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HEAVY OIL PRODUCTION IN OFFSHORE FIELDS: A TECHNOLOGY DEVELOPMENT PROGRAM DEVISED FOR BRAZIL

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Resumo

As reservas brasileiras de óleo com grau API inferior a 19 são superiores a 11 bilhões de barris, representando 26% do total de reservas provadas. Apesar de ser, atualmente, negligível, estudos prospectivos apontam para a necessidade de que tais óleos participem, até o ano 2010, com 20% no total produzido, para que a relação favorável existente entre demanda/produção seja mantida. Para atender tal situação, o Comitê Tecnológico – CTPetro lançou o Programa de Desenvolvimento Tecnológico para a Produção de Óleo Pesado em Campos Offshore. O objetivo deste Programa é buscar soluções tecnológicas, amparadas por desenvolvimento científico sólido, para superar os desafios relacionados à explotação de reservas de óleo pesado de bacias brasileiras. Sua linha de ação está direcionada para a complementação de esforços corporativos já existentes. Assim, a comunidade científica será o agente primário do Programa, sendo apoiada para assumir os riscos de desenvolvimento de tecnologias inovadoras. O foco, o prazo e os limites das aplicações práticas dos resultados alcançados serão estabelecidos pelas companhias envolvidas. O presente artigo mostra a metodologia usada na elaboração do Programa, a partir da identificação dos desafios das várias áreas da explotação de petróleo, até os projetos priorizados, e as ações de curto e médio prazo estabelecidas para sua execução.

Abstract

The Brazilian reserves of oil exceed 11 billion barrels. Oils with API gravity lower than 19 take a 26% share in the proven volumes. Besides being negligible in Brazil nowadays, prospective studies point out that by 2010 the share of such oils shall be above 20% of the total produced volume. To overcome this situation the Brazilian Committee for Research on Oil and Gas - CTPetro - has launched a Technology Development Program for Heavy Oil Production in Offshore Fields. The program focuses on the search of technological solutions supported by scientific knowledge to overcome the challenges associated with the exploitation of heavy oil reservoirs located offshore Brazil. The line of action of the heavy oil program is to supplement the efforts of corporate programs, seeking to aggregate scientific knowledge in a more sound and systematic way. The academic community, primary agent of the program development, will be supported to assume the greater risks associated with innovative technologies. The focus, the timing and the limits of the practical application of proved techniques will be provided by the interested companies. The present paper presents the methodology used to set up the program, starting from the challenges posed by all branches of the exploitation area, up to the projects and the short to medium-term actions envisioned to tackle them.

1. Introduction

To increase the share of heavy oils in total oil production the Brazilian Sectorial Fund for Research on Oil And Gas - CTPetro - has launched a Technology Development Program for Heavy Oil Production in Offshore Fields. The program focuses on the search of technological solutions supported by scientific knowledge to overcome the challenges associated with the exploitation of heavy oil reservoirs located offshore Brazil. The Brazilian reserves of oil exceed 11 billion barrels. Oils with API gravity lower than 19 take a 26% share in the proved volumes. However, if proper productions techniques are developed in the short to medium-term, reserves already discovered may come to

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incorporate another 4 billion barrels, soaring the heavy oil share to figures above 40%. While in the world the percentage of heavy oils is now slightly over 10% of total production, in Brazil the proportion is negligible. Prospective studies pointed out that by 2010 the desired share of such oils should be around 20% of the total produced volume in order the favorable current scenario of demand/production could be maintained (PROPES, 2004).

Around the world heavy oil reservoirs have generally been produced by applying the same techniques as those in the production of light oil. The predictable consequence is that the remaining resources associated with the conventional oils have an even smaller participation in the available natural energy resources, increasing the importance of those resources associated with heavy oils.

The line of action of the heavy oil program is to supplement the efforts of corporate programs, such as the strategic program launched in 2002 by Petrobras, the Brazilian state-owned oil company, seeking to aggregate scientific knowledge in a more sound and systematic way. The academic community, primary agent of the program development, may consciously assume the greater risks associated with innovative technologies. The focus, the timing and the limits of the practical application of proved techniques will be provided by the interested companies. They will be partners in the program, sharing the management of the program and acting in every project of particular interest.

To accomplish with that, more than 150 people, technical managers from oil companies, from both operators and service companies, from the academic community including universities and research institutes, have been interviewed and convened to identify bottlenecks, to propose prospective solutions and to set the priority for 40 selected projects. The present paper reveals, starting from the challenges posed by all branches of the exploitation area, these projects and the short to medium-term actions envisioned to tackle them.

2. Quoting Oil as Heavy

Looking through the history of oil industry one finds that the so-called light or conventional oils dominated the production scenario. The reasons are clearly perceived: light oils are technically easier to be produced, at a lower cost, and their refining yield greater proportions of value-added products like LPG, gasoline, kerosene and diesel. It is also true that heavy oil reserves have been found when, in reality, light oil beds were sought for (Dawe, 2002).

The definition of heavy oil has not been standardized in the industry, in the scientific community, or in the government agencies. In fact, companies and agencies haves their own definition criterion, which account for the business opportunities they have and the technological difficulties they face in such opportunities. As it is usual in industry, if the challenges in processing, from exploration to refining, are a standpoint for analysis, the hydrocarbon might be classified as heavy oil according three main properties: specific gravity, viscosity and sulfur content. The World Petroleum Conference classifies heavy oil as those showing a relative specific gravity above 0.920 - equivalent to 22.3 degrees API. The American Petroleum Institute adopts the definition of heavy oil as being that with relative specific gravity equal to or smaller than 20 degrees API. The North American taxation system has similar criterion, although relating the specific gravity to the reference temperature of 60º F. In Brazil, the ANP (Brazilian National Petroleum Agency) adopts the relative specific gravity as the criterion, setting a range between 10º API and 22º API; those oils with relative specific gravity lower than 10º API are classified as extra-heavy.

Viscosity is also a very substantial criterion for oil characterization. Regarding the processes of fluid transportation, viscosity is a more important property than the specific gravity. If the production takes place in low temperature environments, as in off-shore fields, this is particularly true. For these reasons, some specialists classify as heavy those oils having viscosity between 100 cP and 10,000 cP, in the standard conditions of pressure and surface temperature. Others, focusing on reserves and recovery factor, prefer to tie in the viscosity to pressure and temperature at the reservoir. In this case, a range from 10 cP to 100 cP, keeping within round numbers, is quite referred.

The sulfur content a hydrocarbon holds is another criterion for heavy oil classification: the usual threshold is set to 2% in mass. However, it is important to mention that certain heavy oil may not always simultaneously attain these three properties, specific gravity, viscosity and sulfur content, to be characterized as heavy. Besides, neither viscosity nor sulfur content has a straightforward relationship with specific gravity, nor the former properties among them. The properties of oils from different fields around reveal that, for a given specific gravity, viscosities may usually vary up to two orders of magnitude. Thus, a strict and common worldwide definition of heavy oils does not exist. Nevertheless but, for the purposes intended by a program aimed at overcoming technological challenges, heavy oils are understood as:

- those having specific gravity high enough to cause refining problems in the existing plants;
- also, those with viscosities high enough to bring about productivity problems as they flow through the reservoir and along the well, pipelines and equipment, towards the pre-processing plant over the platform.

Problems, as herein stated, refer to any phenomena that go beyond the limits of the knowledge applied to the current oil production and processing practices, requiring investments in science and technology.

After such remarks, the preference is to adopt, only as major guidelines for the purposes of devising a technology development program to advance knowledge on heavy oil production, the range of relative specific gravity from 10 to 22º API and the range of viscosity from 100 to 10000 cP, both referred to surface pressure and temperature conditions, to classify an oil as a heavy oil.

3. World Resources of Heavy Oil

When heavy oil reservoirs are produced, techniques typical in light oil production are mostly used. Adding to this the fact that light oils have dominated the production scenario, such a strategy has lead to an increasing participation of heavy oils among the natural energy resources available to mankind. In turn, heavy oil production is gaining an ever increasing importance in recent years. Although it is very difficult to obtain a definitive and reliable volume regarding heavy oil resources, due to the lack of a common classifying standard and due to divergences between reserve reports and databases published by countries and international agencies, there is a consensus among specialists that earth's resources of heavy oils, extra-heavy oils, and bitumen go beyond 6 trillion barrels (Butler, 1991). This volume is about three times as large as the known resources of conventional oil, approximately a half of whose reserves has already been produced. It shall be stressed that this huge volume also includes the extra-heavy oils (°API <10) and bitumen (viscosity > 10.000 cp), which are even more difficult to produce and refine than heavy oils.

A recent study carried out by the U.S. Geological Survey (Meyer, 2003) points out the existence of an estimate 434-billion-barrel reserve of heavy and extra-heavy oils. The reserve concept takes into account the technical feasibility of hydrocarbon production, or recovery factor. The geographical distribution of such reserves and the recovery factors assumed as average per area is shown in Table 1:

Table 1: Geographical Distribution of Heavy Oil Reserves

Region	Recovery Factor	Reserves (billion barrels)
North America	0.19	35.3
South America	0.13	265.7
Africa	0.18	7.2
Europe	0.15	4.9
Middle East	0.12	78.2
Asia	0.14	29.6
Russia	0.13	13.4
Total		434.3

It is worth noting in these data the low values assigned to the recovery factor. This implies in extremely high “in situ” oil volumes, pointing out to the necessity of advancements in recovery techniques. Also, it highlights the outstanding participation of South America, exceeding 50%, due to the huge known volumes of heavy oil in Venezuela.

In spite of the huge world reserves, the production of heavy oil accounted for only 3 billion barrels, out of a total 25 billion barrels produced in the year 2000, a mere 12%. It is known that about two thirds of the current production of heavy oils is formed by oils lighter than 15°API, whilst half of the reserves is formed by oils with specific gravity bellow that value.

4. Heavy Oil in Brazil

The Brazilian proved reserves of petroleum were, by the end of 2004, about 11 billion barrels. The reserves of heavy oils were 2.9 billion barrels, a 26% share. Additional 4 billion of barrels might be immediately added if already discovered resources would become technically and economically feasible. In other words, the medium-term perspective is that heavy oils attain a 40% share of Brazil's proved reserves. Additionally, there is a proved "in place" volume of 2 billion barrels of heavy oil in the carbonate layers of Campos Basin's Membro Siri. In the carbonates, the absence of the phenomenon of simultaneous sand production may be seen as an advantage from the point of view of well completion. However, there are production challenges due to the lower permeability of the carbonate formations (Capeleiro et al, 2003).

In terms of production, the current share of heavy oils is negligible. They include only a few low-production on-shore fields and a pioneering offshore site in Jubarte field, also part of Campos Basin. Prospective studies pointed out that by 2010 the desired share of such oils should be around 20% of the total produced volume in order to maintain the favorable current domestic demand/production figures (Minami et al, 2003). There are projects underway directed towards this goal and such a Technology Development Program for Heavy Oil Production in Offshore Fields will support them.

5. Stressing Heavy Oil Characteristics

Specific Gravity. Heavy oils are, basically, composed of hydrocarbons with a high molecular weight, which give them a high relative specific gravity. Intricate molecules, typically with more than 15 carbon atoms in the chain, will have an impact on refining. The refining processes become more complex and require more energy for obtaining high-consumption products such as LPG, gasoline, kerosene and diesel. The higher the specific gravity, the lower the is the value of the distillation yield, because the higher is the retention of such low-value products as fuel oil, coke and asphalt. Specific gravity also means higher contents of such undesired products as asphaltenes, sulfur and metallic components like nickel and vanadium.

Gas-Oil Ratio. Heavy oil reservoirs are low-density energy beds. There are a number of facts to consider leading to this conclusion: the lighter molecules, which make up the light fractions, as properly termed, and the gas are in small proportions; the volumetric compressibility of the light fractions is comparatively larger; the compressibility of gas is typically one to two orders of magnitude higher than that of the oil under the reservoir conditions, pressure and temperature. The result is, therefore, that the self-contained energy of the reservoir is mainly due to the amount of gas it holds, either in the form of free gas or as gas dissolved in oil. In other words, the small content of light fractions in the heavy oils implies in a reservoir with low density of energy, which causes low recovery factors and low productivity rates.

Viscosity. Although there is no straightforward relationship between specific gravity and viscosity, heavy oils usually are highly viscous. As viscosity plays a critical role in fluid transportation, many specialists prefer to establish it as the main property when classifying the crude oils. As viscosity increases, also increases the amount of energy needed to drive the lift process. More powerful pumps, “gas-lift” processes requiring higher pressure and flow rates are needed to carry the oil along the flow lines. It should be stressed that the relationship between viscosity of liquid hydrocarbons and temperature is of an exponential nature. This sets additional challenges when production takes place in harsh environments, as is the case in Campos Basin's fields, where the temperature at the bottom of the sea reaches 4 ºC (Haney, 2003). In regard to the reservoir, the lower oil mobility is due to the higher viscosity, which also causes low recovery factors and low productivity rates. Furthermore, producing viscous oils frequently causes substantial changes in the liquid production profile (water and oil) along the field lifetime, as in the volume of water to be processed, re-injected or disposed.

Emulsion Formation. The formation of stable emulsions of water and oil is a phenomenon frequently found in the production of heavy oils. Emulsion is formed during simultaneous flow of oil and water, although it is also supposed to occur while still in the reservoir. The flow of the mixture of liquids through devices and equipments that impose a high shear rate, such as in pumps and valves, in pipe singularities and even along lines, will induce emulsion formation. Gas and solid particulates are additional factors to increase the shear rate, intensifying emulsification (Harden and Dawne, 1997). Emulsification is a dynamic process, subject to instantaneous local flow conditions and thus to operational conditions that may change along the period the well is producing. Shear rate is a strong factor in emulsion formation, but rheology and fluid properties also play important roles. In short, emulsion formation is indeed a retro-feeding process.

The heavy oil tendency to forming foam is also to be taken into account during the release of dissolved gas, in a type of gas and liquid *limiting compressible emulsion*. All such characteristics will not only influence the flow in the reservoir, wellbore and flowlines, but will also have an impact on other vital processes, such as separation and metering.

Acidity Heavy oils found in offshore fields have in common a high content of organic acidity. The acidity rate, measured by TAN (Total Organic Acid Content), is particularly important to refining processes. Nowadays, few refineries in the world are prepared to receive such oils, with that high acidity level. In fact, the price spread at the oil market is mainly due to this characteristic. Also, the high concentration of organic acids is mentioned to contribute to the precipitation of organo-metallic salts, causing buildups in processing equipment.

Reservoir. Heavy oils, especially those formed by bio-degradation, are found in shallow reservoirs, formed by unconsolidated sands. This characteristic, which brings about difficulties during well drilling and completion operations, may become a production advantage due to a higher permeability (Wehunt, 2003). In many heavy oil reservoirs, especially those with thick sediment layer or great inclination angle and high vertical permeability, an oil compositional segregation will occur. It causes heavier components to stay in the lower portions of the bedrock, according to their specific gravity. Therefore, the difference in the oil specific gravity may reach several degrees API along the depth of the reservoir. This is intensified at the bottom of the reservoir, near the oil-water interface, where bitumen and tar mats have been frequently found.

The overlap of these various heavy oil intrinsic characteristics with typical phenomena in production and processing operations results in scientific and technological challenges yet to be overcome. A possible and immediate approach to be adopted is the extension to heavy oil production, when feasible, of the already established scientific and technological knowledge gained with productions of light oil. Clearly, this line of action will not fulfill in full extension the posed challenges, leaving lacks of coverage, representativiness and reliability in the extended models, although some level of predictability may be achieved. A second and desirable approach is the establishment of a medium to long term research through a scientific and technological development program capable of supporting appropriate, efficient practices that privilege the cost-effectiveness of heavy oil production process in the "offshore" environment. This is compatible with the growing importance this resource is achieving in the scenario of natural energy reserves on Earth.

6. Challenges

The challenges posed by heavy oil exploitation have been classified according the traditional areas of technical activities. They refer to reservoir, wellbore, flow assurance, flow measurement, artificial lift, separation, and characterization. Within these areas more than 40 projects have been identified and ordered, attending criteria like urgency, impact, risk and resource availability. To accomplish with that, more than 150 people, technical managers from oil companies, from both operators and service companies, from the academic community, including universities and research institutes, have been interviewed and convened to identify bottlenecks, to propose prospective solutions and to set priorities, having as start-point the challenges in all branches of the exploitation area. The focus, the timing and the limits of the practical application of proved techniques will be provided by the interested companies. The duty of the academic community will be to overcome the challenges seeking to aggregate scientific knowledge in a coordinated action, focusing on the most imperative demands from the industry, in accordance with the federal planning for the oil sector and the limits of the economic resources made available by the government agencies. Thus, they may consciously assume all large risks related to the work with innovative technologies but, in turn, will be deeply involved in the production and transfer of highly demanded state-of-the-art technology. Industry and academic community will be partners in the program, sharing the management of the program and acting in every project of particular interest. The full version of the report details these projects and the short to medium-term actions envisioned to tackle them.

Reservoir

The portfolio of actions related with reservoir includes:

Thermodynamic Behavior

>> To study the characteristics of the thermodynamic behavior of heavy oils, focusing on the development of correlations for PVT properties and on the development of models for off-equilibrium behavior

Flow Properties in the Formation

>> To study the characteristics and rheological properties of live oil and its potential emulsions with gas, focusing on flow conditions inside the reservoir rock.

Primary Production Mechanisms

>> To develop models for reservoir phenomena associated with the depletion of heavy oils, with main focus on gas entrapment, gravitational flow, and changes to permeability after altering the structure of the porous medium.

Water injection

>> The focuses are two-fold: technical challenges of water injection in heavy oil offshore fields and produced water reconditioning for re-injection and disposal.

Improved Recovery

>> To develop theoretical and experimental models on improved recovery methods applied to offshore heavy oil reservoirs. It is initially proposed that the focus be directed to air injection and its novel techniques, and to steam injection with bottomhole generation.

Wellbore

In this portfolio, priorities are:

Wellbore Stability

>> To develop geomechanical models to anticipate the behavior of heavy oil bearing formations in the limits of the pressure gradients involved in the construction of wells with long horizontal extensions - exceeding 1000m and in thin sediment layers.

Drilling and Completion Fluids

>> Development of fluids appropriate to the construction of wells with long horizontal stretches, with tight gravity and viscosity restrictions.

Drilling Hydraulics

>> To study models for describing the hydraulic behavior of the column-fluid-wellbore-gravel system during the drilling of long horizontal extensions.

Sand Migration

>> To develop descriptive models for sand displacement aimed at production control.

Damage removal

>> To develop techniques and products to remove damages to the formation caused by fluids during drilling and completion operations in horizontal wells.

Well evaluation

>> Development of pressure, temperature and flow rate sensors for bottomhole monitoring during well operations.

<u>Flow Assurance</u>

The focus is on flow characteristics in wellbores, equipment and flowlines.

Phase arrangements in multi-phase flows

>> To generate flow maps for multiphase heavy-oil-flow phase arrangements.

Mechanistic models and correlations in multiphase flows

>> To obtain specific correlations for heavy oil flows. Develop phenomenological models to forecast hold-up and head loss for heavy oils.

Properties of water assisted flow

>> To develop specific correlations for water assisted heavy oil flows: head loss, "hold-up", and criteria for emulsion formation.

Hydrate formation in lines with production transients

>> To formulate objective criteria for identifying hydrate formation in lines under transients.

Heat transfer in submerged lines

>> To scrutiny the heat transfer processes in flow lines and pipelines, under steady-state and shutdown conditions.

Emulsion formation: influence of shear rate

>> To quantify the influence of the shear rate on the formation of water-oil emulsions in heavy oils.

Drag reduction in single and multiphase flows

>> Development of drag reduction additives for heavy oil single and multiphase flows.

<u>Metering</u>

In this portfolio the projects deal with conventional meters and new instrumentation techniques.

Uncertainties of conventional meters

>> To quantify the uncertainty of conventional oil flow rate meters when used in the measurement of heavy oil.

Scale effect on conventional meters

>> To define and quantify parameters to represent size-scale variation in the propagation of measurement uncertainties of flow rate meters applied to heavy oil.

Application of ultrasound meters

>> To develop ultrasound techniques for the measurement of fluid and flow rate characteristics in heavy oil lines.

Multi-phase measurement techniques

>> To access the uncertainty of multi-phase flow meters operating with heavy oil.

Sampling techniques in multi-phase flow lines

>>To develop sampling procedures in heavy oil production lines.

<u>Artificial Lift</u>

Artificial lift projects for offshore production include:

Effects of dimensional scale and viscosity on BCSs performance

>> To study the BCSs performance correction curves for scale and viscosity changes.

General models for the performance of BCSs operating with very viscous fluids

>> To develop a generalizing model to anticipate the performance of BCSs operation.

Novel artificial lift equipment

>> To develop models to anticipate the use of new artificial lift equipment (multi-phase pump, HSPs,).

Mixtures by jet-pumps

>> To characterize mixtures generated by *jet-pumps* injectors (water or gas as the *driving fluid*).

Separation

The focus will be on the use of moderate and intense centrifugal fields to promote phase separation.

Operational range of centrifuges

>> To establish the operational limits for centrifuges used with multi-phase mixture of heavy oil and water.

Centrifuges of simple geometries

>> To analyze multi-phase centrifuges of simple geometry for application to solid-liquid-gas-particulate separation.

Dispersion under centrifugal fields

>> To evaluate numerical models for simulating disperse systems under the action of centrifugal field.

Particulates role in centrifugal splitters

>> To study the effect of solid particulates in the lifetime and performance of centrifuges.

Characterization

Portfolio is targeted on physical and chemical properties of heavy oil and its mixtures.

Heavy oil emulsions

>> To establish an accurate, reliable and fast method to characterize heavy oil emulsions.

Hydrodynamics of dispersed systems

>> To model the behavior of two-phase oil-water mixtures when flowing in pipelines and complex geometries.

Micro-distillation method for TBP determination

>> To develop a method by using distillers with capacity from 100 ml to 1 liter applied to heavy oils.

Adjustments of TBP methods for heavy oils

>> To adjust the existing methods for TBP curve determination, with focus on heavy oils.

Extension of TBP curve and characterization of heavy fractions

>> The objectives are multifold, including the definition of a new method to render the TBP curve extended up to at least 700^{o}C and he establishment of processing strategies for different heavy oils.

De-asphalting for characterization of ultra-heavy residues

>> To develop an experimental method to extract components from ultra-heavy oil residues, accomplish the characterization of the obtained residue and evaluate the use of such residue to produce asphalt.

Precipitation of heavy oil fractions

>> To model the precipitation of heavy oil components and develop mechanisms to deal with it.

Compatibility of mixtures

>> To survey the stability and compatibility indexes of Brazilian oil streams.

7. Final Remarks - Program Management

Management of a program for technology development such comprehensive and complex as the one proposed herein involves much planning, leading initiatives, efforts for plenty of communication between agents of diverse cultures and interests among academia, service companies and operators. The manager must be of such a profile to align and maintain aligned the various components of the program to the objectives posted. And at the same time implement coordinated actions in order to take advantage of the synergy between the different developments, this been one of the reasons for proposing the identified projects as a program. Given the diversity of the agents involved and the multitude of disciplines and subjects of the projects, it is recommended the program to be managed at its top level by a collegiate of few members, picked among the leading agents directly involved with the actions of the program.

The superior collegiate, or simply Board, should be attributed to planning the main actions of the program, to propose the criteria for the selection of the best projects along the development lines of the program, to state the targets to be reached within the time frame for such developments, to timely evaluate and revise performance of project developers.

In order to carry forward all the actions needed in the program regarding its implementation, setting up communications, building means for the continue follow up and evaluation it is wise to count on the existence of a full-time executive. Such role should be for a professional in administration, preferably with experience in technology management.

The projects themselves tend to behave like a self-sufficient entity, after coming out as specific initiatives to

answer for particular challenges, for having targets ands deadlines to meet and for being assigned to bilateral contracts. Therefore, it is important to devise formal links between each particular contract and the program as a whole, otherwise the program ends up as a mere collection of individual projects. The adequate way of establishing links between the projects ant the parent program is to formalize the managerial instance of the management Board and the Executive Manager in the contract, along with rights and duties of the project with respect to the program. Especially the ones related to performance evaluation, technical data and information sharing, technical and financial reporting, communication with peer projects and participation in workshops and technical events of the program.
Similarly to regular research contracts, each contract shall be managed by an executor, who is responsible for the due course of the technology development set forth in its terms. Some projects may involve the interest of various partners, being them from companies or from universities and research institutions. In these cases a multi-client contract shall be considered and the structure management shall include the figure of a Technical Board formed by representatives of the involved partners. Functionality of this Board is left to discretion of the partners in the project, once respected the main rules set for the program the project belongs to.

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