SOFTWARE CEMENT PLANNING EVOLUTION AND ITS APPLICATIONS

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INTRODUCTION

Currently several cementing simulators are available on the market. Essentially, most of them are able to simulate the cementing job from an hydraulic point of view. So, phenomena such as pressure losses in the hydraulic cementing circuit, U tube effect and, sometimes, pore and fracture gradients are calculated and checked. The most important and sensitive variables on which the simulators base the calculations are pump rates and stand off (eccentricity of the casing in the hole).

Besides, these simulators are difficult to be used in order to plan a cementing job due to the complexity of the software and the numerous and, sometimes difficulty available, input data. So, much often cementing operations are not planned in details much time in advance. Infact, input data such as well temperature, pore and fracture gradients, top of cement are known, from electrical logs, only few days before to perform the job and consequently people on the rig can not have useful data on time to perform simulations of the job to be carried out. Besides, when all the input data are available, there is too short time to run the simulator in order to determine all the parameters needed to perform the job. In this way the calculations done before to carry out the job are reduced simply to the calculation of the most important parameters such as volume and the types of the required additives and by a check of the gradients with a roughly estimation of the pressure losses.

Since last year the ENI/Agip Drilling and Completion Department started to develop a cementing simulator running on workstation. This simulator is included in the software package called IWIS developed in house. This software tries to satisfy all the above requirements, trying to solve operational needs such as calculation rapidity and easiness to input data and use the output data. Infact, the way the software has been conceived is to provide a practical tool to support the primary cementing, helping to choose the type of the cementing job to be performed, single or double stage, and giving the pressure distribution of the slurries along the wellbore wall. Furthermore operational parameters such as top cement of the various stages and slurry densities can be calculated and optimised.

The procedure to follow, in order to get a final cementing program as close to the field condition as possible, consists of several steps and can be summarise as follow. Firstly, the simulator is run using all the theoretical input data (coming from the well program) in order to properly design the slurry (top of cement, density and viscosity) and plan the job (pump rate and stand off) giving a first hand approximation of the job to be carried out. Critical parameter such as gas risk migration is checked and the calculation of the required tickening time and the characteristics of the slurry such as fluid loss, compressive strength and viscosity are done.

Later, when the report of the final slurry design is available, the slurry data are sent to the cementing company labs in order to verify the characteristics of the designed slurry. Then, based on the values from cementing company labs test, that should be as close as possible to the theoretical data, the simulator is re-run determining the needed slurry volume and additives and delivering the final reports.

Then, when all the data of the drilled section are available and before to run the casings into the well the simulator is rerun for a third time, permitting the evaluation and the choice of the cementing parameters to be used for the cementing job as close as possible to the field conditions.

After the job has been done, the simulator is run for a fourth time for a post job analysis, making a comparison between calculated and field data recorded during the performed cementation.

Nevertheless, situations in which is not possible to apply this job procedure sometimes could arise. In fact, in remote area, such as drilling in the desert, in the forest and in other very harsh and extreme environment where the communications between headquarter and the rig site could be very difficult, the cementing job must be performed in the best way as well without having recourse to the procedure reported in this paper based on simulator calculation and lab test. In this way a very practical cementing procedure has been developed in order to exploit at the best the performances of the cementing hydraulic circuit without the use of sophisticated simulator and lab test. The maximum displacement pump rate and the maximum available surface pump pressure are quickly calculated on the rig by means of easy calculations and the efficiency of the displacement is ensured as well.

This procedure has been reported and thoroughly discussed in literature [1-4] and should be used when other means of calculations of the operational parameters are not available on the rig site.

HARDWARE EQUIPMENT AND PROGRAM MODULES

The simulator works on workstation HP 9000, model 700, HP-UX 10.20, using the package CA-OpenROAD developed for the DB Ingres of the Associates Computer.

Presently, a new version of the simulator working on PC using Windows 95/NT is under development.

Basic concept in the development of this software is to supply to the drilling engineers working in the districts and the people operating on the rig a practical tool for designing and planning a cementing job that is as user friendly and integrated as possible.

Reasons for a practical, user friendly and integrated cementing program are the following:

- **Practical**. The user, after the data input, can have an immediate answer on the choices done: infact, the software performs a primary analysis of the most important parameters calculating the slurry volumes, the thickening time, the index of the gas flow potential and the hydrostatic pressure reduction. All these data are delivered for a first hand evaluation of the cementing job.
- **User friendly**. The user can work with an interface windows like: mouse and keyboard, menus and/or buttons, help on line of the program performances, check and validation of the input data from the user (i. e. the program does not permit a top of cement greater than the bottom hole depth) can be utilised or done in the same way such as a Personal Computer.
- **Integrated.** The program can interact with IWIS (Integrated Well Information System) database: IWIS consists of a group of engineering software such as **Well Plan** for cluster and well design and definition of the well trajectory; **Cascade** for casing design; **Hydraulics** for the calculation of the drilling fluid hydraulic; **Overpress** for the prediction of the formation gradients using seismic data and also the prediction of overpressured formations. All these programs are interacting using the same data base (DB). In this way, the user has the possibility, while designing and planning a cementing job, to restore the useful data, already saved in the DB from other applications: casing, drilling mud and gradients data. The program allows either the display and the use of the data or the input of new data recalling the relevant windows without going out from the program. However before this action, the user must already have created the cluster and the well, using the program called **Well Plan**. Once the input data has terminated the user has the possibility to save all the data in the IWIS DB.

The cementing program groups together several modules following a logical sequence of the work.
Figure 1 shows the IWIS DB configuration and the data flow of the cementing simulator.
The logical sequence developed consists of the following items:

Cementing decision support. This is the starting module that is run with a double click on the icon "cementing" of the IWIS menu; firstly, in this module the user have to choice the type of the workstation and the relevant database to connect. Infact, it is possible work on a remote host, e. g. make a cementing project on a well of the Ortona district. Then, it is possible to choice the cluster from the list of the selected database and the well from the list of the wells (of the chosen cluster). The lists are automatically displayed on sequence; once defined the well, the user has to choice the size of the casing to be cemented. All these sequential actions are guided, while inputting the data, from the program with simple help video messages.

Volumes calculation. This module is run selecting "Modules - Volumes calculation" from the menu bar of the previous module. The user has to input the top of cement and, if needed, also the target(s) depth and the percentage of the slurry volume excess. Then, the program calculates all the relevant volumes such as open hole volume, cased hole volume, shoe joint volume and total volume for any scenario chosen from the user: conventional cementing or with stinger, single stage or two stages.
Also the program includes the cementing of a liner and a tie back both for on-shore and off-shore wells.
Selecting from the menu bar "File - Load from DB" the user has the possibility to load and work with data of a previous saved project.

Primary slurry design. This module is run selecting "Modules - Primary slurry design" from the menu bar of the previous module. The user has to input the percentages and the densities of the lead and tail slurries in the case of single or double stages. If needed, the user can also input the type, density and volume of the spacer; the program calculates automatically the top of the spacer and, upon the choice of the user, performs the static check of the hydrostatic pressure against fracture gradient at the shoe, the analysis of the gas risk by means the calculation of the index of the gas flow potential and the hydrostatic pressure reduction.

Detailed slurry design. This module is run selecting "Modules - Detailed slurry design" from the menu bar of the module "Primary slurry design". The program suggests some default values of the slurry yield and of the mixing fluid in function of the density and the slurries input in the previous modules, calculating automatically the quantity of the cement and the volume of the mixing fluid. However, all the default values can be modified by the user and the program calculates the output data based on the user data.

Displacement. This module is run selecting "Modules - Displacement calculation" from the menu bar of the module "Primary slurry design". The program calculates the volume of the mud to pump into the well, the total displacement, the final pressure displacement and, upon the input of the displacement pump rate, the time for the displacement. All these data are calculated for all the possible scenario: cementing with stinger or conventional, cementing of a casing, liner or tie back.

Final slurry design and Outputs. This module is run selecting "Modules - Final slurry design and Outputs" from the menu bar of the module "Primary slurry design". This is a summary module where both all the restored data from the database and all the input data from the user in the previous modules are displayed.

The user can also input the fluid loss data, rheology, compressive strength, liquid and powder additives or accept the default data suggested from the system. Selecting from the bar of the menu "File - Save into DB" the user has the possibility to save in database the cementing project located by the code composed by the diameter of the cementing casing plus the string typed by the user in the entry field "Cementing program id.".

Finally, the user has the possibility to print out a first hand report to send to the cementing labs company for the check of the slurry design and, once got the feedback from the labs company and re-input the data, the user can print out the final reports of the cementing program.

DATA PROCESSING AND RESULTS

Once selecting the cluster, the well and the characteristics of the casing to be cemented, the software follows the same philosophy, in restoring the remaining needed data to run the simulator, seen above for the DataBase. Two groups of data are needed in order to perform the calculations for designing and planning the job. They are the following:

- **Gradients data**. The main priority is given to the gradients data saved in DB by the CASCADE application; in the case these gradients are not found the program, automatically, searches for the possible gradients saved by the application SEISMIC OVP or previously manually input by the user. In any case, the reference depths for the search of the gradients data are the following:
  - ⇒ the reference depth to be considered for fracture gradient is the casing shoe depth
  - ⇒ the reference depth to be considered for pore gradient is the depth input by the user where the gas risk test is wanted to be performed

  Anyway, in the case of lack of restoring from the gradients DB, the user has the possibility to input manually the gradient data at the desired depth by means the window of gradients data input of the IWIS DB.

- **Mud characteristics data**. The main priority is for mud data saved in the HYDRAULICS application DB; if there is no data stored in the DB, the program searches for possible mud data previously input by the user. In any case the mud characteristics present at the bottom of the section while drilling are restored. In the case of lack of restoring from the DB the user has the possibility to input the actual field mud using the window of mud data input of the IWIS DB.

The above gradients and mud data are used to run the simulator and also in order to perform a primary analysis, doing the following calculations:

1. **Static check calculation**. This calculation is made in order to check the balance of the static pressures in the annular section after the cementing job has been performed. The difference between the hydrostatic and the fracture pressure at the casing shoe, Π, is given by the following expression:

$$\Pi = P_{hydr} - P_{fract} \quad (1)$$

having set:

$$\mathrm{P_{hydr}} = g_{\mathrm{slurry}} \cdot \mathrm{H_{slurry}} + g_{\mathrm{mud}} \cdot \mathrm{H_{mud}} + g_{\mathrm{spacer}} \cdot \mathrm{H_{spacer}} \quad (2)$$

$$P_{fract} = \frac{\left(G_F \cdot H_{shoe}\right)}{10} \quad (3)$$

where has been set:

γ_{slurry}	=	slurry density
H_{slurry}	=	height of the slurry column (up to the top cement)
γ_{mud}	=	mud density
H_{mud}	=	height of the mud column
γ_{spacer}	=	spacer density
H_{spacer}	=	height of the spacer
G_F	=	fracture gradient at the shoe
H_{shoe}	=	casing shoe depth

In the case Π has positive values a possible formation fracturing at the casing shoe can arise.

2. **Gas risk analysis**. The possibility to have a gas flow in the annulus is investigated doing two separate check. The gas risk analysis is performed by means the calculation of the gas flow potential index, GFP, and the reduction of the hydrostatic head due to developed gel, ΔP.

The **gas flow potential** is given by a dimensionless number that represents the probability to have a potential gas flow. This parameter is given by the following expression:

$$\mathrm{GFP} = 1.67\ \frac{\mathrm{L}}{\mathrm{OBP}\left(\mathrm{D} - \mathrm{d_e}\right)} \quad (4)$$

where has been set:

L	=	height of cement column, ft
D	=	average diameter of the hole, in
de	=	outside diameter of the casing, in
OBP	=	initial overbalance pressure (initial hydrostatic pressure with cement place - gas zone pressure), psi

GFP factor can vary between 0 and infinity and the evaluation is based on the premise that gas flow in the cemented annulus occurs via percolation through the cement slurry, and the gel strength development can arrest the invasion.

The above equation (4) is infact a modified version of the standard shear stress equation used to calculate the pressure required to break circulation. The technique assumes that a static gel strength of 500 $lb/100{\cdot}ft^2$ (240 Pa) indicates sufficient resistance to the macroscopic shear forces developed by migrating gas bubbles.

Table 1 shows the level of probability (GFP severity) to get a potential gas flow in the annulus against the calculated GFP. In the same table is also reported the suggested type of slurry to be used in function of the determinated GFP severity condition.

GFP	GFP severity	slurry type
0 ÷ 2	null	normal slurry
2 ÷ 4	low	low-water loss
4 ÷ 7	medium	delayed gel gas block thixotropic slurry
7 ÷ 10	high	gas block
10 ÷ 14	very high	gas block special gas block

Table 1

The **reduction of hydrostatic head** due to the cement slurry gel strength development, fluid loss volume, volume reduction because of hydration and the slurry compressibility factor is estimated by empirical method and predicted by the following expression:

$$\Delta P = \frac{(SGS \cdot L)}{300(D - d_e)} \qquad (5)$$

where has been set:

ΔP = hydrostatic pressure change across column length, psi
SGS = Static Gel Strength, $lb/100 \cdot ft^2$
L = height of the cement column, ft
D = average diameter of hole, in
d_e = outside diameter of the casing, in

The equation (5) can be rewritten in function of the fluid loss and hydration reduction volumes and the slurry compressibility factor in this way:

$$\Delta P = \frac{(FLVR + HVR)}{CF} \qquad (6)$$

where has been set:

FLVR = fluid loss volume reduction
HVR = hydration volume reduction
CF = slurry compressibility factor, psi^{-1}

Table 2 reports the SGS values against the head and tail slurry densities.

head slurry density [SG]		SGS [$lb/100 \cdot ft^2$]
from	to	
1.40	1.65	50
1.65	1.91	100
1.91	2.20	130
tail slurry density		
-	-	500

Table 2

After the ΔP value is calculated, a check of the hydrostatic pressure in the annulus is performed in order to verify that the reduction of the hydrostatic head due to the gel does not affect the pressure balance after the cementing job is performed.

After all these calculations the final report is print out and promptly delivered to the Engineer Department in the District, the operational people on the rig and the cementing company in order to permit them to supply all the materials needed for cementing and plan all the works.

After the casing has been cemented the job can be re-examined in order to make a post job analysis of the cementing job, re-running the simulator using the field data and making a comparison between calculated and field data and the quality of the cement job. The quality of the performed job is checked by carrying out electrical logs such as Cement Bond Log, CBL, Variable Density Log, VDL, Temperature Log or Cement Evaluation Log, CEL.

ANALYTICAL MODELS

The mathematical models used in the simulator, in order to determine all the hydraulic flow parameters such as frictional pressure losses in the wellbore and U tube effect, are based on two rheological models. The rheological equations chosen for predicting the behaviour of the drilling muds and the cementing slurries are the Bingham and Ostwald & de Waele (power law) models. They are the following:

$$t = YP + PV \cdot \dot{g} \tag{7}$$

for plastic behaviour fluids, and

$$t = K \cdot \dot{g}^{n} \tag{8}$$

for pseudoplastic fluids. The rheological parameters of the models (plastic viscosity, PV, and yield point, YP, for Bingham fluids and consistency index, k, and flow behaviour index, n, for power law fluids) are determined from measurements got from test performed on a slurry sample at the Fann VG 35 viscometer. After that, is very important to determine the flow regime in order to plan the best mud displacement. In the annular section the flow regime is individuated computing the critical Reynolds number. Knowing there is two critical Reynolds numbers that define the passage between laminar and transitional flow and between transitional and turbulent flow, the calculation is done applying the following equation:

$$Re_{cr,lam\text{-}trans} = 3250 - 1150 \cdot n' \tag{9}$$

for the passage between laminar and transitional flow, and the following:

$$Re_{cr,trans\text{-}turb} = 4150 - 1150 \cdot n' \tag{10}$$

between transitional and turbulent flow. Where has been set:

$$n' = n \tag{11}$$

where n is the flow behaviour index, for pseudoplastic fluids. For plastic behaviour fluids the expression of n' is given by the following:

$$n' = \frac{1 - \frac{3}{2}y + \frac{1}{2}y^{3}}{1 - y^{3}} \tag{12}$$

having set:

$$y = \frac{YP}{t_w} \tag{13}$$

The passage between plug flow (that exists only for fluids having plastic behaviour and at very low pump rate) and laminar flow is very difficult to calculate. Infact, there is not an exact critical Reynolds number defining the change from plug to laminar flow regime. However, this change of state can be exactly determined considering the critical Bingham number as follows:

$$Bi_{cr,plug\text{-}lam} \approx 112 \tag{14}$$

where the dimensionless Bingham number is given by the following:

$$Bi = \frac{YP\left(D - d_e\right)}{PV \cdot V} \tag{15}$$

For values of Bingham number greater than 112 the regime has plug flow characteristics, while for values of Bingham number below the critical Bingham number the flow starts in laminar conditions.
The annular pressure losses can be computed determining the friction factor given in the following Fanning equation:

$$\Delta p = 2 \cdot f \cdot \rho \frac{V^2}{D - d_e} L \tag{16}$$

where the friction factor, f, is given by the following expression:

$$f = 2\frac{YP}{\rho \cdot V^2} \tag{17}$$

for plug flow, while for laminar flow is given by the following expression:

$$f = \frac{24}{Re} \tag{18}$$

The friction factor for transitional flow is calculated by a log-log interpolation between the friction factor for laminar and turbulent flow. The procedure for calculating the friction losses is then similar to that for plug, laminar or turbulent flow.

While again for turbulent flow is given by:

$$\frac{1}{\sqrt{f}} = \frac{4}{n'^{0.75}} \log\left(\frac{2}{3} Re \cdot f^{(1-n'/2)}\right) - \frac{0.4}{n'^{1.2}} \tag{19}$$

Where n' in the equation (19) is given by the expression (11) for power law fluids and by the expression (12) for Bingham fluids.

For what the U tube effect is concerning when the cement is pumped into the casing a hydrostatic imbalance develops between the casing and the annulus due to the higher density of cement with respect to mud. If this imbalance is greater than the frictional pressure losses in the casing, the fluids in the casing will start flowing at a rate greater than the input rate. The fluid level inside the casing will then start falling in trying to reach equilibrium and therefore the pressure at the casing top will be zero or even negative.

When the cement rounds the casing shoe the hydrostatic imbalance decreases and the fluid level inside the casing rises until it reaches the casing top and U tube ends. During that time the flow rate in the annulus is smaller than the input flow rate.

Good cement bonding depends greatly on the flow rate in the annulus, among other factors. Therefore it is imperative to be able to predict the start and the end of U tube and the flow rate in the annulus while U tube occurs.

The momentum balance for a selected portion of drilling fluid of length L deviated from the vertical at an angle θ gives:

$$L \cdot \rho \cdot \frac{\partial V}{\partial t} = (\pm) L \cdot g \cdot \rho \cdot \cos(\theta) - \frac{4 \cdot L \cdot \tau_w}{d_i} - \Delta p \tag{20}$$

where the (+) sign is for flow in the casing and the (-) sign is for flow in the annulus, Δp is the pressure increase in the direction of the flow and d_i is the inside diameter for pipe flow. Summation of all contribution from all the well sections and all fluids yields:

$$P_s - P_{bp} = \sum_{\text{fluid sections}} \left[L \cdot \rho \cdot \frac{\partial V}{\partial t} \; (\pm) L \cdot g \cdot \rho \cdot \cos(\theta) + \frac{4 \cdot L \cdot \tau_w}{d_i} \right] \qquad (21)$$

In order to solve the expressions (19) and (20) the well is divided into different sections within which the geometry is constant. For each time step, the surface pressure at the top of the casing is calculated using the (21). If this value is zero or negative, U tube has started. During the occurrence of U tube, a trial and error procedure is employed to determine the level of the free surface inside the casing (void height), satisfying the condition that the pressure at the free surface is zero. The increase (or decrease) in the void height during successive time steps is translated into a flow rate which when added to the input rate gives the annulus flow rate. The software calculates also the pressure behaviour in special events during pumping, such as stopping the flow to drop the plugs.

CONCLUSIONS

1. In order to supply to the operational people with a useful tool for designing and planning a cementing job, a simulator has been developed that would be as close as possible to the needs of the people operating in the districts and on the rig sites. The simulator can also be used for post job analysis, comparing calculated and field data to the quality of the cement job, in order to make a critical evaluation of the performed job.
2. The simulator takes into account all the possible cementing scenario such as conventional or with a stinger; single stage or two stages; cementing of a casing, liner or a tie back and for an on-shore or off-shore (jack up or semisub rig) well.
3. The utilisation of a simple and user friendly interface gives the software an high degree of simplicity and easiness to use. This fact permits utilising the simulator even to few trained people.
4. The present version runs on workstation HP 9000 using UNIX as operative system. A new version of the cementing simulator working on PC using Windows 95/NT is under development.

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NOMENCLATURE

YP	=	yield point
PV	=	plastic viscosity
k	=	consistency index
n	=	flow behaviour index
n'	=	local power law index
Bi	=	Bingham number
CF	=	slurry compressibility factor
D	=	outside diameter of annulus
d_e	=	inside diameter of annulus
d_i	=	inside diameter of pipe
f	=	friction factor
g	=	gravity constant
G_F	=	fracture gradient at the shoe
H	=	depth or height
L	=	length
Δp	=	pressure drop
P	=	pressure
Re	=	Reynolds number
V	=	average flow velocity
t	=	time

Symbol

τ = shear stress
τ_w = wall shear stress
γ = density
ψ = dimensionless shear stress
θ = hole inclination

Subscript

cr = critical flow conditions
fract = fracture
hydr = hydrostatic
lam = laminar flow
mud = referred to mud
bp = back pressure
plug = plug flow
s = surface
shoe = referred to the casing shoe
slurry = referred to slurry
spacer= referred to spacer
turb = turbulent flow

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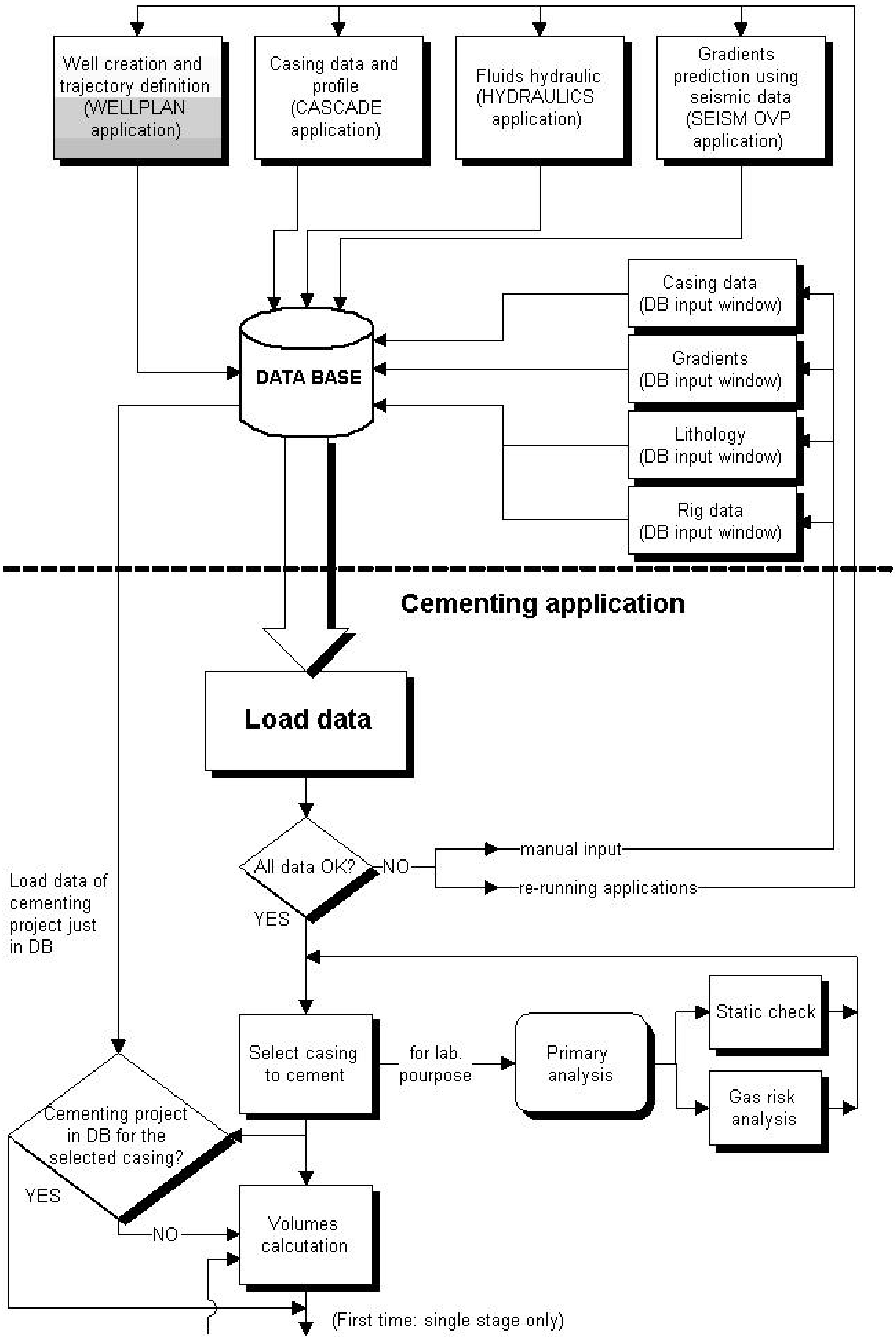
Well creation and trajectory definition (WELLPLAN application)
Casing data and profile (CASCADE application)
Fluids hydraulic (HYDRAULICS application)
Gradients prediction using seismic data (SEISM OVP application)
Casing data (DB input window)
Gradients (DB input window)
Lithology (DB input window)
Rig data (DB input window)
DATA BASE
Cementing application
Load data
All data OK?
NO
YES
manual input
re-running applications
Load data of cementing project just in DB
Select casing to cement
for lab. pourpose
Primary analysis
Static check
Gas risk analysis
Cementing project in DB for the selected casing?
YES
NO
Volumes calcutation
(First time: single stage only)

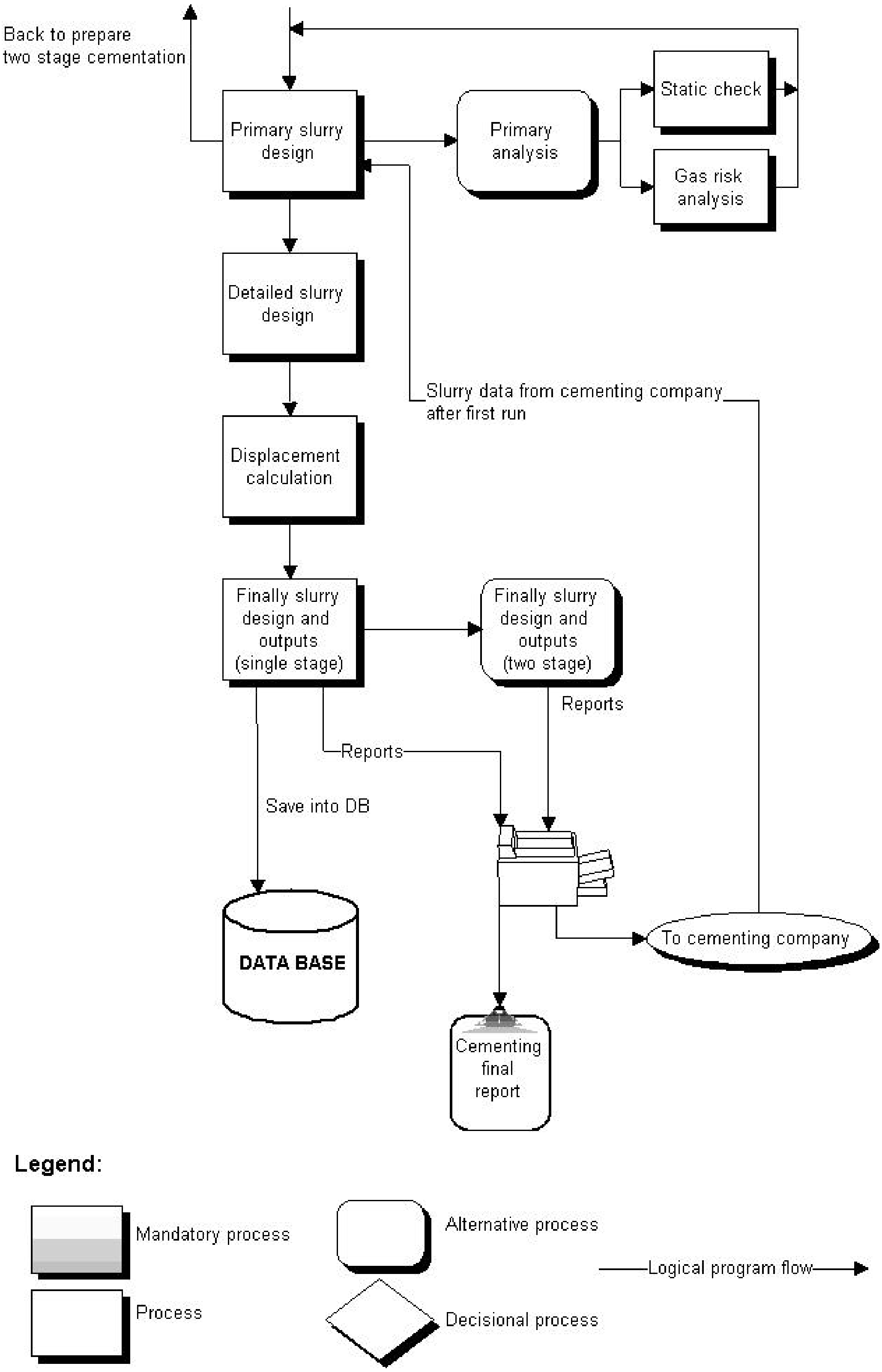

Figure 1 - IWIS DB configuration and data flow of the cementing simulator