over the whole surface. In a three-phase stratified flow, it is the oil phase which is in contact with the gas and which would therefore be the phase which is entrained as droplets; if the aqueous phase is not entrained, then corrosion inhibition will not be achieved at the upper surface of the pipe. Fortunately, however, the two liquid phases are likely to be mixed in the stratified layer at the bottom of the tube and entrainment, and consequent transport to the top of the tube, of both phases is likely. Another important question is whether, even in these circumstances, the water phase would wet the upper surface. The emergence of this concern has focussed attention on the fact that practically nothing is known about three-phase stratifying annular flow, which is a commonly-occurring regime in production pipes. This has led several sponsors to give this area priority, hence the decision to select this area for central funding. The work will focus on obtaining data for stratifying annular three-phase flow; axial view photography will be used to elucidate the processes involved and sampling probes used to determine the composition (water cut) of the entrained phase. Wetting behaviour will be determined using conductance or hot film probes. Consideration will also be given to means by which transport of the liquid phase carrying the inhibitor to the upper surface might be enhanced.

Elements of technical work for which EPSRC funds are being sought:

- Measurements of wall and interfacial friction. Axial development. Interfacial friction in transients (Imperial)
- Use of interface tracking computational methods to follow spatial and temporal development of the interface (Imperial)
- Development of improved closure models for use in 1-D codes, specifically for entrainment phenomena and the more accurate evaluation of shear stresses. This work would be supported by the measurements referred to above (Imperial)
- Studies of droplet entrainment and subsequent behaviour in stratified and annular flows (Imperial)

Sub-Project 5: Slug Control
Project Coordinator: Hoi Yeung

Rationale: The occurrence of severe slugging presents a major potential problem in the operation of hydrocarbon recovery systems. Classically, the problem has been addressed by having separators ("slug catchers") which are large enough to contain the largest conceivable slug. In recent years, there has been a growing tendency to tackle the severe slugging problem by using some form of control system. As part of the TMF3 project, an Assessment Study was done on such systems and the proposal to carry out work in this area in TMF4 is based on the recommendations in the report of that study. It is considered important, in the proposed work, to address the problem in terms of advanced control models (for which there is extensive experience in the Centre for Process Systems Engineering at Imperial College) and to validate these models on the large scale flexible riser facility at Cranfield University. Close contact with industry will be maintained throughout to ensure the practicability of any control schemes emerging.

Investigators:

Cranfield:	Principal Investigator: Hoi Yeung
	Co-Investigator: Yi Cao
Imperial:	Principal Investigator: Charles Immanuel
	Co-Investigator: Geoff Hewitt

Allocation of centrally funded students: Cranfield (1)

Element of technical work to be supported by central (industrial) funds:

- *Setting up of selected control schemes on the Cranfield flexible riser facility and comparing performance with prediction (Cranfield).* The centrally-funded student will work on the Cranfield facility to set up various control schemes and to make measurements of the transient flow parameters (flow rates, pressures and phase hold-ups) achieved by these schemes. Work in this direction was done in the TMF3 assessment study and demonstrated the viability of the approach.

Elements of technical work for which EPSRC funds are being sought:

- Development of advanced control models using existing Imperial College generic software and exploitation of these models in investigating various control strategies (Imperial and Cranfield)
- Development of a methodology for slug controller design.

Sub-Project 6: Thermal Management
Project Coordinator: Joe Quarini

Rationale: It is often necessary to maintain hydrocarbon production streams at a sufficiently high temperature, during pipeline transport, to prevent the deposit of waxes, asphaltenes and hydrates. Such deposition may lead to serious loss of production and, in extreme cases, to complete blockage of the pipes. Where temperature maintenance is not possible using insulation, *active* heating by hot water streams is often used in which *tube bundles* are constructed carrying the heating and production pipes. CFD prediction of the performance of such bundles, coupled with experimental validation, has formed an important part of the TMF2 and TMF3 projects. The essence of the work is the prediction of natural convection heat transfer inside the complex cross-sectional geometry of the bundle. The work has focussed on horizontal and slightly inclined bundles and has led to a consistent methodology for prediction of such systems. Briefly, this methodology involves carrying out a matrix of CFD calculations to cover the likely range of tube surface temperatures encountered, the fitting of the resultant data for heat transfer coefficient using neural network techniques and the use of these fits within a spreadsheet programme to calculate temperature profiles along the bundle. For horizontal and slightly inclined bundles, therefore, the emphasis in TMF4 will be on the transfer of the technology developed in TMF2 and TMF3 to industry. In TMF4, priority will be given in the research activity in tackling the much more difficult problem of thermal management in vertical or highly inclined bundles. Whereas the heat transfer in the horizontal case could be treated as two-dimensional, three-dimensional effects are very much to the fore in the vertical/highly inclined case. However, this case is becoming ever more important as more and more deepwater fields are being developed; for these fields, thermal management of the very long vertical and highly inclined risers is of vital concern. In principal, natural circulation of the fluid between the tubes in the bundle in such cases could take place over the full length of the riser, a situation for which it would be difficult to do meaningful calculations. It seems more likely, however, that tube supports would divide the riser bundle into a series of separate zones which (though the convection is three-dimensional within each zone) could be calculated in a similar manner to that used for the horizontal bundles (though this has yet to be established).

Investigators:
Bristol: Principal Investigator: Joe Quarini
Imperial: Principal Investigator: Geoff Hewitt
Co-Investigator: Stephen Richardson

Allocation of centrally funded students: Bristol (1)

Element of technical work to be supported by central (industrial) funds:

- *Development of CFD methodologies for non-horizontal bundles (Bristol).* The centrally-funded student would concentrate on the vertical/highly inclined case described above, carrying out CFD calculations and embodying the results into a package (on the lines of that developed under TMF3 for horizontal bundles) suitable for use by industry.

Elements of technical work for which EPSRC funds are being sought:

- Experiments on vertical/highly inclined bundles (Imperial). The selection of bundle geometries for these experiments will reflect the differences in optimised bundle geometry between the near-vertical and near horizontal cases.
- Assessment of the effects of local variations in heat transfer in bundles ("cold spots") (Bristol)
- Investigation of the effects of joints between risers and flow lines (Bristol)

6. PARTICIPATION IN TMF4

Companies are invited to participate as Sponsors of this Joint Project on Transient Multiphase Flow and Flow Assurance (TMF4). The ticket price is £29000 per annum for three years. For this contribution, Sponsors would be assured of a centrally-funded activity of around £1M over 3 years (assuming a similar participation to TMF3) in which 8 postgraduate students and a postdoctoral worker would be employed on the projects described above, all of which have been carefully selected, in consultation with TMF3 Sponsors to meet the needs of industry. In addition, funds will be requested from the UK Engineering and Physical Sciences Research Council (EPSRC) to support extended engineering science work in each of the selected areas. Joint projects with industry (partly sponsored by the UK Department of Trade and Industry) to promote technology transfer will also be actively pursued

G.F.Hewitt, January 3rd, 2006