Final Technical Report

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Acronym: EVIDENT

TITLE: EXTENDED VISCOSITY AND DENSITY TECHNOLOGY

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I. EXECUTIVE SUMMARY

During crude oils or natural gases exploitation, wells productivity is directly related to the viscosity of the reservoir fluid.

The cost of an extra well in the North Sea can induce the abandonment of the reservoir development project, the latter becoming non-economical. A recent evaluation indicates that the cost of 100 wells on-shore is equivalent to the cost of 5-10 wells off-shore. In the case of deep off-shore reservoirs, this cost corresponds to only 1-2 wells.

If the reservoir fluid recovery is enhanced by the implementation of gas injection, the efficiency of such a process highly depends on both the mobilities of the injected gas and the in-place fluid, such mobilities being directly related to their viscosities.

Recent discoveries at high depths mostly concern rich condensate gases. Because of that, this project has mainly focused on such fluids.

All these industrial facts made it necessary to develop prediction models for the viscosity of reservoirs gases in high pressure-high temperature (HP-HT) conditions. As viscosity is strongly correlated with density and temperature, it is compulsory to simultaneously make available to users appropriate models for density computation.

This project aimed thus to develop reliable and accurate models for predicting both densities and viscosities of HP-HT rich condensate gases, these models being necessarily built on a consistent data base.

Therefore, the main results produced at the end of this 4 years project are of two kinds.

First of all, a large set of experimental data has been measured and their accuracy evaluated. These data are relative to:

- 6 pure hydrocarbons (C_1, C_2, C_3, C_4, C_5 and C_{10}) ;
- 8 binary mixtures ;
- 2 ternary mixtures ;
- 3 multicomponent synthetic mixtures ;
- 7 real reservoir condensate gases.

Next a new semi-empirical viscosity model has been proposed. This model has further been evaluated with a range of "conventional" North Sea crudes for which viscosity data were available at reservoir conditions. The average absolute deviation of viscosity predictions is around 15%. In contrast, the Lohrenz-Bray-Clark correlation which is normally used in reservoir simulators clearly fails to provide any reasonable viscosity prediction for North Sea crude oils.

Finally, the viscosity of the real reservoir condensate gases experimentally studied in this project has been computed with this model and compared to the measured data. It has been found that the obtained average absolute deviations between 1 and 5% are in agreement with the order of magnitude of the experimental uncertainty (± 1%). Therefore this project results are satisfactory for most applications related to the oil and gas industry.

Considering the economical impact of these results, a reservoir performance as measured in terms of the cumulative hydrocarbons production is sensitive to the viscosity of the fluid stream.

For light streams such as the ones which are the target of this project (having a viscosity lower than 0.5 mPa.s), simulation work indicates that a ± 10% error on computed viscosity will produce an uncertainty of ± 1-2% on the cumulative hydrocarbons production. In terms of the present oil and gas value, this would correspond to a variation of ± 75 million Euros on the revenue resulting from the reservoir exploitation. This clearly shows that the improvement brought by the results of this EVIDENT project can be extremely beneficial for the economics of reservoirs exploitation within the European Community.

II. OBJECTIVES OF THE PROJECT

During crude oils or natural gases exploitation, wells productivity is directly related to the viscosity of the reservoir fluid.

The cost of an extra well in the North Sea can induce the abandonment of the reservoir development project, the latter becoming non-economical. A recent evaluation indicates that the cost of 100 wells on-shore is equivalent to the cost of 5-10 wells off-shore. In the case of deep off-shore reservoirs, this cost corresponds to only 1-2 wells.

If the reservoir fluid recovery is enhanced by the implementation of gas injection, the efficiency of such a process highly depends on both the mobilities of the injected gas and the in-place fluid, such mobilities being directly related to their viscosities.

Recent discoveries at high depths mostly concern rich condensate gases. Because of that, this project has mainly focused on such fluids.

All these industrial facts made it necessary to develop prediction models for the viscosity of reservoirs gases in high pressure-high temperature (HP-HT) conditions. As viscosity is strongly correlated with density and temperature, it is compulsory to simultaneously make available to users appropriate models for density computation.

This project aimed thus to develop reliable and accurate models for predicting both densities and viscosities of HP-HT rich condensate gases, these models being necessarily built on a consistent data base.

Therefore the project involved four main tasks:

I.   data acquisition on synthetic mixtures representative of natural fluids;

II. build-up of appropriate models, as viscosity is one of the weakest parameters predicted for complex hydrocarbon mixtures under high pressures;

III. data acquisition on a set of selected real reservoir condensate gases;

IV. models evaluation and validation in order to test the accuracy of their results in a wide range of industrial applicability.

Presently, at the end of this 4 years project, the implementation of the developed models in industrial simulators helps to measure the efficiency of the new equations for a better estimation of wells productivity and deliverability.

It is important to emphasize here that such models are not only needed to improve the performance of wells and the recovery of natural gases, but also to better design the fuel injectors in diesel engines for obtaining very small-sized drops, thus reducing the emission of carbon particles in the exhaust gases.

When compared to other physical properties, there are a very limited number of viscosity data, which usually are in restricted areas of industrial operating conditions: pressure-temperature-composition. In fact many experimental data and correlation models are available

for liquid systems at low pressures. However models applicable for liquid mixtures are much less accurate when dealing with gases, even if these are dense because of pressure conditions.

A recent evaluation performed by some of the project partners indicated that available models usually overestimate by 50-70% the values measured for complex gaseous hydrocarbon mixtures under high pressures.

At the start of the project, very few data were available for dense gases because of:

- high pressure conditions;
- relatively low viscosity values.

Therefore, several of the partners have built, before the start-up of this project, equipment capable of determining the density, viscosity and phase behaviour of HP-HT reservoir fluids.

From a simulation point of view, most of existing viscosity models are purely empirical correlations. In this project, a molecular dynamics approach has been developed in order to have better predictive performance due to physically sound model parameters.

This methodology could be further extended to all transport properties (i.e. diffusion coefficients, heat conductivities, …).

Such viscosity models based on molecular simulation have a large number of applications outside HP-HT reservoir development: chemical engineering, design of diesel engine injectors, …

It is important to note that such a research approach has been very successful for fluid density computation. These results have been made possible because many European researchers have developed reliable statistical thermodynamic models.

The semi-empirical viscosity models designed in this project are much more reliable than the previously existing ones as they have been built and validated on a large data base. These data have been obtained by different experimental techniques implemented by the project partners: capillary tube and falling plug. Cross-check of the data has been carried by dealing with a common reference mixture, thus ensuring the consistency of the whole set of measured values.

The following technical risks have been critical to the success of the project within a pre-fixed duration:

- solid (waxes, diamondoïds, resins) deposition in measuring equipment when studying real HP-HT rich condensate gases;

- temperature influence on high pressure gauges;

- combined pressure and temperature working limits of parts of the equipment (valves, seals, …), these last two risks inducing preventive measures in the design of the experiments;

- the new molecular dynamics model approach could not always represent the measured data with an acceptable accuracy; this is the risk of not achieving the fixed goal, but constitutes nevertheless an important information on model limits and a step towards its improvement.

All these risks would simply lead to restrictions on the pressure-temperature-composition domains to be studied with the modeling tools completed during the duration of this project.

III. SCIENTIFIC AND TECHNICAL DESCRIPTION OF THE RESULTS

III.1 Introduction

An important aspect and vital component in reservoir and well calculations is the ability to determine the physical properties of the fluids, which influence flow and volumetric behaviour.

Viscosity and its related property of density are such properties. The ability to predict accurately their volumes for complex fluids such as natural gases, in large operating conditions range (from reservoir to stock tank pressure and temperature), is essential for optimized process, well and reservoir design.

Predictive methods, such as the ones aimed to be developed within this project, are generally progressed in parallel with current needs and circumstances. The rational behind Task I is the underlying question as to what extent are existing data providing sufficient information and scope for extending predictive capabilities to meet the needs of reservoir fluids at high pressure and temperature (HP-HT) conditions. In assessing the status of such data, limitations in the quality and scope of the data should be revealed.

There are two classifications of data being considered in this task; those in the open published literature and those not in the open literature but being provided by some of the partners from their own associated research and field related studies.

III.2 Task I: Data acquisition on representative synthetic mixtures

IFP (Partner two), HWU (Partner three) and TFE-UPPA (Partner four) have been involved in task I.

This task is divided into three subtasks for which the main results will be outlined in the following sections. These three subtasks are: I.1 "Evaluation of published data", I.2 "Cross-checking of experimental techniques" and I.3 "Viscosity and density data acquisition for a selected set of synthetic mixtures in extended pressure-temperature ranges".

The objectives of the three subtasks are to identify existing viscosity and density data relevant to the project, examine the quality of data generated by the partners by carrying out a consistency study across the partners involved in the experimental part of the programme, and generating novel data for use in models validation.

The facilities used by IFP for its contribution to Task I is the HERCULE HP-HT cell which has been designed in-house for measuring both density by pycnometry and viscosity by capillary flow at working conditions up to 150 MPa (1500 bar) and 200°C.

At HWU, the HP-HT cell available to the project at its start was developed for phase volume measurements only, and did not feature high pressure viscosity and density measurements. It had maximum working limits of 138 MPa (1380 bar) and 200°C. One of the early objectives within the EVIDENT project has therefore been to implement an in-line viscosity measurement using a capillary tube into the HP-HT facility.

Concerning TFE-UPPA, at the beginning of the EVIDENT project, the laboratory had only equipment able to measure the viscosity up to 100 MPa of systems which are in a liquid state at atmospheric pressure. One of the early objectives of the project has therefore been to design and develop a viscometer able to measure low viscosity for systems containing gases. As the other partners (IFP and HWU) used capillary tube viscometers, it was decided to build a new falling plug viscometer in order to verify the capability of the various techniques.

In parallel with equipment improvement and adaptation for fulfilling the objectives assigned by Tasks I.2 and I.3, Task I.1 has been carried on by the three "experimental" project partners.

III.2.1 Task I.1: Evaluation of published data

IFP (Partner two) first collected published viscosity and density data for model systems representative of high pressure and high temperature reservoir fluids. Particularly, these data have been evaluated with the following criteria: temperature range, pressure range, measurement method, estimated data accuracy and components purity.

HWU (Partner three) has examined data sets from research projects carried out over recent years in the context of phase behaviour studies on gas condensate and volatile oil fluids. The research had been funded by a number of companies and the UK Department of Trade and Industry through joint venture collaboration. These previous measurements concerned both viscosities and densities of three binary hydrocarbon mixtures, one ternary system, one synthetic gas condensate, one synthetic near critical fluid (NCF) and one blend made of a field derived gas condensate mixed with the NCF.

TFE-UPPA (Partner four) has used a data base of 40 PVT reports containing viscosity measurements at reservoir conditions for testing four viscosity correlations generally used by the industry. The number of measured values is around 300 in the range 0.04 to 1.95 mPa.s, the pressure-temperature range being from 100 to 1200 bar (10 to 120 MPa) and from 40 to 180°C.

Taking into account that experimental error on viscosity determinations is ± 20%, it has been found that the correlations tested lead to absolute average deviations ranging from 6 to 30% while their bias is between -1 and -21%. However, in some cases the deviation exceeded 100% and this is not acceptable for industrial purposes.

As well as providing data for model validation purposes, some interesting (unexpected) results have been underlined: for a number of fluids, particularly those near their critical pressure, increasing viscosity with pressure reduction has been observed.

III.2.2 Task I.2: Cross-checking of experimental techniques

Task I.2 has been a very critical part of the project. This task was where all the partners involved in the experimental phase carried out the same measurements on the same "reference" fluid mixture using different measurement methods. Clearly, if different laboratories are unable to obtain equivalent results, then future separate results would be in question.

Prior to this, the three partners involved in Task I performed a quality check of in-house measured data for pure components (nitrogen and light hydrocarbons) with literature values gathered during Task I.1. All in-house results compared well with literature published viscosities within a few percents.

A "reference" fluid for the comparison test has then been selected by the partners as a 95 mole % mixture of methane and n-decane. This "reference" mixture has been revised when it was observed that viscosity values were too low for some partners to measure accurately. The revised fluid was a 60 mole % mixture of methane and n-decane for use as the "reference" fluid. This mixture has been made up at each partner laboratory, therefore there were slight variations in the final composition for each partner fluid. However the "reference" mixture also enabled comparison of project results with the literature data gathered for this fluid during the course of Task I.1.

Prior to data acquisition on this "reference" mixture, IFP (Partner two) spent time in calibrating its HP-HT facility against a pure component (toluene), both for density and viscosity measurements.

On its side, HWU (Partner three) spent time in installing and commissioning a capillary tube viscometer in its HP-HT facility and calibrating it against a pure component (n-decane).

As per TFE-UPPA (Partner four), this partner had to build a falling plug viscometer as mentioned earlier in the introductory section of Task I and further to calibrate it against several pure components (light hydrocarbons from methane to n-decane). Propane was then chosen as a test substance for the evaluation of the correct operation of this apparatus.

IFP prepared the "reference" mixture: methane-n-decane, 60%-40% respectively on a molar basis. The estimated precision in the preparation of the mixture is ± 1% on a molar

composition basis. Then both the viscosities and densities of this reference mixture have been measured at 377.6 K (104.4°C) between 30 and 140 MPa (300 up to 1400 bar). It should be noted that the error in temperature is estimated as ± 0.5 K whereas the error in pressure is ± 0.05MPa.

HWU has carried out tests on its "reference" fluid between 24.15 up to 103.42 MPa (241.5 up to 1034.2 bar). As an internal check, this partner carried out measurements at the lower pressure range on both rigs it possesses in its laboratory while determinations in the high pressure range have been carried only on the HP-HT facility. This demonstrated that the same results were obtained for both rigs within their working pressure range.

TFE-UPPA has measured a thorough set of data for the binary "reference" mixture methane + n-decane in the concentration range ~30 to ~76 mole %, within the temperature interval 293.2 to 373.2K (20 to 100°C) and at pressures up to 140 MPa (1400 bar). These viscosity data compare favorably with previously published data with a deviation not exceeding ± 3% for all temperatures except the highest one (100°C) for which the deviation reaches ± 5%.

In carrying out this cross-checking of experimental techniques, the three "experimental partners" data have confirmed that the results were in very good agreement, giving confidence for future independent tests. One issue which did arise was on the uncertainty with respect to the "reference" mixture composition. For the mixture selected, a deviation of ± 1 mole % in composition can result in a relative error ranging between ± 3% up to ± 10% on viscosity according to the pressure-temperature-composition domain. Moreover, the results have been compared to some literature data collected during Task I.1. The viscosity values measured in this project compare very well with the most recent data obtained in 1990 with another experimental technique: the oscillating cup viscometer.

III.2.3 Task I.3: Viscosity and density data acquisition for a selected set of synthetic mixtures in extended P-T ranges

To implement this task, the project partners decided to select a set of six binary mixtures in order to provide those involved in the modeling part with useful data. The industry experts from TFE and IFP advised the three project partners involved in this experimental task to investigate mixtures containing methane as the basic component altogether with various liquid or solid hydrocarbons representative of the main chemical families found in high pressure-high temperature reservoir gases: i.e alkanes, naphtenes and aromatics. The mixtures chosen as well as the pressure-temperature ranges aimed at providing new data valuable for models validation and for building more accurate, reliable as well as predictive models.

For these purposes, the following work programme has been decided in common by all the project partners.

IFP (Partner two) has investigated two binary mixtures: methane-n hexadecane and methane-α methyl naphtalene.

The first binary system involved the preparation of three mixtures having the following compositions.

methane- n hexadecane	
weight %	mole %

69.7 - 30.3	97.0 - 3.0
50.4 - 49.6	93.5 - 6.5
26.5 - 73.5	83.6 - 16.4

To start with, the saturation pressures of each of these mixtures have been measured at three temperatures: 50, 100 and 150°C. Then, both the viscosities as well as the densities of each system have been determined at these temperatures between the observed saturation pressure and 140 MPa (1400 bar).

The second binary system study involved the preparation of four mixtures having the following compositions.

methane- α methyl naphtalene	
weight %	mole %
6.2 - 93.8	37.1 - 62.9
6.0 - 94.0	36.0 - 64.0
4.6 - 95.4	30.0 - 70.0
2.6 - 97.4	19.0 - 81.0

The two mixtures having close compositions (6.2 and 6.0 weight % of methane) have been investigated in order to test both the reproducibility of the measured properties (saturation pressures, viscosities and densities) as well as the influence of small composition variations on these properties as we have seen previously (in section III.2.2) the impact of composition uncertainties on property deviations.

For this system also, the saturation pressures of each mixture have been determined at 50, 100 and 150°C. The obtained results showed that a 0.2 weight % variation in methane content (equivalent to 1.1 mole %) induces up to 22 bar change in the saturation pressure.

Further the viscosities and densities of each system have been measured at these temperatures between the observed saturation pressure and 140 MPa (1400 bar). The comparison of data obtained for the two mixtures having close compositions shows that the determined properties exhibit consistency and reliability.

For all the viscosity data, another test has been carried for each mixture and temperature. This ASTM-type test shows that the viscosity values follow a linear correlation log (log(η)) versus pressure, thus indicating the overall consistency of the measured data.

On its side, HWU (Partner three) has investigated two other binary mixtures: methane-methylcyclohexane and methane-cis decahydronaphtalene.

For each mixture, the experimental rig has been loaded gravimetrically and the obtained compositions are given in the following table.

methane - methylcyclohexane	methane - cis decahydronaphtalene
(weight %)	(weight %)
24.6 - 75.4	25.0 - 75.0
24.8 - 75.2	25.1 - 74.9
25.0 - 75.0	
49.4 - 50.6	49.7 - 50.3

49.9 - 50.1	50.0 - 50.0
50.3 - 49.7	
75.3 - 24.7	
75.4 - 24.6	75.0 - 25.0
75.5 - 24.5	

To start with, the saturation pressures of each of these mixtures have been measured at three temperatures: 50, 100 and 150°C. Then, both the viscosities as well as the densities of each system have been determined at these temperatures between the observed saturation pressure and 140 MPa (1400 bar).

For all the measured data, the following experimental uncertainties have been estimated:

- composition $\pm$ 0.4 weight %;
- temperature $\pm$ 0.5°C;
- pressure $\pm$ 0.02 MPa ($\pm$ 0.2 bar);
- saturation pressure $\pm$ 0.2 MPa ($\pm$ 2 bar);
- viscosity $\pm$ 1% (in the range 20-500 µPa.s);
- density $\pm$ 0.5% (in the range 100-700 kg/m^3).

As per TFE-UPPA (Partner four), its team has been involved in the study of five methane-n decane mixtures and also five methane-toluene mixtures. The compositions of the ten binaries investigated are given in the following table.

methane-n decane	methane-toluene
(mole %)	(mole %)
31.24 - 68.76	25.03 - 74.97
48.67 - 51.33	37.19 - 62.81
60.00 - 40.00	50.02 - 49.98
75.67 - 24.33	64.11 - 35.89
95.75 - 4.25	95.00 - 5.00

For each of these ten mixtures, both their densities and viscosities have been measured between 20 and 100°C at pressures up to 140 MPa (1400 bar). This represents a set of 575 data values: 295 data for the methane-n decane system and 280 data for the methane-toluene system.

In addition to the above mentioned work, the properties of a ternary liquid system representative of a natural gas condensate having an average boiling temperature of 237°C (510 K) under atmospheric pressure have been measured.

The three pure components with which this liquid system has been prepared are: α methyl naphtalene, n tridecane and heptamethylnonane. Each of these compounds has been selected because it has a boiling temperature close to 237°C at atmospheric pressure and is also representative of the main chemical families present in natural gas condensates: aromatics, normal and iso paraffins.

Thus 21 ternary mixtures have been made with these components. For each of these ternaries, both density and viscosity have been measured at 7 temperatures from 20 to 80°C and at 6

pressures up to 100 MPa (1000 bar). The overall results represent 1911 experimental density values altogether with 882 viscosity data.

III.3 Task II: Build-up of reliable and accurate models

This task is also divided into three subtasks for which the main results will be highlighted in the following sections. These subtasks are: II.1 "Evaluation of existing models", II.2 "Development of an innovative approach" and II.3 "New model validation with synthetic mixtures".

The objectives of the three subtasks are first to determine the operating limits of existing models as well as their accuracies, both for semi-empirical models usually used by the oil and gas operating companies, as well as for more "theoretical" models deriving from molecular dynamics.

The next objective is to propose better models, both in terms of reliability, accuracy and application ranges: pressure, temperature, mixtures composition. Finally the last objective of this task is to validate the new models developed in subtask II.2 with the data measured in subtask I.3.

TFE-UPPA (Partner four), TUD (Partner five) and FEUP (Partner six) have been involved in this task as described hereafter.

III.3.1 Task II.1: Evaluation of existing models

During the early life of this project, TFE-UPPA (Partner four) has used a data base of 40 PVT reports containing viscosity measurements at reservoir conditions for testing four viscosity correlations generally used by the oil and gas operating companies. The number of experimental values is around 300 in the range 0.04 to 1.95 mPa.s (40 to 1950 µPa.s), the pressure-temperature ranges being from 10 to 120 MPa (100 to 1200 bar) and from 40 to 180°C.

The models tested are:

- the Lohrenz-Bray-Clark (LBC) correlation which is used in many reservoir simulators;
- two models based on the corresponding states principle with one and two reference fluids, respectively CS1 and CS2 ;
- the self-reference viscosity correction model as applied to the CS1 model (CS1nn).

Viscosity is strongly linked to density and some correlations (i.e. the LBC one) need density as an input value. The Peng-Robinson equation of stage (PR-eos) has thus been used for the PVT calculations and the critical properties of the heaviest condensate or crude fractions have been fitted on the experimental PVT data.

This is one of the most tricky points when dealing with REAL reservoir fluids: there is an important part of the fluid which is unknown and the estimation/fitting method can sometimes have a strong influence on the calculated properties. Moreover, viscosity not being a thermodynamic property, a good match of the set of experimental thermodynamic properties is not a guarantee for a good estimation of viscosity.

The following table gives the overall deviations of the different correlations tested for the whole data base.

	LBC	CS2	CS1	CS1nn
AAD	30.07	29.65	25.07	5.92
BIAS	-11.07	-20.96	-18.68	-0.88

with:

$$AAD = \frac{100}{N} \sum_{i=1}^{N} \left| DEV(i) \right| \quad \text{: average absolute deviation;}$$

$$BIAS = \frac{100}{N} \sum_{i=1}^{N} DEV(i) \quad \text{: average deviation;}$$

$$DEV(i) = \frac{\eta_i \; calc - \eta_i \; \exp}{\eta_i \; \exp} \quad \text{: deviation;}$$

N being the total number of experimental values.

It can be seen that the average deviation is not so bad taking into account the numerous causes of error. But in some cases the deviation exceeded 100% and this is not acceptable for industrial purposes.

For the LBC correlation, the deviation increases with the average molecular weight of the fluid and a correction is recommended for high molecular weight condensate gases, which is generally the case for the HP-HT fluids considered in this project.

The overall results of the CS1 method are better than those of the CS2 method, but the potential improvements for the first are smaller than for the second. However, the errors for both these methods also increase with the average molecular weight of the fluid.

The method called hereabove CS1nn gives the best results but it requires a reference experimental viscosity value, thus it is not "predictive" like the three previously mentioned ones.

In parallel with this work, TUD (Partner five) performed a survey of existing viscosity models, either semi-empirical but used by the oil and gas industry in its reservoir simulators or derived from the corresponding states principle. Based on this survey, it has been decided to evaluate four viscosity models over wide ranges of high pressures and temperatures (above 5 MPa or 50 bar and 300 K or 27°C).

The tested models are all applicable to both gases and liquids made of pure hydrocarbons and their mixtures. They are:

- the LBC correlation as it is used in many reservoir simulators;
- the corresponding states model CS1 with one reference fluid;
- the corresponding states model CS2 with two reference fluids;
- a viscosity model derived from the Peng-Robinson equation of state (PR-eos).

In order to perform these models evaluation, a data base has been gathered by collecting experimental but recommended viscosity data for 35 pure hydrocarbons and 31 synthetic

mixtures, altogether with few important non-hydrocarbon components such as: water, nitrogen, carbon dioxide and hydrogen sulfide. All these components are generally found in HP-HT reservoir gases which are the main targets of this project.

For pure components, the overall average absolute deviation as defined hereabove (AAD) of the LBC, CS1 and CS2 viscosity models is nearly the same (16-17%). However, for the LBC and CS1 models, the AAD increases with the carbons number of the hydrocarbons.

The PR-eos viscosity model gives the poorest results (AAD ≈ 22%).

The overall conclusion is that the CS2 model is the best existing one for estimating the viscosities of pure hydrocarbons at high temperatures and pressures.

This conclusion holds also for well-defined mixtures, the CS2 model giving the lowest overall AAD (13.3%) when compared to the three other ones (20.2 - 22.3%).

As per the work which has been performed by FEUP (Partner six) in this subtask II.1, it consisted in the evaluation of more theoretical methods proposed in the literature in order to represent the viscosity of fluid mixtures, the main criterion of model selection retained being its predictive character.

As a result of this literature survey, it has been pointed out that available "theoretical" methods were too specific to a given type of application, i.e. limited in the pressure or temperature range or in the nature of the considered phase (either liquid or gaseous). Additionally, no models based on molecular dynamics were found working in the targeted high pressure-high temperature (HP-HT) domain. This literature survey made it possible to identify a number of models based on statistical mechanics showing some potential for their application to HP-HT natural gases. However, this application would actually be possible only after introducing some modifications into the published methods described hereafter.

The models thus selected have been tested using the data collected by IFP, HWU and TFE-UPPA during subtask I.1 as well as by TUD at the start of this subtask II.1. The methods considered are the following:

- for liquid mixtures, the reaction rate theory as applied to viscosity by Eyring and his coworkers coupled with Kanti's correlation previously developed by TFE-UPPA for extending the pressure range up to the high values targeted by the industrial applications of this project;

- for dense gases, the model built by Chung and his coworkers which is based on the Chapman-Enskog viscosity equation which is derived from the kinetic theory of gases.

The qualitative conclusions reached at the end of this evaluation of previously published theoretical models were quantitatively reinforced by the tests carried with the selected methods, i.e. the specificity of each model with regard to the pressure and/or temperature range as well as to the phase identity, and to their high sensitivity to the input data.

These conclusions emphasized the fact that the results of such "predictive" models would only be improved if a large amount of experimental information could be gathered (as performed in subtask I.3, the results of which have been described before).

III.3.2 Task II.2: Development of an innovative approach

In this task, the development and further testing of new viscosity models has been carried on.

TUD (Partner five) thus proposed two new viscosity models, one based on the corresponding states principle with two reference fluids called hereafter NCS2, altogether with another one derived from the friction theory (f-theory).

The new NCS2 model uses as reference fluids methane and either n-hexane or n-decane. The equation used for estimating the reference components viscosity is a function of the density and of the temperature. For estimating the density of the reference fluids, a new equation of state (eos) has been proposed, the Soave modification of the Benedict, Webb and Rubin eos called hereafter SBWR.

This NCS2 model has been tested on 34 pure hydrocarbons, plus carbon dioxide, nitrogen, water and hydrogen sulfide over wide ranges of high pressures and temperatures (above 5 MPa or 50 bar and 300K or 27°C). For light paraffins, the NCS2 method gives a much lower average absolute deviation that the CS2 model while the results are significantly better for heavy paraffins.

For non-hydrocarbon components present in natural gases, predictions have also been found better than with the previously evaluated models in subtask II.1.

However, for hydrocarbon mixtures, the two methods lead to nearly the same results. As no marked improvement has been found, no further work has been carried out with the application of the NCS2 model to hydrocarbon mixtures and a new viscosity theory has been proposed: the f-theory. Below, this new theory is summarized as well as its main results are further presented.

The f-theory is based on the friction concept of classical mechanics coupled with the Van der Waals theory of fluids. The main difference between the new friction theory and other available models is that the viscosity is seen as a mechanical property rather than a transport property.

The viscosity is expressed as the sum of a dilute gas viscosity and a residual friction viscosity connected to Van der Waals repulsive and attractive pressure terms. As a result, a rather simple cubic equation of state can be used as a basis for obtaining highly accurate modeling of the viscosity of fluids from low to extreme high pressures.

This viscosity model, being based on physical assumptions describing the repulsive and attractive parts of intermolecular forces, can in principle be used for all pressures and temperatures. It has been tested on pure normal alkanes from methane to decane with better results than those obtained with all the previously evaluated models (LBC, CS2, PR-eos and NCS2).

The f-theory viscosity model has further been tested on binary paraffinic mixtures with also improved results when compared to other existing models.

Based on these favourable comparisons, as well as on the fact that the friction theory contains realistic physical assumptions, it has been decided to continue all the coming work on this last model.

Therefore a new method has been proposed in this task to calculate the viscosity of a mixture knowing only its composition altogether with the pure components viscosity, the latter being also computed by this model. Moreover this method has the advantage that when applied to the mixture investigated, pseudo-critical properties are not necessary.

The main goal assigned to FEUP (Partner six) for this task is the development of a new "theoretical" viscosity model based on molecular simulation.

The first phase of the work consisted in the evaluation and the validation of computer codes used for the simulation of viscosity phenomena. The convenience of selecting a Lennard-Jones model fluid as a reference for the computation of real fluid viscosities has been further investigated with the aid of the data base elaborated in the previously described tasks.

The Lennard-Jones (LJ) fluid has been retained as it shows a good balance between simplicity and realism. Thus it captures much of the essential physics of real fluids. Another important feature is that a large number of simulation data is available in the literature for the LJ fluids.

For the 39 pure components tested in the reservoir pressure-temperature window defined by [30 ≤ P ≤ 150 MPa ; 50 ≤ T ≤ 200°C], the comparison of predicted viscosity values with experimental data indicates that the average absolute deviation (AAD) is reasonably low when considering that the only input information are just the components critical temperature and pressure.

For improving the quantitative agreement between computed and experimental pure component viscosities, three adjustable parameters have been used for describing the temperature dependency of the Lennard-Jones intermolecular potential parameters (ε and σ) as well as to fit the value of the critical viscosity. These parameters thus allow to reduce the gap between LJ model fluids and real fluids viscosity behaviour. In this case, the AAD range is from 1% to 14% for 6441 data points, with a global average of 4.1% which can be regarded as an overall primary measure of the LJ model performance.

In order to extend this molecular based viscosity model to mixtures, the "one-fluid" approach with conventional quadratic mixing rules for the Lennard-Jones parameters (ε and σ) has been tested with the reference mixture methane-n decane studied in subtask I.2 by the "experimental partners".

The main drawback of straight molecular dynamics (MD) is the huge computation time needed, which is not compatible with the constraints required by industrial needs.

To develop such a model which would overcome the limits of MD simulation but still be based on a microscopic picture of fluids, two analytical relations that represent well MD data obtained for the Lennard-Jones fluid have been used: the Kolafa-Nesbeda equation of state (KN eos) and the Roawlay-Painter viscosity eos (RP eos). The first one relates the LJ intermolecular potential parameters with pressure, temperature and density while the second eos relates the LJ potential parameters with temperature, density and viscosity. It is thus possible to compute viscosity versus temperature, pressure and density.

This computation scheme has finally been applied within this task to a set of mixtures for which the experimental data have been gathered in subtask I.1. Without any specific tuning

with mixtures viscosity data, there is a satisfactory agreement between computed and experimental values for the different binaries tested, as well as for three other synthetic systems (one ternary, one quaternary and one quinary mixture) in large pressure and temperature ranges.

III.3.3 Task II.3: New models validation with synthetic mixtures

During the performance of this subtask, TUD (Partner five) evaluated the capability of the f-theory developed within the previous subtask (II.2) for viscosity predictions of hydrocarbon mixtures over wide pressure and temperature ranges.

By coupling an equation of state (eos) with the viscosity equations deriving from the f-theory, it is possible to accurately predict (i.e. with no specific mixture parameter tuned to represent experimental data) both the density and viscosity of hydrocarbon mixtures.

For liquid mixtures, the following table compares the predicted viscosities with experimental data for the f-theory coupled with either the Soave-Redlich-Kwong eos (f-SRK) or with the Stryjek-Vera-Peng-Robinson eos f-PRSV. The absolute average deviations (AAD), as well as the maximum deviation (MxD), are given for these models altogether with the LBC correlation which has been presented earlier in this report as it is widely used by the oil and gas industry.

Mixture	AAD (%) / MxD (%)		
	f-SRK	f-PRSV	LBC
$nC_5 - nC_8$	3.53 / 11.26	3.42 / 11.18	8.93 / 23.21
$nC_5 - nC_{10}$	3.32 / 14.03	3.57 / 14.10	9.98 / 23.86
$nC_6 - nC_7$	0.53 / 1.03	1.03 / 1.74	5.95 / 16.56
$nC_7 - nC_8$	2.82 / 8.66	2.33 / 8.33	9.34 / 26.80
$nC_7 - nC_9$	0.97 / 2.37	0.67 / 1.70	5.46 / 15.06
$nC_8 - nC_{10}$	2.75 / 7.05	4.31 / 9.57	6.56 / 15.35
$nC_5 - nC_8 - nC_{10}$	4.11 / 18.14	3.77 / 17.54	5.14 / 14.21

From these results, it is obvious that the f-theory developed within this project leads to better performance than the LBC correlation which is classically implemented in industrial simulators.

For methane containing synthetic mixtures, the Soave modification of the Benedict-Webb-Rubin eos (SBWR) has been used in order to compute accurate densities as it is also one of this project targets. The following table shows a comparison of the viscosities thus predicted by the f-theory coupled with the different equations of state mentioned hereabove.

For the sake of comparison, the results obtained for a liquid quaternary mixture are also given.

Mixture	AAD (%)		
	f-SRK	f-PRSV	f-SBWR
C_1 - C_2	6.19	5.55	3.91
C_1 - C_3	2.28	2.37	4.21
C_1 - C_4	3.38	2.55	2.42
C_1 - C_6	4.43	4.27	4.06
C_1 - C_{10}	7.60	6.37	15.75
nC_{10} - nC_{12} - nC_{14} - nC_{16}	1.39	1.63	5.68

As all the viscosities obtained by the three models mentioned in this table are predicted without using an empirical parameter tuned to represented at best experimental data, the results shown can be considered satisfactory.

For highly asymmetric mixtures such as methane-n decane, the fitting of such a parameter reduces the AAD to 5.37% if the f-SBWR model is used.

Finally, the f-theory model has been used to compute synthetic mixtures viscosity for systems studied earlier in this project. In the case of the methane-methylcyclohexane binary investigated by HWU (Partner three), the f-PRSV method gives an AAD of 3.15% for this mixture density and an AAD of 7.98% for its viscosity.

For the ternary system "α methylnaphtalene-n tridecane-heptamethylnonane" experimentally studied by TFE-UPPA (Partner four), the viscosities predicted by the f-PRSV model lead to an absolute average deviation of 4.49% which is extremely satisfactory.

In parallel with this work, FEUP (Partner six) compared predictions obtained with the Lennard-Jones based viscosity model to the experimental data measured by IFP (Partner two), HWU (Partner three) and TFE-UPPA (Partner four) during subtask I.3.

The following table summarizes the obtained results.

Mixture	AAD (%) / MxD (%)
C_1 - n decane	9 / 35
C_1 - methylcyclohexane	18 / 40
C_1 - cis decahydronaphtalene	15 / 36
C_1 - n hexadecane	14 / 64
C_1 - toluene	10 / 23
C_1 - α methylnaphtalene	17 / 37
α methylnaphtalene - n tridecane	14 / 26
n tridecane - heptamethylnonane	7 / 23
α methylnaphtalene - heptamethylnonane	11 /22
ternary made of the last three binaries	13 / 28

This table shows that predictions made with molecular dynamics simulation are reasonably good.

III.4 Task III: Data acquisition on real reservoir HP-HT condensate gases

This task is divided into two subtasks for which the essential results will be emphasized in the following sections. These are subtasks: III.1 "Characterization of typical HP-HT gases" and III.2 "Viscosity and density data for real HP-HT gases".

The three "experimental" partners involved in this task are IFP (Partner two), HWU (Partner three) and TFE-UPPA (Partner four).

III.4.1 Task III.1 Characterization of typical HP-HT gases

TFE-UPPA (Partner four) has sent to IFP (Partner two) two down-hole samples coming from typical North Sea natural gas reservoirs. These samples have been analyzed by gas chromatography according to the CARBURANE procedure. The following table gathers the obtained analytical results altogether with the dew pressure P_D measured at wellhead temperature 50°C, the Gas-Liquid Ratio (GLR) determined for each sample and finally the stock tank condensate density (ρ).

Components	North Sea 1 (NS1)	North Sea 2 (NS2)
	(weight %)	
N_2	0.00	0.72
CO_2	2.59	2.83
C_1	25.25	26.91
C_2	6.29	6.49
C_3	4.77	4.89
C_4	3.84	4.11
C_5	2.81	3.31
C_6	3.04	3.40
C_7	3.76	4.47
C_8	3.80	4.55
C_9	3.07	3.67
C_{10}	3.23	4.03
C_{11}	2.68	2.90
C_{12}	2.42	2.30
C_{13}	2.48	2.61
C_{14}	3.42	2.20
C_{15}	2.54	2.28
C_{16}	2.29	2.06
C_{17}	1.96	1.67
C_{18}	2.50	1.96
C_{19}	1.14	0.91
C_{20}	1.27	1.18
$C_{20}+$	14.85	10.55
TOTAL	**100.00**	**100.00**

Properties	North Sea 1(NS1)	North Sea 2 (NS2)
GLR (std m^3/m^3)	716	810
ρ @ 15°C, Patm. (kg/ m^3)	793	789
P_D @ 50°C (bar)	317	310

HWU (Partner three) has on its side contributed to this subtask III.1 by characterizing three typical North Sea condensate gases HWGCE1, HWGCE2 and GCE00-1. For preparing the first of these, a separator gas sample has been blended with a dead condensate North Sea fluid. Some intermediate hydrocarbons have also been added to the mixture in order to satisfy the required phase and volumetric behaviour. A compositional characterization has been carried on the dead condensate to measure its composition as well as the molecular weight and the specific gravity of its fractions.

The dead condensate composition has been measured by packed-column gas chromatographic analysis. Further the stabilised liquid sample has been fractionated to single carbon group cuts (SCN) by True Boiling Point distillation (TBP). Then the molecular weight of each SCN group has been measured by cryometry using water-saturated benzene as solvent. Finally, the density of the SCN fractions has been determined with an Anton Paar densitometer.

Concerning the PVT characterization, a constant composition expansion (CCE) test has been carried out on the gas condensate both at separator temperature (37.8°C) and at reservoir temperature (100°C). The measured dew pressures are 38.59 MPa (#386 bar) at 37.8°C and 37.82 MPa (#378 bar) at 100°C.

The same characterization procedures have been performed with the synthesized gas condensate sample HWGCE2. The CCE tests have lead to dew pressure values of 37.20 MPa (#372 bar) at 37.8°C and 34.68 MPa (#347 bar) at 100°C. This sample has been prepared from a stabilized North Sea condensate liquid close to the previous one, to which a separator gas and some intermediate hydrocarbons have been added, the latter replacing those components that had been lost from the condensate liquid during weathering. However, the CCE tests have shown that HWGCE2 is leaner than HWGCE1 with a maximum liquid fraction of less than 5% at 100°C while it is approximately 13% for the latter.

For this HWGCE2 sample, a constant volume depletion test (CVD) has also been carried out at 100°C. This test has been mainly designed to simulate in the laboratory this condensate gas phase behaviour during reservoir pressure depletion.

Finally, HWU (Partner three) has characterized a real HP-HT condensate gas provided by TFE-UPPA (Partner four): GCE00-1. This fluid has been sampled at bottom hole conditions of 187°C and 110.5 MPa (1105 bar). After its full compositional characterization according to the procedures described hereabove, its saturation pressure has been measured at various temperatures going from the reservoir value to the separator one.

Fluid GCE00-1		
Pressure (MPa)	Temperature (°C)	Saturation (type)
29.94	50	bubble point
31.06	100	bubble point
31.05	150	dew point
29.94	187	dew point

In parallel with the characterization work performed by IFP (Partner two) and HWU (Partner three), TFE-UPPA (Partner four) has extensively investigated the experimental behaviour of three real HP-HT condensate gases called A, B and C.

The first fluid A is a HP-HT fluid having a dew point pressure (P_D) of 337 bar at reservoir temperature 196°C while the static bottom hole pressure at mean perforation depth is 1130 bar. Its Gas-Liquid Ratio is 1440 std m^3/m^3 and it leads to a maximum condensate deposition of 8% of the reservoir fluid volume at dew point pressure during a constant mass expansion (CME). This CME has been repeated at 100°C and 50°C where the dew pressures are respectively 374 bar and 375 bar. A constant volume depletion has also been carried on this gas at reservoir temperature 196°C.

Regarding fluid B, its dew pressure is 314 bar at reservoir temperature 182°C while the reference bottom hole pressure is 1103 bar. Its GLR is 678 std m^3/m^3 and its maximum condensate deposition reaches 34% of the reservoir fluid volume at P_D during a CME. This CME has also been repeated at 150°C (P_D = 322 bar).

The third HP-HT condensate gas investigated C has a P_D value of 304 bar at reservoir temperature 187°C, the bottom hole pressure being 1105 bar. Its GLR is 664 std m^3/m^3 and it leads to a maximum condensate deposition of 30% of the reservoir fluid volume at dew pressure during a CME. This CME has been repeated at 150°C showing a dew pressure of 311 bar.

All these three real HP-HT condensate gases coming from North Sea have been extensively analysed by gas chromatography following the CARBURANE procedure. Their heavy fraction $C_{11}+$ varies from 2.3 mole % for fluid A up to 5.2% mole for fluid C.

III.4.2 Task III.2: Viscosity and density data for real HP-HT gases

For the two North Sea natural gas samples provided by TFE-UPPA (Partner four) to IFP (Partner two) which have been characterized in the previous subtask by the latter, the following data have been measured within the present subtask.

For NS1, both densities and viscosities have been determined at well head temperature 50°C in the pressure range going from around 40 MPa (400 bar) up to 150 MPa (1500 bar). The data thus obtained are shown in the next table.

North Sea 1 (NS1) @ 50°C		
Pressure (MPa)	Density (kg/m^3)	Viscosity (mPa.s)
40.3	529	0.125
49.8	547	0.131
75.1	579	0.186
100.9	604	0.202
126.3	623	0.238
150.3	639	0.264

The densities of sample NS2 have been measured at three temperatures in approximately the same pressure range. Unfortunately, the viscosities could not be determined as the equipment underwent a very important break-down.

The density data are the following.

North Sea 2 (NS2)			
Pressure (MPa)	Density @ 50°C (kg/m^3)	Density @ 100.3°C (kg/m^3)	Density @ 138.5°C (kg/m^3)
35.1	499	-	-
40.1	-	465	430
50.1	528	488	459
70.1	555	522	498
90.1	575	546	525
110.1	591	566	547
130.1	606	582	565
148.7	623	598	579

HWU (Partner three) has in parallel contributed to this subtask III.2 by measuring the densities and viscosities of samples HWGCE1 as well as HWGCE2 et 50, 100 and 150°C between around 40 MPa up to 140 MPa. Finally, HWU gathered the same type of data for the bottom hole sample provided by TFE-UPPA (Partner four) at 50, 100, 150 and reservoir temperature 187°C in the same pressure range.

On its side, TFE-UPPA has determined the viscosities of the three HP-HT condensate gases previously characterized: A, B and C. These have been measured at 138, 154 and 171°C between 54.5 MPa and 74.5 MPa. Further the data obtained for each sample have been extrapolated to bottom hole conditions: for A -196°C and 113.1 MPa; for B -182°C and 110.3 MPa; for C -187°C and 110.5 MPa.

III.5 Task IV: Model evaluation and validation

This task is divided in two subtasks for which the main results obtained will be underlined in the following sections. These are subtasks: IV.1 "Use of analytical data in viscosity models" and IV.2 "Viscosity model validation with real HP-HT gases".

III.5.1 Task IV.1: Use of analytical data in viscosity models

IFP, HWU, TFE-UPPA and TUD have all experience in reducing analytical data for real reservoir fluids in order to compute their PVT (volumetric and phase behaviour) properties. This experience has lead them to define optimal methodologies for reducing the analytical data measured in subtask III.1 with different "classical" analytical procedures (i.e. Gas Chromatography, True Boiling Point Distillation) for obtaining the compositional vector, and the corresponding pseudo-component properties matrix, to be used with the new viscosity models developed in task II, in order to validate them versus the data measured in subtask III.2.

III.5.2 Task IV.2 Viscosity model validation with real HP-HT gases

Further to the analytical data reduction performed in the previous subtask, the two "modeling" partners have tested the models they have developed earlier with the real fluid data collected both from the literature and within this project.

TUD (Partner five) has first evaluated the friction theory with a range of "conventional" North Sea crudes for which viscosity data were available at reservoir conditions. The average absolute deviation of viscosity predictions is around 15%.

In contrast, the LBC correlation which is normally used in reservoir simulators clearly fails to provide any reasonable viscosity prediction for North Sea crude oils.

Finally, the friction theory approach for viscosity modeling has been extended to HP-HT natural gases which are the main concern of this EVIDENT project. Thus the viscosity of six natural gases experimentally studied here have been predicted and compared to the measured data. It has been found that the obtained average absolute deviations between 1 and 5% are in agreement with the order of magnitude of the experimental uncertainty ($\pm$ 1%). The maximum deviations reaches around 11%. Therefore this project results are satisfactory for most applications related to the oil and gas industry and the f-theory can be considered as a powerful tool in the simulation of the behaviour of reservoir fluids.

Concerning the molecular simulation based model developed by FEUP (Partner six) for a reference Lennard-Jone fluid, it has been tested with a purely paraffinic natural gas. In this case, the viscosity prediction leads to an average absolute deviation of 11% and a maximum deviation of 13%. However, the extension of such a "theoretical model" to reservoir fluids containing components different from normal paraffins is still to be performed in the coming future.

IV. LIST OF DELIVERABLES

IV.1 Reports

Task I.1
- Collection of literature viscosity data for model systems representative of high pressure and high temperature reservoir fluids.
- Evaluation of published and existing data (binary, ternary and synthetic mixtures, real fluids).
- Viscosity data for reservoir fluids.

Task I.2
- Viscosity and density of reference mixture: methane-n decane (60%-40%) at 377.55 K.
- Development of an isobaric transfer falling body viscometer operational up to 140 MPa.

Task I.3
- The viscosity and density of methane-methylcyclohexane and methane-cis decahydronaphtalene binary mixtures (from saturation pressure up to 140 MPa) at 50, 100 and 150°C.
- The viscosity and density of methane-methylcyclohexane binary mixtures (from saturation pressure up to 140 MPa) at 50, 100 and 150°C.
- Viscosity and density measurements of methane-decane binary system.
- Density measurements of methane-toluene binary system.
- Density and viscosity measurements of methane-toluene binary system.
- Density and viscosity measurements of the systems: methane-decane and α methylnaphtalene-n tridecane-heptamethylnonane.

Task II.1
- Evaluation of existing viscosity models.

Task II.2
- Development of an innovative approach.
- Viscosity modeling of hydrocarbon mixtures.
- The friction theory (f-theory) for viscosity modeling.
- Free-volume viscosity model for fluids in the dense and gaseous states.
- Equivalent analytical relationships for the viscosity of model fluids.
- Representation of macroscopic observables through effective molecular level parameters of classical fluids.
- A study of Lennard-Jones equivalent analytical relationships for modeling viscosities.
- One parameter friction theory models for viscosity.
- Recommended viscosity data and models: n-alkanes.

Task II.3
- Accurate density and viscosity modeling of non-polar fluids based on the f-theory and a non-cubic eos.
- Mixture viscosity prediction based on the f-theory.
- Viscosity modeling of the ternary system α methylnaphtalene-n tridecane-heptamethylnonane.

<u>Tasks III.1 and III.2</u>
- Viscosity measurements on two reservoir fluids in HP-HT conditions.
- Data acquisition on model HP-HT fluids. Viscosity and density measurements up to 140 MPa and 150°C.
- Data acquisition on real reservoir condensate gases.
- Data acquisition on real reservoir HP-HT condensate gases.
- Viscosity on real HP-HT fluids.
- Viscosity and density data on two North Sea gas condensate samples at temperatures to 423 K and pressures to 140 MPa.

<u>Task IV.1</u>
- Data acquisition on real reservoir HP-HT condensate gases. Analytical data reduction.

<u>Task IV.2</u>
- Viscosity modeling of characterized reservoir oils with the one parameter friction theory models.
- Viscosity prediction of natural gas using the friction theory.

VI.2 Data base

As a large part of this project has been first to collect and evaluate viscosity data previously published, and next to measure viscosity altogether with density data both for synthetic mixtures as well as for real HP-HT condensate gases, a data base has been built by HWU (Partner three).

This base exists either in a printed format or in a CD version. It contains two sections. The first one gathers all the data measured within this EVIDENT project, the second part proposing a set of recommended/evaluated data for pure normal paraffins from methane to octodecane.

V. COMPARISON OF INITIALLY PLANNED ACTIVITIES AND WORK ACTUALLY ACCOMPLISHED

When considering at this final stage the description of the subtasks in the project programme and comparing it with section III "Scientific and technical description of the results", it appears that there is not any "major deviation" between the two.

The results obtained within this project completely agree "quantitatively" with the initially planned activities.

From a qualitative point of view, the only minor deviation between our initial hopes and the obtained results is that the theoretical model described hereabove, which is based on molecular simulation background, is not presently able to compute the viscosity of any real high pressure-high temperature natural gas in industrial conditions.

Nevertheless, the new semi-empirical model developed within this project has proved to lead to satisfactory results when applied to real reservoir fluids: crude oils and natural gases, both in conventional as well as in HP-HT operating conditions.

VI. MANAGEMENT AND COORDINATION ASPECTS

The communication between the partners has been excellent all over the 4 years of this project. From January 1998 up to June 2001, all the partners had meetings twice a year. At each meeting, every partner described the results obtained during the last semester, then the project technical coordinator would compare the work actually accomplished with the initially planned activities. From this comparison, the project partners established at each meeting, all together, the work programme for the next semester.

During the period between two meetings, a lot of bilateral communication existed by all means available: mail, phone, fax and mainly electronic mail as well as personnel mobility.

Two good illustrations of this human mobility are:

- a senior member of TUD (Partner five) delivered lectures on the newly developed model within this project to IFP (Partner two) staff concerned by viscosity computation;

- a junior member of TUD spent 6 months working on this project with the staff of TFE-UPPA (Partner four).

All the project partners have been highly dedicated to the work planned, however delay in supplying the deliverables (advancement and final reports) occurred because of several problems, mainly:

- high pressure-high temperature equipment breakdown within the labs of the three "experimental" partners (IFP, HWU and TFE-UPPA);

- lack of experience of junior personnel able to handle complex fluids (i.e. natural gases) viscosity computation based on molecular simulation concepts in the labs of the partner in charge of this part of the programme (FEUP).

Nevertheless the "List of Deliverables" given in section IV shows that the results finally obtained are very close, both qualitatively as well as quantitatively, to those expected at the stage of planning this project programme.

Concerning the follow-up of the project, the persons indicated hereafter could be contacted if necessary:

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VII. RESULTS AND CONCLUSIONS

The partners of this project have produced two types of important results.

First of all, a large set of experimental data has been measured and their accuracy evaluated. These data are relative to:

- 6 pure hydrocarbons (C_1, C_2, C_3, C_4, C_5 and C_{10}) ;
- 8 binary mixtures;
- 2 ternary mixtures;
- 3 multicomponent synthetic mixtures:
- 7 real reservoir condensate gases.

Next a new semi-empirical viscosity model based on the friction theory has been proposed. This model has further been evaluated with a range of "conventional" North Sea crudes for which viscosity data were available at reservoir conditions. The average absolute deviation of viscosity predictions is around 15%. In contrast, the Lohrenz-Bray-Clark correlation which is normally used in reservoir simulators clearly fails to provide any reasonable viscosity prediction for North Sea crude oils.

Finally, the viscosity of the real reservoir condensate gases experimentally studied in this project has been computed with this friction theory based model and compared to the measured data. It has been found that the obtained average absolute deviations between 1 and 5% are in agreement with the order of magnitude of the experimental uncertainty ($\pm$ 1%). Therefore this project results are satisfactory for most applications related to the oil and gas industry.

Considering the economical impact of these results, a reservoir performance as measured in terms of the cumulative hydrocarbons production is sensitive to the viscosity of the fluid stream.

For light streams such as the ones which are the target of this project (having a viscosity lower than 0.5 mPa.s), simulation work indicates that a $\pm$ 10% error on computed viscosity will produce an uncertainty of $\pm$ 1-2% on the cumulative hydrocarbons production. In terms of the present oil and gas value, this would correspond to a variation of $\pm$ 75 million Euros on the revenue resulting from the reservoir exploitation. This clearly shows that the improvement brought by the results of this EVIDENT project can be extremely beneficial for the economics of reservoirs exploitation within the European Community.

VIII. ACKNOWLEDGEMENTS

This project has involved in each of its (sub) tasks a relatively large number of researchers:

- Ph.D. Students;
- Post-Doctoral Scientist(s);
- Visiting Scientist(s) and Professor(s);
- (Associate) Professors;
- Lab Technicians;
- Engineers
as well as of:
- Administration and Finance Officers.

The technical coordinator of this project, being the writer of this Final Technical Report, wishes to acknowledge the contribution of all those who have been associated to it during its four years duration.

IX. REFERENCES

The 33 reports quoted hereabove in the "List of Deliverables" section contain a very large number of literature references. Any reader of this Final Technical Report interested by some of these can contact one of the 6 persons mentioned in section IV "Management and Coordination Aspects".