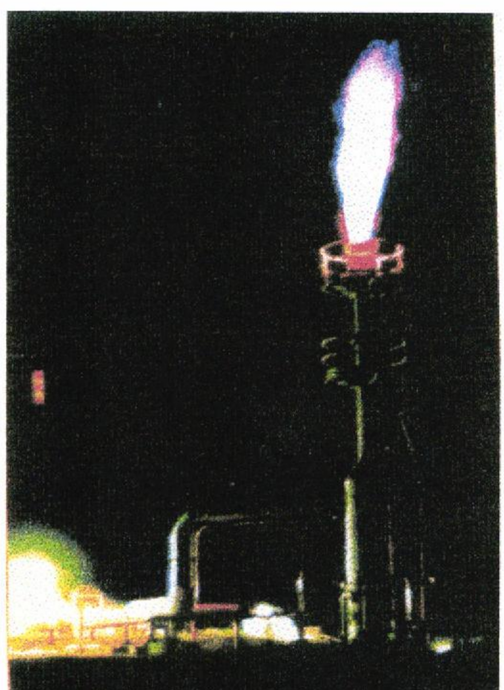
-UNDERGROUND COAL GASIFICATION-

FIRST TRIAL IN THE FRAMEWORK OF A COMMUNITY COLLABORATION

FINAL SUMMARY REPORT

JULY 1999



UNDERGROUND GASIFICATION EUROPE (UGE),AEIE
CALLE HERMANOS NADAL, 27-1°
44550 Alcorisa (Teruel), Spain

1 SUMMARY

The objective of the project was to demonstrate the technical feasibility of underground coal gasification in coal seams at 600 metre depth, in order to assess its potential as a means of energy exploitation in Europe. The trial was based on the use of deviated boreholes and a retractable injection system, techniques, which have both been developed by the oil and gas industries. One borehole, the injection well, was drilled in the coal seam. The other, the vertical production well, was run to intercept it in the lower part of the coal seam as closely as possible, in order to construct a continuous channel for gasification.

The wells were completed with casing and concentric tubing to provide the necessary paths for production, injection, purging gas and cooling water flows. A coiled tubing located in the injection well was used to execute the retraction (or CRIP) manoeuvre, which is a process in which the injector head for the gasification agents, i.e. oxygen and water, and the ignitor, are directed to a specific section of the coal seam. The gasification products passed to a surface production line for flow measurement and sampling of gas and condensate products. Production gases were either flared or incinerated, while the liquids were collected for appropriate disposal.

The first trial achieved its principal objectives of in-seam drilling, channel communication, the CRIP manoeuvres and the gasification of significant quantity of coal. The post-gasification study also identified the shape and extent of the cavity.

The study has demonstrated the technical feasibility of underground coal gasification at the intermediate depths of European coal and proposals are made for further development and semi-commercial exploitation of this promising extraction technology.

The CRIP denotes “Controlled Retraction Injection Point”.

Contents

2. PROJECT DESCRIPTION

2.1 Aim of the Project

Underground coal gasification (UCG) is an exploitation process for coal seams that provides a clean and convenient source of energy, and could be used where the traditional mining methods are impossible or uneconomical. The coal reserves of Europe, which are found in relatively thin seams at great depth, are becoming increasingly difficult to mine economically, and alternatives are sought to utilise these indigenous reserves.

The simplicity of the UCG process, which injects oxygen and water/steam into one well and recovers combustible gases from another in a form that is suitable for industrial use such as power or chemical feedstock, is very attractive. However, the technical issues of well construction, well completion and process control are only partly resolved although considerable progress has already been made in previous trials. Gasification at depths relevant to European coal reserves, in particular, needs more development before industrial exploitation of the process can take place.

The long term objective of the European development programme is to demonstrate the feasibility of underground coal gasification at commercial scale in typical European coal seams by means of field trials and the development of semi-commercial plant.

Two field trials at intermediate and great depth (500-700 and 1000 metres respectively) were proposed as the first step, for which the deliverables would be;

- the production of the desired product in terms of both quality and quantity;
- the employment of an appropriate monitoring and measurement system, enabling an interpretation of process behaviour, and the generation of process control and prediction concepts;
- The investigation of the maximum number of technical uncertainties at an acceptable cost and risk.

The current project is the first of the two planned trials. The objectives were set as follows:

1. Demonstration of the drilling of long holes in coal seams by deviated wells drilled from the surface.
2. Establishment of competent gas flow circuits by connection of the in-seam holes to other wells.
3. Ignition and start-up of reactors.

4. Effect of CRIP (Controlled Retraction of Injection Point) in thin coal seams.
5. Cavity growth, to determine attainable sweep, and to assess the relevance of roof collapse models.
6. Feasibility of filtration gasification.
7. Determination of effects of operational parameters.
8. Constant product gas quality and process control: evaluation of principal chemical process parameters.
9. Well corrosion: evaluation of the main technical problems at the appropriate operating pressure.
10. Environmental hazards: evaluation of all significant hazards.
11. Development of database and modelling to aid process understanding and extrapolation to other sites and coals.
12. Analysis of data and results from the first field test. Preparation of proposals for the second field-tests.

The operations of the trial were considered in three stages:

1. **Preparatory stage** The geology of the selected site was to be subjected to detailed evaluation, and an analysis of the coal and adjacent strata obtained. If satisfactory, design and construction of the wells and the surface plant would then proceed. The major activities of this phase were drilling, completion of the boreholes, and installation and commissioning of the surface equipment.
2. **Gasification activities** The gasification stage was to involve the drying, pressurisation and ignition of the coal and the subsequent development of the cavity by the means of the CRIP manoeuvre. During the test, specific parameters such as reactor lifetime, cavity growth mechanisms, sweep efficiency, energetic efficiency, gas quality, etc. were to be determined.
3. **Postburn activities** The first priority of the postburn programme was to determine cavity shape by drilling. A second objective was to validate and improve the gasification models used to improve process efficiency and control. Finally, reporting and site restoration will conclude the activities of the field test.

2.1.1 European Working Group on UCG

The European Working Group played a key role in the development of the UCG programme and the objectives of this first trial. It was formed in April 1988, with encouragement and support from the CEC, by six Member States who evaluated the results of the joint Belgium and German trial at Thulin, conducted a feasibility study of UCG in Europe and made proposals for the new Community UCG project.

The Group studied the present state of technical understanding, process behaviour and the feasibility of UCG in relatively thin deep seams, and they undertook an economic assessment which indicated that the technique had potential as a competitive technology for the production of medium quality gas. They concluded that UCG could be technically feasible in the thin deep coal seams of Europe, and the prospects were enhanced by new oil industry drilling techniques.

The programme of development of UCG in Europe to semi-commercial scale over a 15-year period was proposed. The first phase consisted of two field trials and supporting research using directional in-seam drilling for the first gasifier construction.

The first trial at about 600 metres would transfer the experience of the Thulin and American trials, and would be targeted to give confidence that the new techniques for deviated drilling and well completion can operate successfully under the European conditions.

2.2 Description of the Site

The European Working Group report identified the Oliete-Ariño coal basin in the Province of Teruel, Spain as one of several potential sites for an underground coal gasification on the grounds that the coal characteristics, thickness and depths met the requirements of the proposed trial. The prospect of a trial in Spain led the Group to examine the available geological data in detail.

2.2.1 Geological Description

The proposed site was already well known from previous mining activity and in fact had been chosen by the State Power Company, ENDESA as a UCG site some years ago, although the trial never took place.

ENDESA, provided detailed stratigraphic sequences from previous exploration wells and supplied seismic data for two locations within the coal basin, namely the Val de Ariño and El Tremedal. The first site conflicted with the requirements for a safety zone between the gasification position, the nearby underground mine (minimum distance 500 m), and the local potable aquifers. El Tremedal Figure 1, on the other hand, offered the benefits of two available coal seams, good seismic data and a satisfactory separation distance from other mines and water supplies. The evaluation of this geological data, led to the EC proposal that the first trial would be undertaken in one of the two coal seams of the El Tremedal reserves at a preferred depth of 500-700 metres.

The preliminary selection of the test site within the reserve was based, primarily on the 1:25 000 and 1:10 000 detailed geological and bore-hole studies of the El Tremedal anticline structure carried out in the late 1970´s to exploit new areas for coal production in the area. It showed that the proposed test site had:

- two dipping coal seams separated by 7 to 14 metres of limestone
- the required depth of 500-700 metres

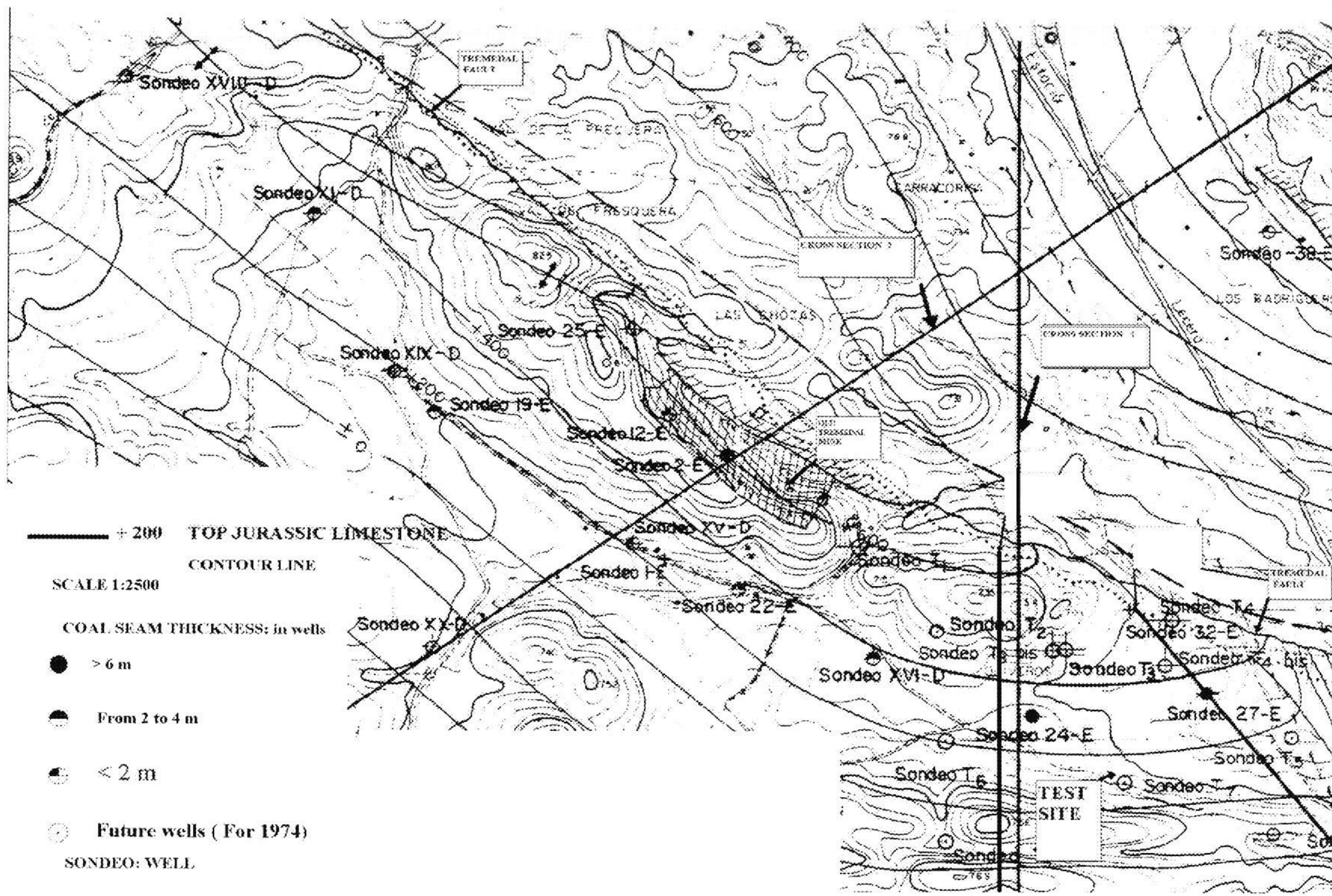


FIGURE 1 Location of Exploratory Wells on the Limestone Topographic Map

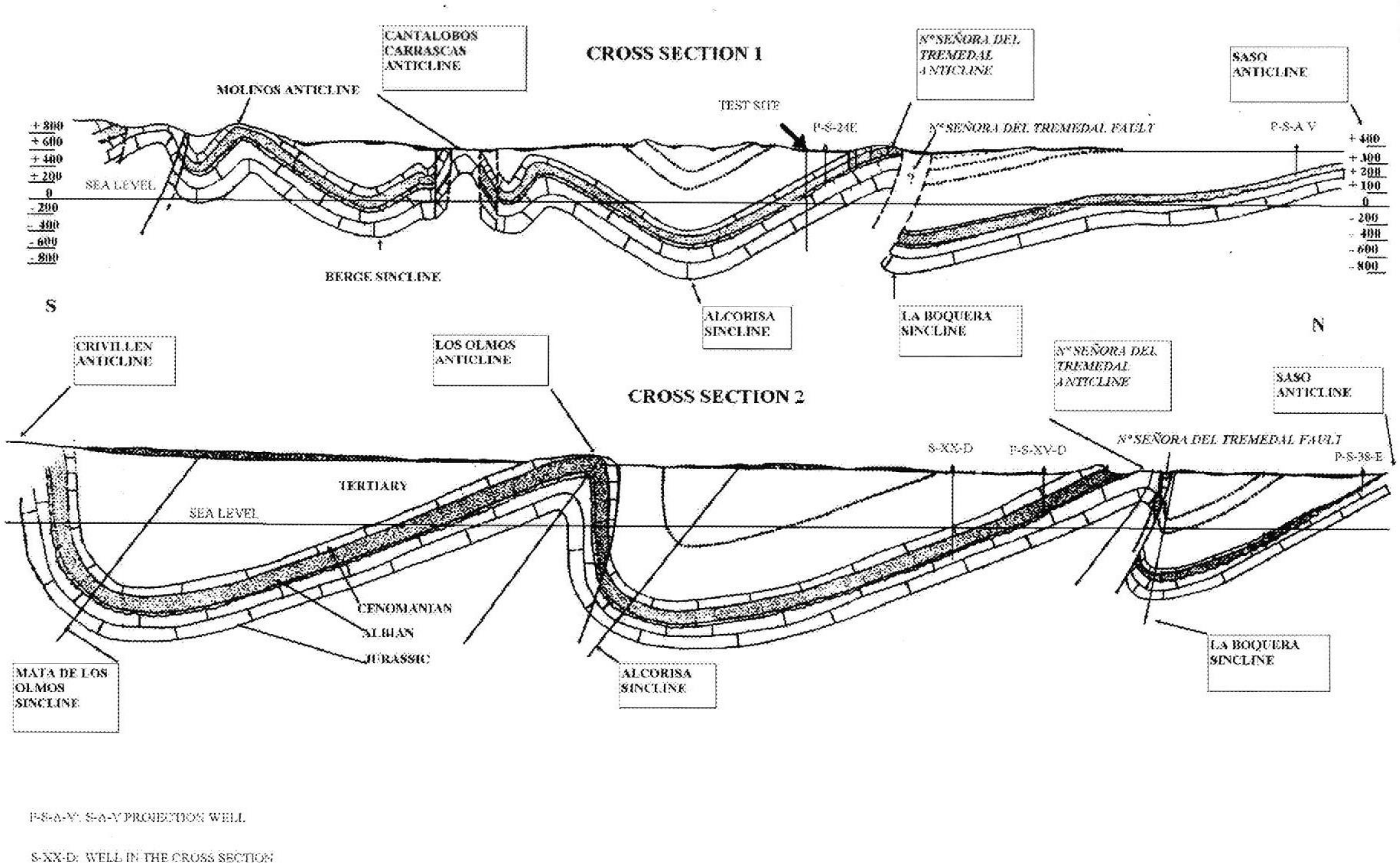


FIGURE 2 General Tectonic Cross Section

- a seam thickness between 1,9 and 7,0 metres
- a thin layer of carbonaceous clay lying under both coal seams
- an area of continuous coal seam at least 200 metres from any significant faults.

Figures 2 shows the Tectonic framework of the selected area.

These factors were highly favourable to gasification and meet the criteria specified in the EWG report for a future trial site. The site was subsequently identified in the EC project proposal as the preferred site, subject to a detailed exploratory well investigation to confirm the coal seam structure and composition.

2.2.2 Coal Chemistry

The ASTM ranking as a sub-bituminous C with a Vitrinite reflectance ranging from 0,36 to 0,43 % classifies the coal in the selected seam. The classification is very close to the lignite boundary.

The analysis of the samples, as received by the test laboratory, C.S.I.C., gave the following average results

Proximate Analysis:

	Upper Seam	Lower Seam
Moisture	22,5%	19,1%
Ash	17,7%	28,2%
Vol. Matter	26,5%	24,4%
Fixed Carbon	33,3%	28,2%
Gross Calorific Value	16 795 MJ/kg	14 705 MJ/kg

Elemental composition:

Carbon	45,14%
Inherent Hydrogen	2,44%
Nitrogen	0,38%
Organic sulphur	4,02 %
Oxygen (by difference)	5,60%
Mineral matter (calculated)	20,35%
Water content	22,07%

Low nitrogen and high sulphur content are a characteristic of the Teruel coal. The total sulphur was calculated to be 7,26 % of which 55% is in organic form and 45% as mineral matter.

Variations in the composition of the coal were observed between exploratory wells and between the two seams. In general the upper seam has a greater consistency, and the quality, as defined by the rank and gross calorific value, is better in the upper seam. Carbonaceous layer clay, of thickness between 0,3 and 0,7 metre, lies below both seams.

The main disadvantage is the exceptional high sulphur content, which requires special attention to be paid to the corrosion phenomena and material selection in the recovery well and production lines.

The data was validated by correlating Ash Vs Gross Calorific Value (dry), and Volatile Matter Vs Gross Calorific Value (maf). The results, figure 3, show evidence of changes of rank with depth. The transition from coal to carbonaceous mudstone found in the upper seam, show that it has a higher quality and is probably more suitable for gasification.

The coal has been subjected to pyrolysis tests at pressures from 5 to 25 bar, by the Institute of Carboquimica C.S.I.C., and results show a highly reactive coal, which produces about 20% gas, 5% tar and 50% water under pyrolysis conditions at underground reaction temperatures.

Measurements were also made of the reactivity of the coal by carrying out the combustion and gasification reactions in a thermo-gravimetric analyser at various pressures. They found that the El Tremedal coal shows a high reactivity, and that the effect of pressure is to enhance the methane forming reactions.

The US tests were carried out in similar sub-bituminous coal to that at El Tremedal, whereas the Thulin test, in Belgium, operated in less reactive anthracite although gasification was still achieved.

2.2.3 Exploratory Well Study

The objective of the vertical exploratory wells was to provide information on the exact thickness, depth, composition and overburden sequence of the two coal seams.

Two wells were planned originally, but a third well, ET3, was subsequently drilled close to the proposed site of the production well to make a triangular correlation over the future reaction zone. The three wells were all cored and logged around the coal seam, and an extensive programme was undertaken to measure the permeability of each strata.

The coring lithology of the exploratory wells is shown in Figure 4.

The drilling located the exact position, thickness and dip of the two coal seams, and confirmed the geological configuration that had been deduced from the previous borehole study. In addition, the nature of the adjacent sand, limestone and carbonaceous layers were established.

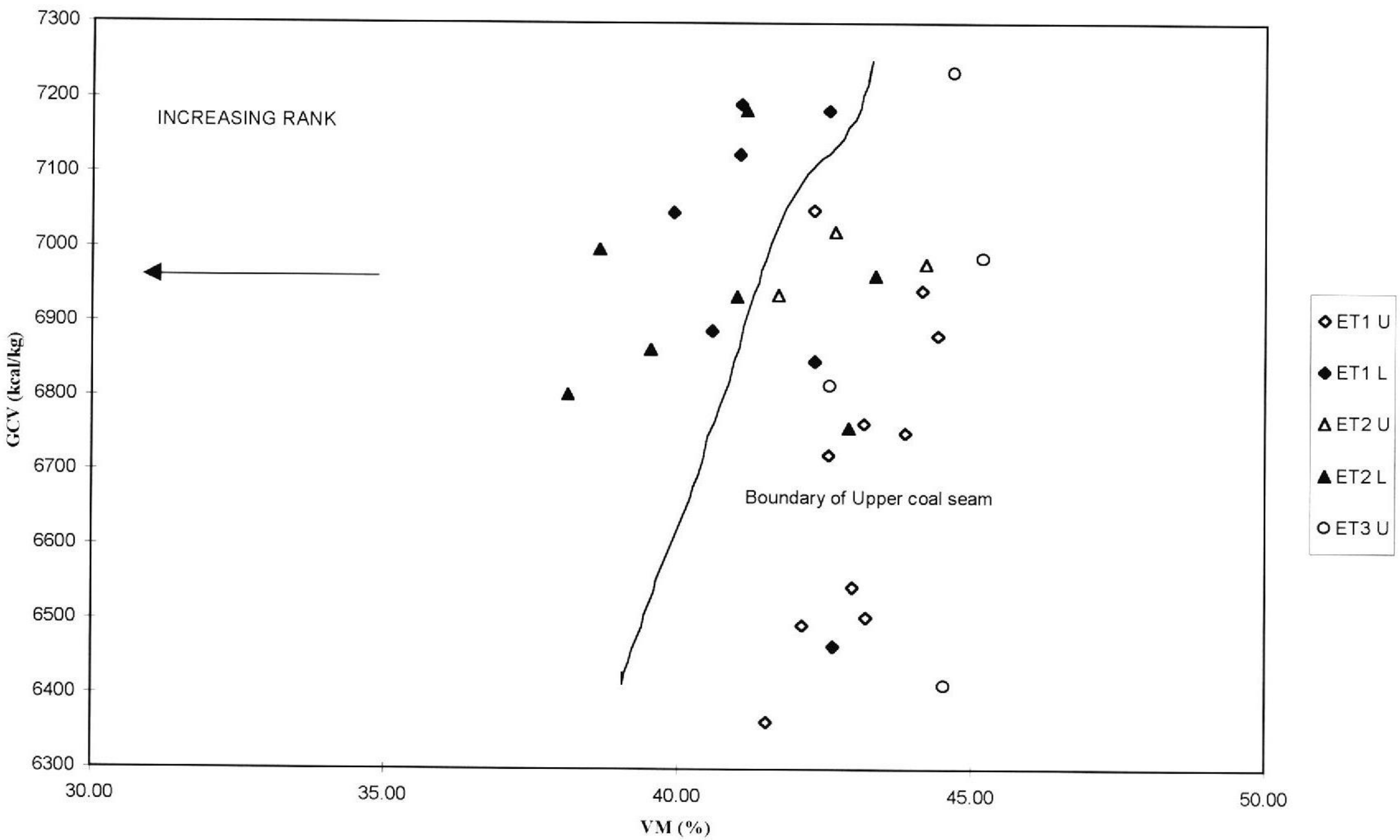


FIGURE 3 Tremedal – Volatile Matter Vs. Gross Calorific Value (daf)

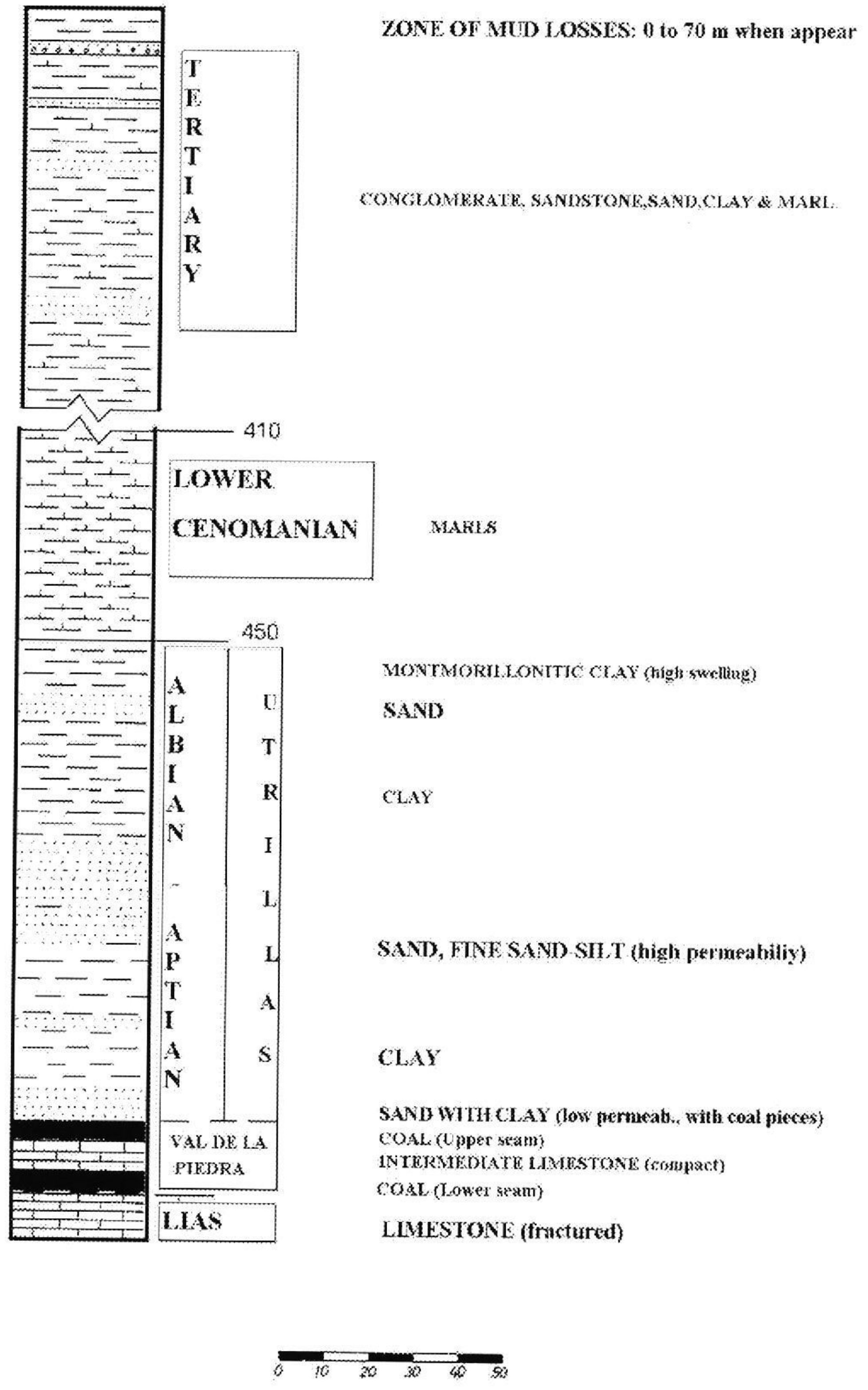


FIGURE 4 Lithology – Vertical - Section

The main conclusion was that the quality of the lower coal seam around the proposed position of the production well had diminished. The upper seam also showed evidence of erosion, but a thickness of over two metres was observed throughout the triangular area formed by the three exploratory wells. Furthermore, there was no indication of faults in this area. These factors all favoured the use of the upper seam for gasification.

2.2.4 Site Hydrogeology

A general study was undertaken by the Regional Office of ITGE in Zaragoza to establish that the hydrogeological conditions of the El Tremedal site would be suitable for the gasification trial. It used the existing geological and borehole data to locate permeable strata in both the Albian layers above the coal seams and the Jurassic layers below.

The hydrogeological functioning of the area follows closely the tectonics, and results in a complex of local flow channels for which the transmissivity varies considerably. The drainage direction is generally to the NE, and the general vertical flow, at least in the tertiary, is upwards. The urban and agricultural use of the underground water is light and no water for industrial or domestic use is taken from the vicinity of the site.

The general hydrogeological study based on permeability and injectability tests in boreholes and exploratory wells focused on the two coal seams and the sand above. It established that the permeability of the coal and the adjacent layers is very low, although the clayey sand layer immediately above could act as a path for small flows of gas and water.

The permeability tests in the exploratory wells found that:

- coal permeability at 1,96mD
- sand permeability at 17,6mD
- the natural flow tendency is from the coal to the sand but the thick cover of clay lying above would act as a seal
- The very low permeability limestone strata below the coal seams will separate the cavity from the Lias aquifers.

It was concluded from these tests that neither coal seam could cause contamination of the local aquifers, furthermore the upper seam has a greater isolation from the main aquifer of the area, which is located in the lower part of the Lias. The connection of the upper seam to the sand may act as a short circuit for the gas, but liquids will not escape far from the immediate area of the cavity and certainly not towards the aquifers.

2.2.5 Final Selection of Seam

The final choice of seam was taken largely on the basis of coal quality, seam thickness and the degree of isolation of the future cavity from the important aquifers.

The upper seam had a more consistent coal than the lower seam and it was better isolated from the main aquifer of the area in terms of water contamination. On the other hand, the upper seam suffered a significant reduction in seam thickness in the vicinity of the proposed production well and porous sand above was likely to increase the water ingress.

On balance, the safety issues prevailed, and the upper seam was selected. Construction of the process wells and the rest of the installation immediately followed as now described.

2.3 Design of the Installation

2.3.1 The Process.

Underground Coal Gasification (UCG) is the in-situ conversion of coal into combustible gases, hydrogen, carbon monoxide and methane which takes place by the interaction of the coal with oxygen and water/steam. After coal is ignited, the gasification agents are introduced through an injection well, reaction takes place in a cavity in the coal seam, and the products further react with the surrounding coal to produce the combustible gases. These gases are then brought to the surface via a production well for subsequent use in chemical or energy production.

Previous American trials have shown that enlargement of the gasifier area needs to be managed by the use of a moveable injection point for the gasification agents. The technique is known as the CRIP (Controlled Retracting Injection Point) manoeuvre, and is achieved by mechanical control from the surface.

The main operational parameters of the gasification process are the pressure within the underground reactor, the flowrates of the injected gasification agents and the temperature at the bottom of the production well; all of which must be controlled from the surface. In addition, a field trial needs detailed measurement of the input and output gas flows, a continuous analysis of production gas composition, the monitoring of underground temperatures, and finally a method of burning the combustible gases before discharge to atmosphere.

The installation is in two parts: an underground section with the necessary well configuration and completion, and a surface installation for the supply and disposal of gases, process control and analysis.

2.3.2 Process Well Configuration

The process wells were equipped with a series of concentric tubes in order to provide the necessary annuli for the process flow requirements. Three process wells (figure 5) were planned.

Deviated injection well (Figure 6)

This well had an in-seam section of 100 metres and was located at the bottom of

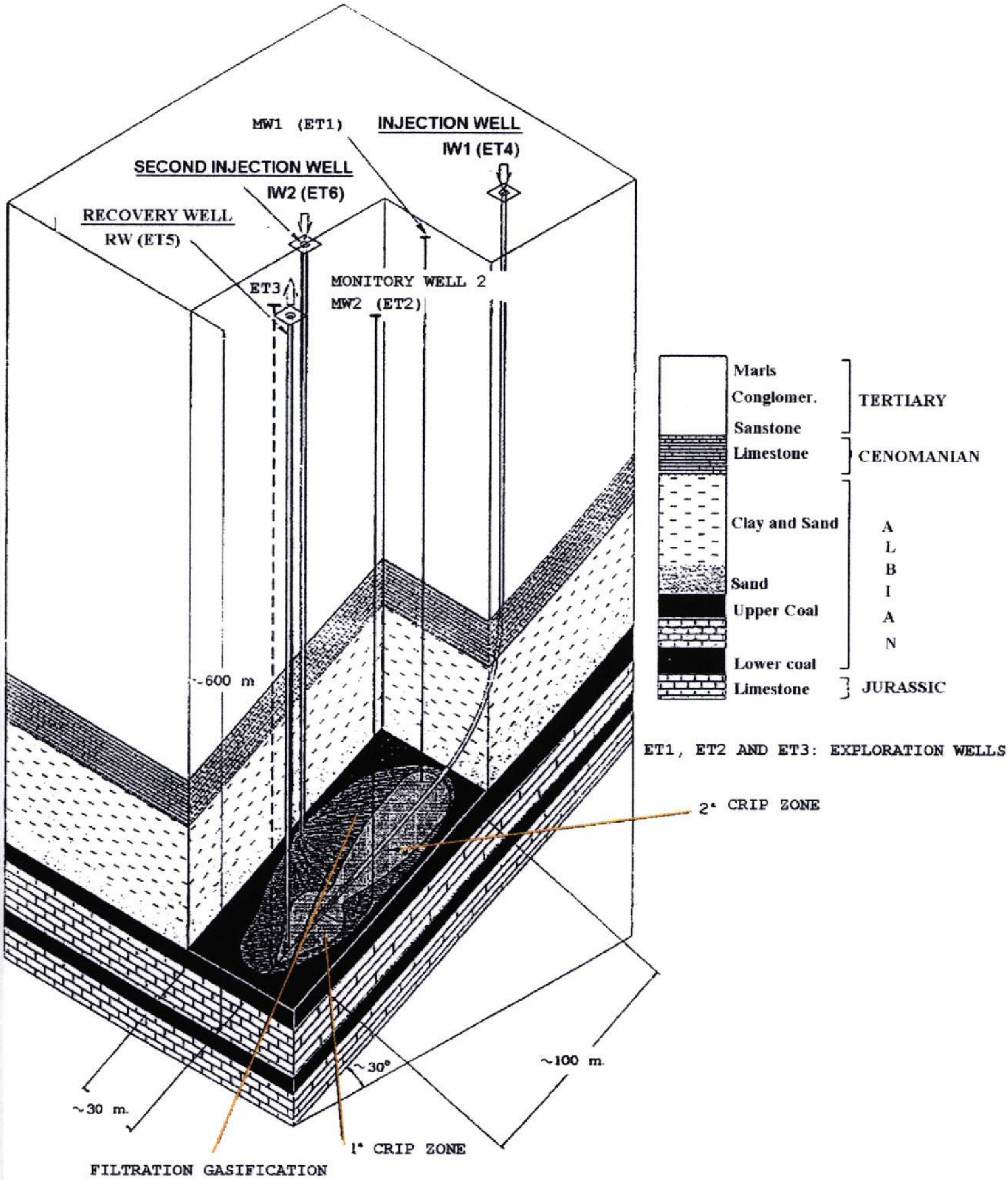


FIGURE 5 Well Layout

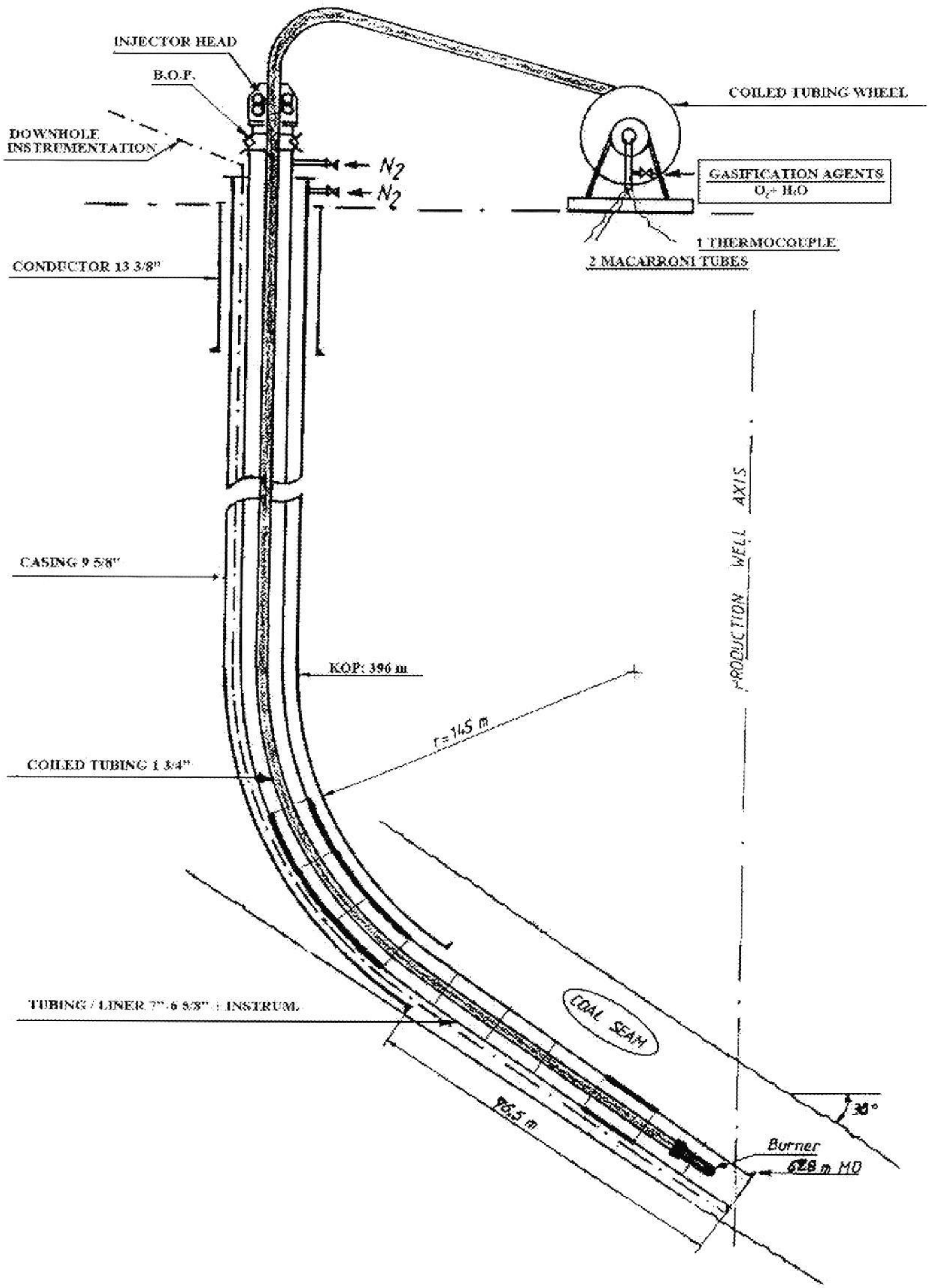


FIGURE 6 Completion of the In-Seam Injection Well

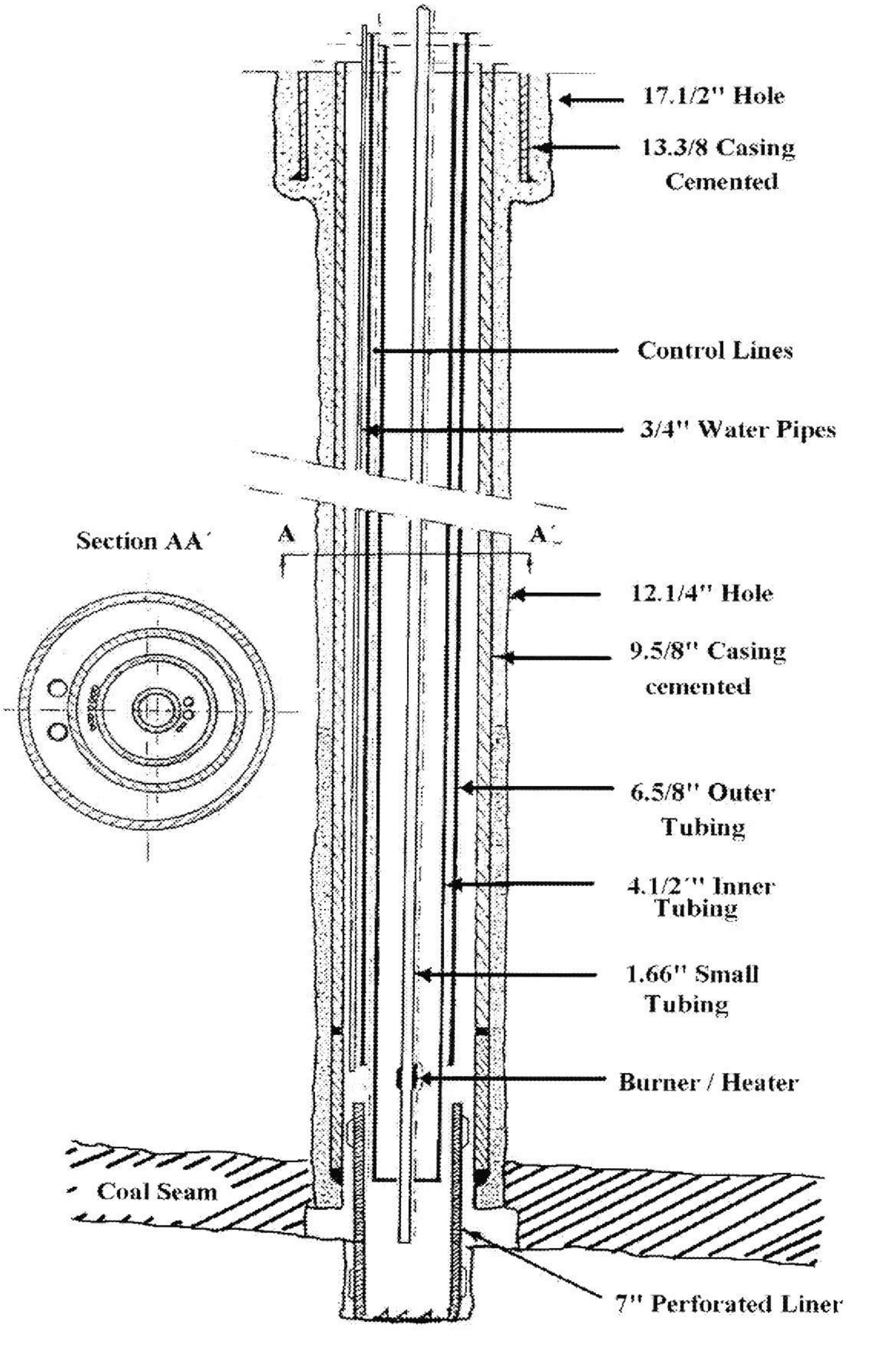


FIGURE 7 Final Production Well Completion

the coal seam. It consisted of three concentric tubes:

- An inner coiled tubing for the gasification agents
- A 7" pipe to maintain a channel for the coiled tubing and to complete the gas circuit between injection and production wells.
- An external pipe of 9 5/8", without any process function, required to keep the vertical section open.

Production well (Figure 7)

This was constructed as an S shaped well, which was drilled to intersect the end of the injection well as closely as possible. The wellheads of the production and injection well were separated at the surface by 150 metres. The process annuli were formed with four pipes as follows:

- An inner low flow gas production pipe of 1,66" diameter.
- A liner of 4 1/2" outer diameter for high flow gas production.
- A pipe of 6 5/8" to insulate the inner production pipes.
- An outer cemented casing which formed an annular to run pipes for cooling to the bottom of the well.

Second injection well

This was another S shaped well with its bottom located at a lateral distance of 30 metres from the axis of the in-seam deviated well. The internal arrangement was simply a fixed inner tube located in a cemented casing.

The two injection wells were supplied with the necessary oxidants, burner fuel and surface well heads.

Injection well coiled tubing

The Injection Well-1 had to perform the CRIP (Control Retraction Injection Point) manoeuvre, which involved mechanical movement and control of the injection head and igniter from the surface. To execute the action, a modified form of the equipment used by the oil and gas industry was leased to coil the tube at surface on a special drum, and control its entry into the well by a mechanical driven injector head (Figure 8).

The tubing had to carry pure oxygen for the gasification; it needed to be resistant enough to endure the friction forces and fatigue stresses of moving, and the system had to be perfectly gas-tight to avoid high pressure oxygen leaks into the annular. The end of the coiled tubing was equipped with a burner to perforate the in-seam liner and ignite the coal.

2.3.3 Surface Installation

An 18 500 sq.metre piece of land was required above the selected part of the coal seam to accommodate the wellheads and surface plant.

The objective of the plant was to supply, handle, store and inject process fluids, then treatment, analyse and finally dispose of the production gases and liquids.

Considerations of safety and topography led to the preparation of separate platform levels for the supply, production and control sections of the plant. Figure 9 shows the general plant layout and Figure 10 is a view of the whole site, showing the drilling of the production well on the upper platform. The construction of the three platforms, and the upgrading of the access road were undertaken at the beginning of the project in preparation for the drilling programme.

The requirements of the surface plant were based on a sequence of operational phases, which were developed to prepare the wells, achieve ignition, then undertake the gasification experiment in the two injection wells and finally close down the process after gasification. A general process flow diagram is shown in figure 11.

Lower platform: Utilities and supply systems

The lower platform contained the in-seam injection well, the machinery to operate the coiled tubing, the feeding and manifold systems for the gasification injection agents (oxygen, nitrogen and water), most of the plant utilities and the delivery area (Figure 12).

The oxygen for the gasification and nitrogen for purging and controlling the backflow of reactants were supplied from cryogenic units. The cryogenic storage tanks had a capacity equivalent to 1,5 days of supply, and a rack of 24 high-pressure gas cylinders, acting as a lung area, provided additional back-up storage for the nitrogen.

Process water for gasification and cooling were supplied from a storage reservoir. Positive displacement pumps were chosen to meet the high flow and pressure requirements of the well. The process water pumping and storage system was also designed as a means to improve the communication between the wells by hydrofracking.

The piping of the gas injection systems to the wells was via a manifold assembly, which measured and controlled the injection and purging flows. It had been foreseen to install a by-pass at the entrance of the gas and water lines in each injection well in order to inject deuterium and helium tracer pulses into the process flow.

The utility area consisted of the electrical distribution system, an 8 bar compressed dry air supply for instrumentation, and a general 9 bar nitrogen supply for inert purging. Process steam for the production line heating and cryogenic vaporisation was provided at 9 bars throughout the site and a propane network, with liquid storage was installed to supply the boiler, combustor and flare. A delivery area for the large road tankers was also located on the lower platform.

Middle platform: Control room and vertical injection well

The wellhead and associated manifolds for the second injection well together with the control room, site office, facilities, parking, and equipment storage were all located on the middle platform. The control room was situated above the meeting room from which the whole surface plant could be seen.

A data acquisition and control system, adapted to the process phases of gasification, presented all the data and control synoptics. It provided:

- Control and indication of process variables
- Display and monitoring of strategic point alarms
- Control loop tuning
- Data processing, storage and reporting

The system was installed in the plant control room as a turnkey package, complete with support and maintenance, the interfacing hardware and the back-up power supply. The plant instrumentation, gas analysis unit and most of the plant control systems were linked to the central control room by a 20mA digital connection. Separate systems were installed for radio communication and to process the fibre optic system for temperature profile acquisition.

Upper platform: Production analysis and disposal

The recovery wellhead, production lines, sampling systems, combustor and flare were located on the upper platform (Figure 13).

The wellhead had connections for nitrogen, cooling water and the downhole instrumentation. Outflow pipes were provided for the high and low flow production lines, and the removal of foul water from the well.

Large choke valves controlled the pressure of the underground gasification reactor, one for each production line. These valves let down the pressure of the product gas from the operating pressure to the intermediate line pressure and were duplicated for ease of maintenance.

The product gas, which at times had a high water content was passed into the heat exchangers (which used steam from the boiler) to raise the temperature and suppress condensation in the production and flow measuring sections. Downstream of the heat exchangers, the gas flow in each line was passed.

FIGURE 8 Coiled Tubing Surface Installation

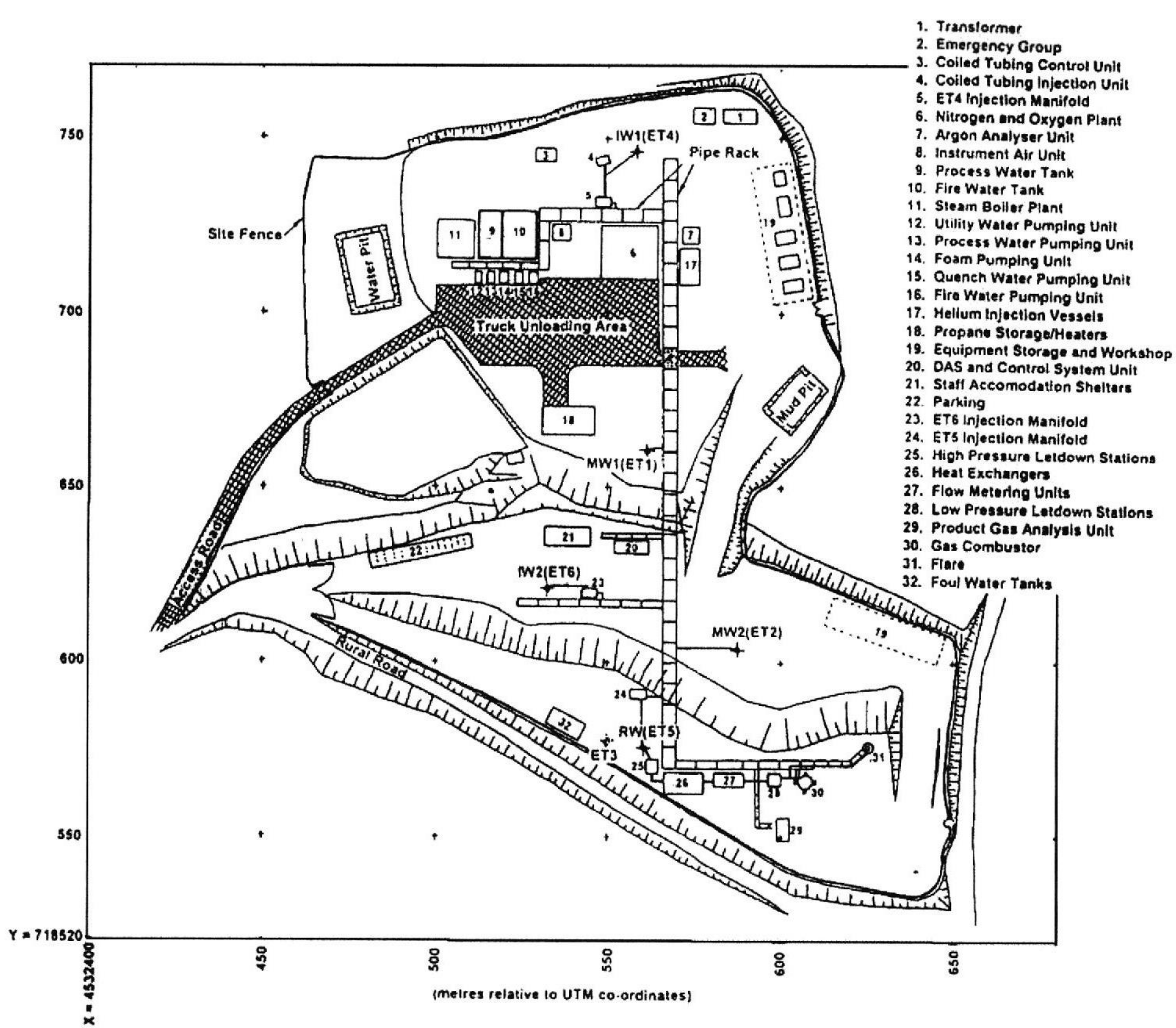


FIGURE 9 " El Tremedal" Site Layout

FIGURE 10 Production Well Drilling Works

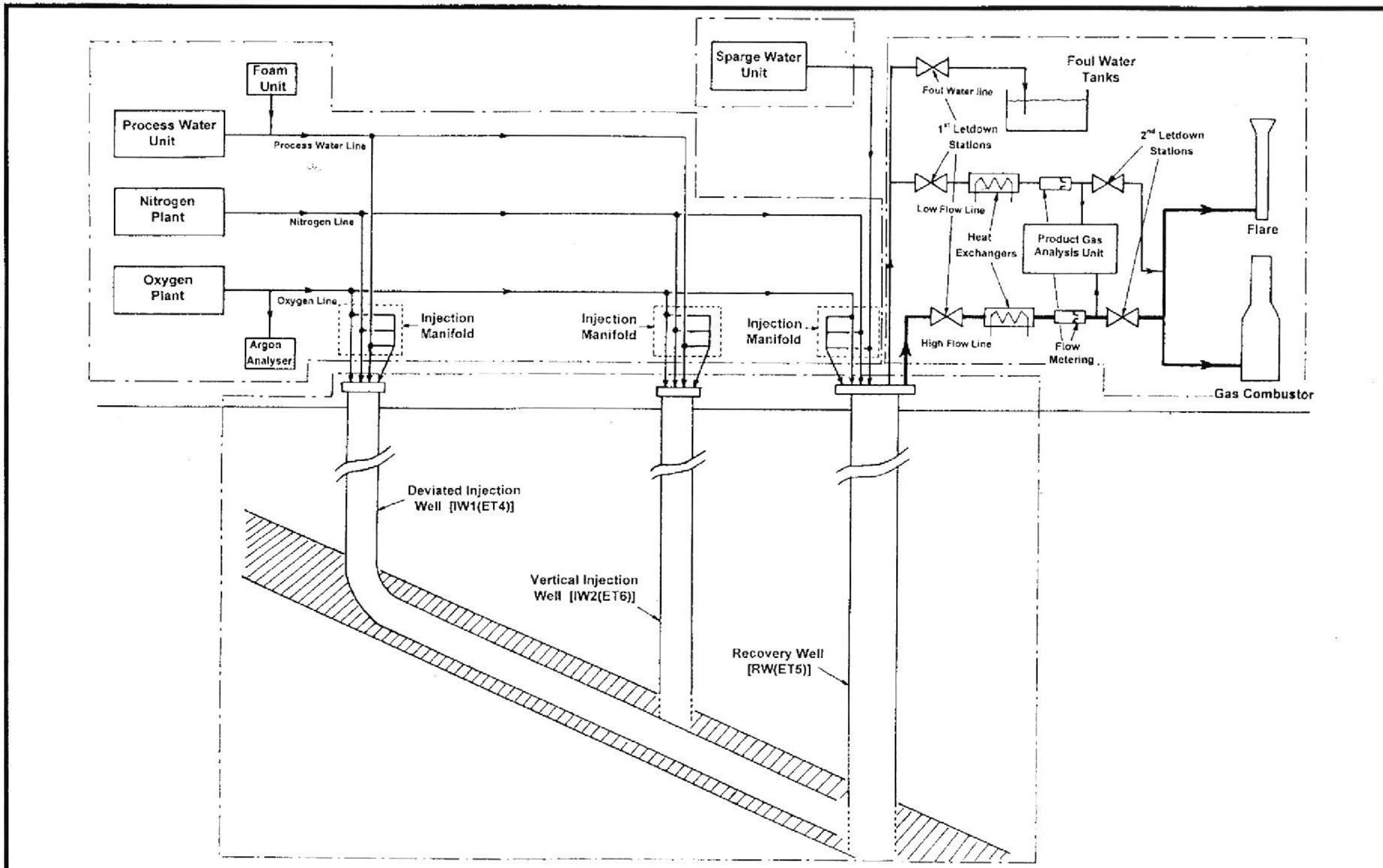


FIGURE 11 El Tremedal UCG Trial – Process Flow Diagram

FIGURE 12 Injection Plant and Utilities Area

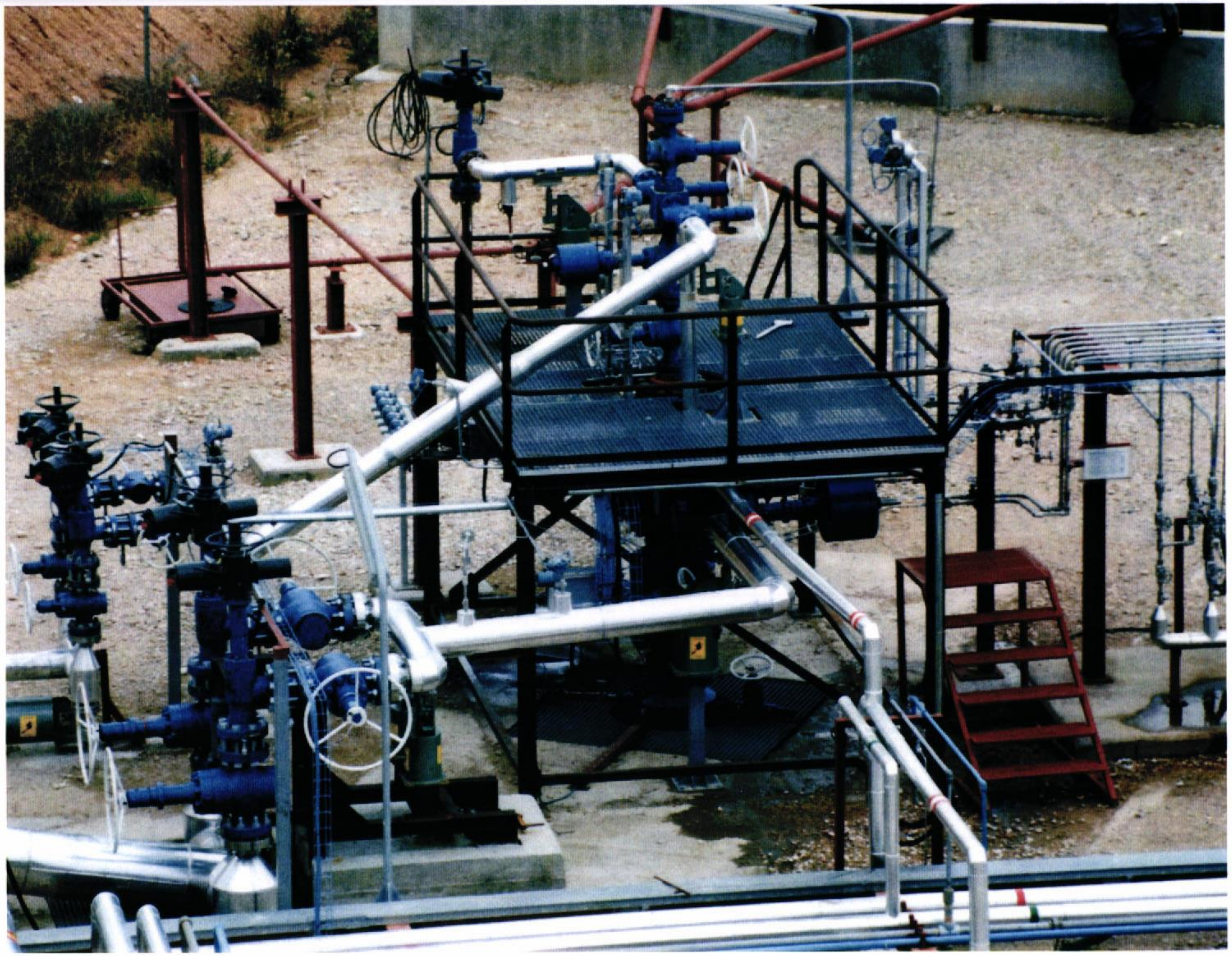


FIGURE 13 Production Well Configuration

FIGURE 14 Gas Combustion at Flare

through a flowmeter, after which gas samples were extracted for on line and batch analysis of the product stream.

The remainder of the gas, after further decompression to ambient pressure, was passed to a combustor or a flare to be burnt. Both units had continuously burning pilot flames and the combustor could also injected propane into the product gas, when required, in order to ensure complete combustion (Figure 14). Special alloys were used for the Production lines.

2.4 Description of the Monitoring and Measuring System

2.4.1 Injection Flow Measurement

The measurement of oxygen, nitrogen and water flows in the injection lines were made on-line with Coriolis type mass flowmeters and were used to provide feedback for the process control loops.

Advantage was taken of the fact that argon is an impurity of industrial grade liquid oxygen and nitrogen and could be used as a natural tracer for the estimation of gas recovery rate. An argon analyser was installed to measure concentrations in both the injection and product gas streams.

Helium tracer gas pulses, introduced into the oxidant stream from a vessel of known volume and pressure monitored the growth of the underground cavity. The concentration build-up and decay of helium in the product stream was measured by the mass spectrometer placed in the gas analysis unit.

2.4.2 Underground Measurements

Underground gasifier pressure had to be controlled accurately to minimise underground water influx or gas losses through the strata. Choke valves in the production lines controlled reactor pressure.

The temperature profile along the wells was measured by a combination of standard thermocouples and an optical fibre system, which provided a continuous reading of temperature for each metre of fibre length. This was the first time that optical fibres had been used underground near to a reactor, and represented an important innovation.

Optical fibres and thermocouples were protected in metal tubes and set inside plastic covered flat packs, specially designed for the process. These flat pack cables were inserted into the injection, monitoring and recovery wells.

2.4.3 Product Gas Measurement

The flow rate of the product gas was determined by a differential pressure flowmeter (type nozzle) located in each production line. The corrections required for gas composition, temperature and pressure were made in the data acquisition system.

A sampling line for the production gases was taken from the intermediate pressure section and a system of gas conditioning was used to remove solids and condensate. The gases were then fed to the gas analysis unit. It was equipped with on-line process analysers and a mass spectrometer to continuously measured the composition of the gas. The two systems worked in parallel to provide updated readings every few seconds.

The main gas components, namely methane, carbon monoxide, carbon dioxide hydrogen, hydrogen sulphide and oxygen were obtained from both systems, giving replicated readings. In addition the mass spectrometer analysed six minor compounds (ammonia and hydrocarbons) and the two tracer elements (argon and helium). Batch samples of gas, and condensate from the sample conditioning units were taken daily for laboratory analysis.

The coal consumption, the underground water ingress and the underground gas losses have to be calculated from the direct measurements of flow and gas composition. A mass balance of the elements, which take part in the process: Carbon, Oxygen, Hydrogen, Nitrogen, Sulphur and Argon is made to determine the underground parameters.

Assumptions have to be made about the char composition left underground, to close the mathematical equations and these can introduce a degree of uncertainty into the calculated results.

3. CONSTRUCTION, INSTALLATION AND COMMISSIONING

The key constructional phases were:

- Drilling of the exploratory wells.
- Drilling and completion of the process wells.
- Installation of the surface plant.
- Installation of instrumentation and data acquisition system.
- Plant commissioning and external certification.

The phases were largely sequential because the major investments in plant and completion could not be made until the geological uncertainties had been resolved by exploratory drilling. Access was also required for heavy drilling equipment, which delayed plant construction.

Exploratory wells

The exploratory wells and the coring of the coal seam were the first opportunity to gain experience of drilling on site. Standard drilling rigs were used to core and log the three wells and provide the information on lithology, seam location and coal chemistry upon which the future decisions on process well drilling were based.

Process wells

The drilling strategy for the process wells was to complete the more difficult well first, namely the deviated in-seam injection well. Its position would be accurately surveyed before the vertical production well was drilled to meet the injection well inside the coal. The final connection between wells would be improved, if the drilling connection was inadequate, by hydrofracking or retro-combustion during the process operations.

The injection well required accurate targeting, high angles of deviation (or build rates) to enter the coal seam and considerable precision in the control of the down hole motor along the coal seam by "Measurement While Drilling" logging. These requirements were at the limit of deviated drilling technology and the success in achieving the target trajectory is discussed below.

The target for the recovery well was also demanding. It was a larger diameter well which had to make a vertical entry into the coal at a point within one metre from the end of the surveyed location of the injection well shoe. Deviated drilling in an S shaped well was used to achieve the target accuracy.

The drilling of the vertical injection well IW2, and the workover of two of the exploratory wells for monitoring completed the drilling programme.

Gyro logging

A full gyro survey in four wells was then undertaken to improve the definition of the well trajectories and to define accurately the seam disposition for subsequent cavity growth evaluation. Linear interpretation of the new logging results showed that the correlation for the reference points with previous dipmeter/MWD logs was very close.

Well completion

The process wells were completed, immediately after drilling, with cemented outer casings to avoid well collapse. They were then equipped with a set of concentric tubes attached to the well head, to provide the necessary annuli for the process gases, cooling flows, burner control and instrumentation.

The design and material selection for the completion of the process wells to meet the operational requirements and the high temperatures of the product gas were particularly onerous. The installation of multi-concentric pipes, high wellheads, and complex instrumentation needed special procedures. These were outside the scope of standard completion practice and the UGE team constructed a purpose-designed platform and developed the installation procedures themselves.

The coiled tubing for the injection pipe required special attention. It had to meet stringent requirements for reliability. The final design, which incorporated the downhole burner and macaroni supply tubes was constructed offsite to the UGE specification, and was supplied complete with spool and injection head. The coiled tubing entered the well by means of a chain-driven injector head which allowed the injection point and the system was also equipped with a means to measure and weigh the coil tubing burner in order to position it accurately for the CRIP operation.

Surface plant

The surface plant was constructed under the supervision of the contractor. Specialist companies were used for three sections, namely:

- The surface plant piping, machinery and instrumentation.
- The plant data acquisition and control system.
- The gas analysis unit.

The basic specifications were prepared according to the process requirements and Contractors were selected on the basis of a technical and economic evaluation.

The Gas Analysis Unit was designed as a mobile instrument cabin which could be used again if required. Packaged units were specified for the oxygen, nitrogen, steam, compressed air and propane supplies. The combustor and flare were delivered as complete fixed units.

Commissioning

All pressure components and pipe sections had to be certified and authorised for operations by the Mines and Environmental Quality Department of the Diputacion General de Aragon (DGA).

Commissioning and training were planned simultaneously. Operational and safety training was a major pre-occupation in the 6 months prior to gasification. A detailed safety manual was prepared and both staff and contractors were trained and their performance was audited externally before operations commenced. Experienced plant operatives were contracted for the gasification phase, and a safety committee was formed to oversee all safety-related activities and encourage staff safety awareness.

3.1 Suppliers of Equipment and Services

The management strategy was to contract out the entire specialist engineering including the drilling, plant design and all surface construction. The in-house team would act as contract manager and provide the process know-how of gasification.

3.2 Problems and Successes of Construction

Well construction

An early noteworthy achievement of the project was the connection between the recovery and deviated injection wells, which was immediately established without the need for hydrofracking or retro-combustion.

The drilling of the deviated injection well itself was also successful but maintaining the channel trajectory in the seam itself over an extended length proved more difficult than expected. The ability to drill deviated wells with complex trajectories was further demonstrated with the construction of the monitoring and vertical injection wells IW1, MW2 and IW2. The monitoring well MW2 was unusual because of the high build rates for the directional drilling and the upward trajectory required to reach the monitoring position. These small diameter wells were completed by means of a coiled tubing which also carried the downhole instrumentation.

The recovery well construction went according to plan and excellent accuracy was achieved by directional control. Gyro measurements showed that the final trajectory in the X-Y plane at well bottom was within 0,5m of the target. The techniques used to protect the coal seam from debris and excess pressure worked satisfactorily.

Logging

A comparison of the measurement while drilling system (MWD) and the final gyro survey of the IW1 trajectory indicated that the limiting factor was rather the control of the down hole motor rather than the measurement techniques themselves. The main problem was the distance of 12 metres between the MWD equipment and the drill bit, which made correction difficult. Equipment is becoming available in which the MWD equipment is located much closer to the bit, which should greatly improve the control.

Furthermore, the need to confirm the position of the coal seam and any associated faults with a high degree of accuracy is a continuing theme in underground gasification.

It was decided to undertake a full gyro logging survey of all wells to TD at the end of the drilling programme and correlate the data on seam position, dip and azimuth. This work confirmed the presence of a fault in the vicinity of the vertical injection well.

3.3 Modifications and Over-runs

Well construction was a continuous process of target modification, as more information became available about the geology and characteristics of the coal seam. The original plan was to use the general borehole and seismic information from previous mining activities and validate this data with one or two exploratory wells.

This exploratory drilling programme had to be expanded to improve the accuracy of the data. on seam thickness, coal composition and the possible presence of faults near to the proposed cavity position. This involved additional drilling, gyro logging and a detailed interpretation of position data.

The subsequent drilling of the process wells was conducted one at a time, because the outcome of in-seam drilling of dipping coal seams also had its risks and uncertainties. The deviated drilling of the injection well was successful but changes to the recovery well trajectory had to be made to achieve a satisfactory intersection of the process wells in the coal seam. Controlled drilling by downhole motor was used for all process and workover wells, because of the accuracy required. The original plan to use a vertical production well had to be changed to an S shaped well because the intersection point moved away from the one that was planned during construction of the injection well.

The difficulty of initiating the project in a relatively remote region, finding offices and preparing access to site delayed the start of the project.

An important benefit of the process was the proof that high accuracy intersections can be made at great depth, and a significant amount of potentially lost time was saved by avoiding the need for hydrofracking or retro-combustion to achieve a good underground connection.

Surface plant design and construction experienced some delays due mainly to the availability of the special materials for production well completion. Erection of the plant was relatively straightforward and time was gained by the use of packaged units for utilities, gas combustion and data acquisition.

3.4 Time Schedule

Originally, the field trial was planned as a four-year programme, which involved two years of preparatory work, 1,25 years of gasification and one-year of post gasification activities. This had to be extended, figure 15, because the geology had to be confirmed before the major investments in plant and underground equipment could be made.

The result was that the preparatory works, which included all underground works and the design and construction of the surface plant, were responsible for the major delays in the programme.

Other factors which contributed to the delays were the difficulties of recruiting and training the project team, the need to redesign the coiled tubing system, availability of specialist materials and the unfamiliarity of the process to the regulatory authorities.

In summary, the over-run of the project was mainly an unavoidable consequence of the uncertain geology, which had to be thoroughly investigated before the planned trial could start. Any future trial or commercial project will need to allow for this type of investigation.

3.5 Project Costs

The cost of the trial was estimated in 1991 at 19,0 MEURO. The breakdown by stage are given in the project proposal and these are compared with the final out turn in figure 16 below.

The final out-turn for the project is estimated to be 17,48 MEURO which represents an under expenditure of 7,9%. The preparatory works and the post-gasification studies were virtually on budget, and the underspend was incurred for the gasification tests.

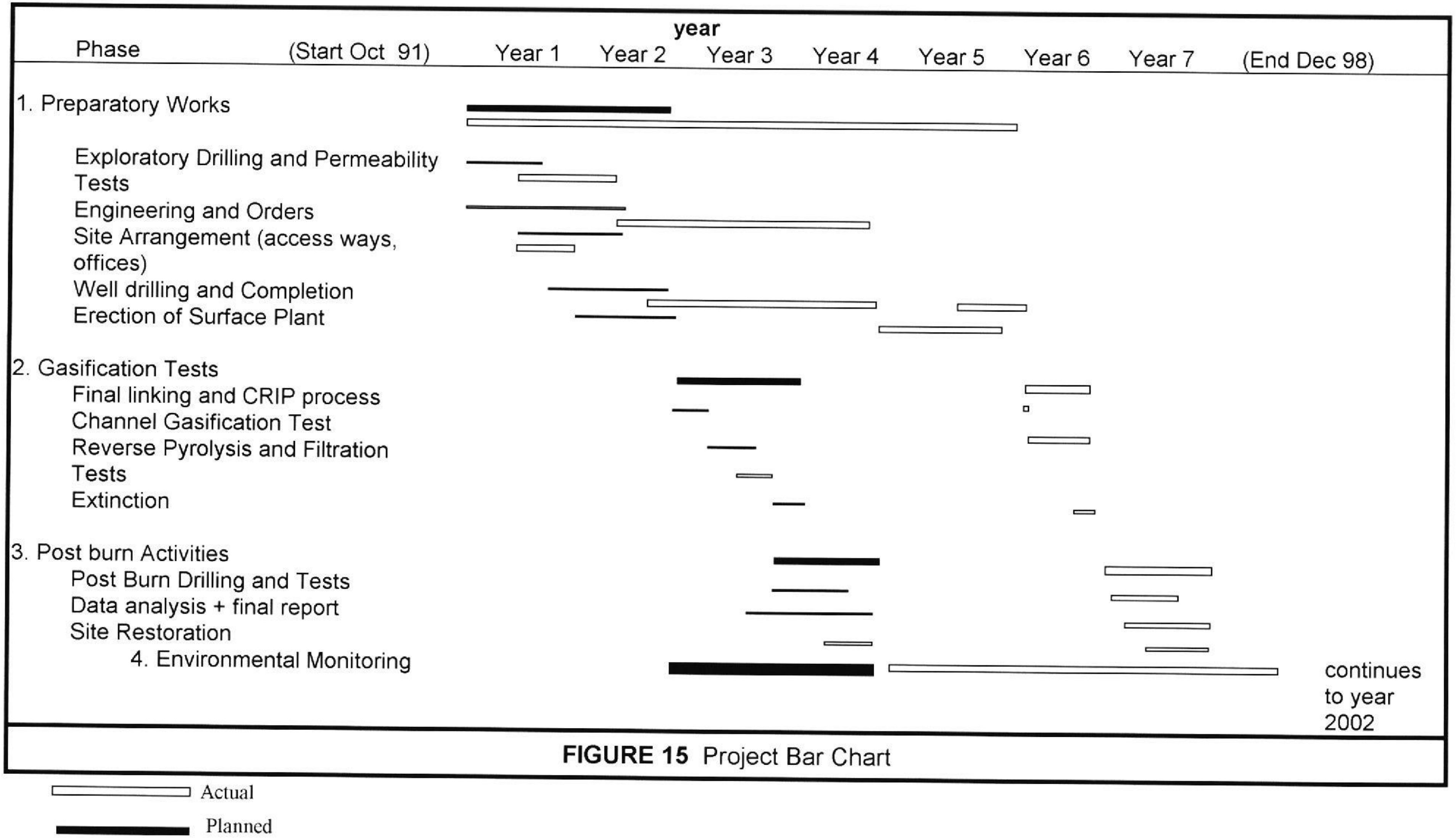


FIGURE 15 Project Bar Chart

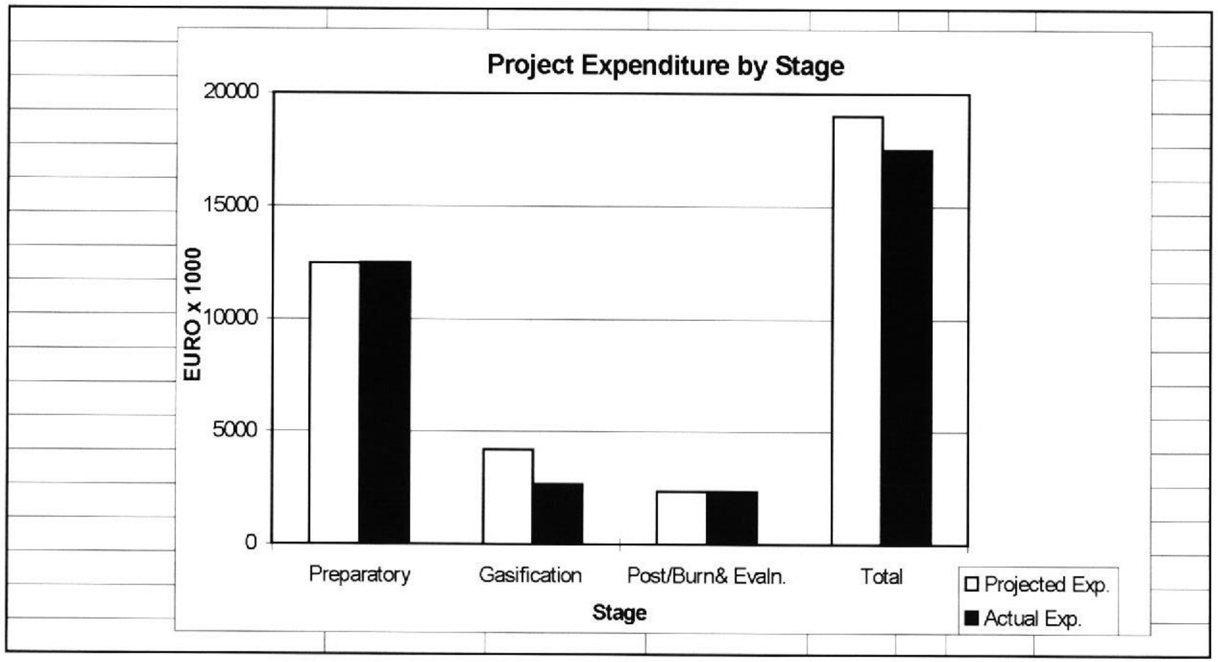


FIGURE 16 Project Costs by Stage

4. OPERATIONS AND RESULTS

4.1 Operating History

Taking into account the objectives of the UGE project, and the available coal in the gasification channel, it was clear that the operations would be of short duration. Two periods of gasification were carried out which lasted 9 and 4 days respectively. It included three ignitions and seven CRIP manoeuvres and is summarised in figure 17.

Operations began on the 30th June 1997 with tests to confirm the continued existence of good water communication between injection and recovery well.

First ignition took place on July 21st at a point close to the bottom of the production well, and the process ran for 9 working days. The process was then stopped to make modifications to the production lines to improve water-handling capabilities.

Nitrogen communication was resumed in mid September 1997 and on the 1st of October, the re-positioning of the burner and coiled tubing was followed by a second successful ignition. This time, the oxygen injection rate was increased rapidly.

A third ignition was made on the 4th October at a point 60 metres upstream of the first cavity but the violence of the ignition caused some damage to the ignition well. Sixteen hours later, a premature depressurisation of the well led to the end to gasification in this channel. The process was finally shut down on the 6th October.

The recovery well completion tubing was removed for examination and corrosion tests in March 1998 and a programme of post gasification drilling and coring of the cavity took place in June/ July 1998.

Wells were fully sealed with high pressure concrete in September and the plant finally dismantled in December 1998. A total of 301 hours of gasification were achieved.

4.2 Operational Performance

A detailed plan of operations was produced at the start of the project, in the form of a process manual. It took into account the project objectives, the anticipated response of the system, the geological conditions and the expected gas flow patterns inside the reactor. During gasification, these were modified and adjusted as knowledge of the operating characteristics evolved.

The key goals of the gasification stage of the project, in relation to the objectives in section 2.1 were as follows:

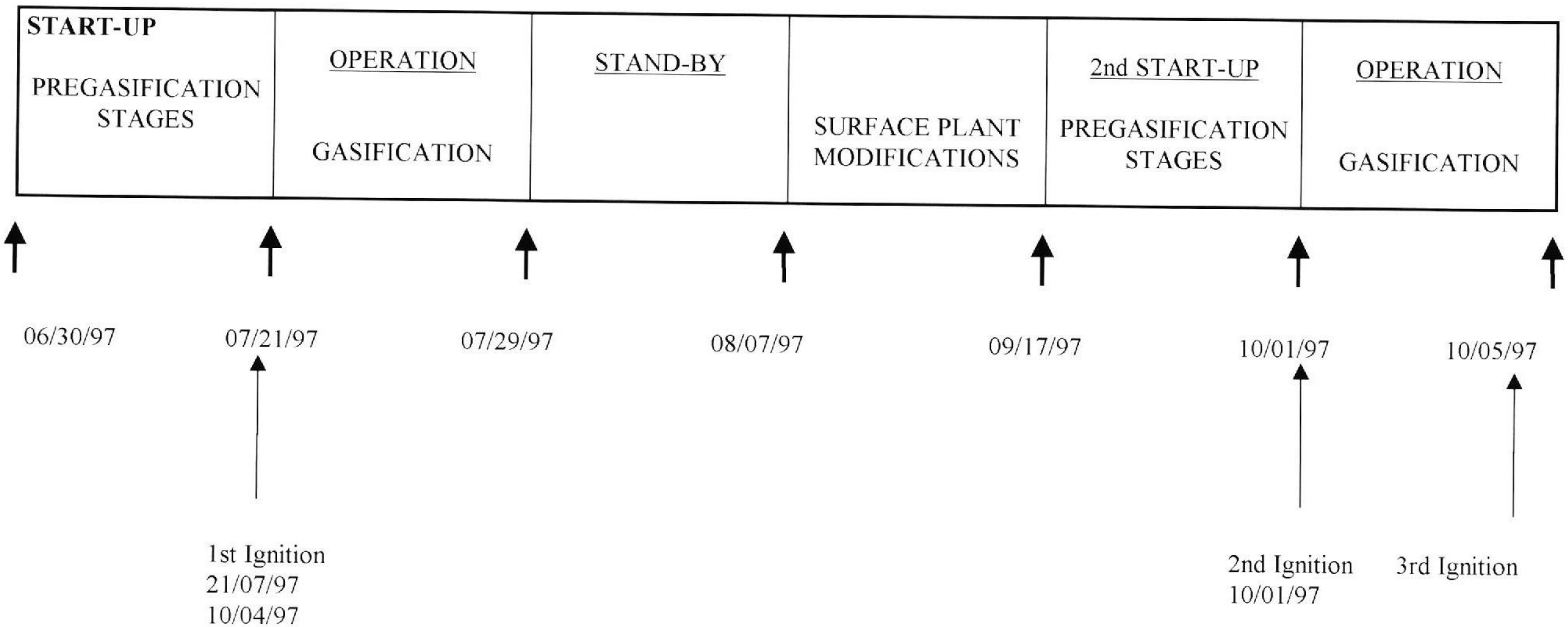


FIGURE 17 Sequence of Operations

- Achievement of final linking between Injection and production wells (Objective 2).
- Preservation of the flow circuit between wells. (Objective 2).
- Development of a channel gasification test by CRIP manoeuvre and studying the possibility of enlarging the gasified area by a transverse filtration gasification test (Objectives 3, 4, 5, 6, 7 and 8).

The gasification operations were designed to address these three key points, namely the final linking, the preservation of the flow circuit and the development of the channel by gasification. In the proposed programme of operations (Section 3.6 of the project proposal), these key points were considered under the following headings:

4.2.1 Final Linking

Originally, it was anticipated in the project proposal that the final linking of the process wells would require the sustained use of techniques such as hydrofracking and retro-combustion to achieve a satisfactory connection. The success of these measures was uncertain, since they were strongly dependent on the distance between the points to be linked. The operation, as discussed in Section 3, was not necessary because an excellent linking was achieved by the initial accuracy of the drilling process. This key point was therefore quickly achieved.

Moreover, the gas flow circuit between the wells was maintained throughout the gasification operations. Neither roof collapse nor the possible accumulation of tar, rubble or water at the well bottom created any significant restriction to the gas flow. This was another key point of the project.

4.2.2 Use of the CRIP Process (Controlled Retraction Injection Point)

A true CRIP manoeuvre is one in which the position of the injection point is moved in order to permit the controlled extension of the gasification channel along the injection well. In the current test, three ignitions were carried out by moving the coiled tubing, with its burner at the tip, to different positions along the borehole.

In addition to these manoeuvres, the coiled tubing and the burner were retracted live, i.e. with gas flowing, to safe positions in the well far away from the high temperatures of the cavity. In all, the coiled tubing was moved seven times during the gasification periods, and although the resultant shape of the cavity is not known for certain, the combination of ignition and CRIP maneouvre achieved a lengthening of the cavity which would not have occurred otherwise.

The tests are further proof that the CRIP manoeuvre, which is the key to channel gasification worked successfully, both mechanically and thermodynamically.

The third ignition point was located to the rear of the limestone section, where the channel made further contact with the coal. The CRIP manoeuvre itself was successful but the ignition was uncontrolled and led to a later failure of the injection well, as discussed in the next section.

4.2.3 Development of Channel Gasification

The goal of the gasification tests was to create a sequence of connected cavities along the injection channel using the CRIP manoeuvre described above.

The operation was performed in three stages, two of which resulted in sustained gasification operation.

The first stage, which lasted 9 days, was carried out at low oxygen injection rate. The quality of the product gas obtained from the first moment was very close to the theoretical predictions for the test conditions and both the gasification operation and the control of the process progressed satisfactorily. Nevertheless, the water content in the product gas was much higher than predicted after the second day of gasification. It was probably caused by the cavity growing and reaching the higher permeability sand layer above the seam roof.

The water created handling difficulties in the surface plant, which had only limited liquid disposal capacity. Further ignitions were delayed until a review of the plant had taken place. The outcome was a decision to temporarily stop the process while modifications to the plant were undertaken.

The second stage was then initiated. The modifications to the surface plant allowed the second gasification stage to be performed with the process totally under control and at much higher oxygen injection rates. The cold and previously flooded reactor was successfully re-ignited (a first in underground gasification), and this time, the oxygen injection was rapidly increased in order to raise cavity temperatures quickly. Again, gas quality was high and satisfactory control of both the underground reactor and surface plant was maintained. The process responded well to variations in the oxygen-input rate.

The decision to move to the third stage was made even though gasification was proceeding satisfactorily. It was taken in order to access a much larger area of virgin coal and involved performing a CRIP operation and stopping the oxygen injection for a few hours, prior to the preparation of the third ignition.

The objective of creating a gasified channel along the whole length of the borehole was not totally reached, but the operation of the coil tubing and its ability to make repeated ignitions worked well.

The aim of the retro-combustion test and second gasification tests was to check the possibility of using the filtration process to gasify the coal surrounding the already gasified channel. The vertical injection well located thirty metres from the axis of the channel would be used and past experience in other field trials indicated that retro-combustion would be required in order to achieve the necessary permeability.

The abrupt end of the channel gasification test led to the abandonment of this test, in spite of having the Injection Well (IW2) pressurised and ready for operations. It was considered that success would be very low due to:

- The short length and lateral extension of the channel gasifier which had been created,
- The impossibility, because of the damaged injection well (IW1), of progressively transferring the injection from IW-1 to IW-2.
- Previous modelling of the local geophysical conditions, which suggested that the conditions were unfavourable to the filtration process.

The remaining project effort was focussed on the investigation of injection Well-1, an assessment of the possibilities of injection well repair, the evaluation of drilling another deviated injection well and finally the post-burn investigations.

4.3 Equipment Performance

4.3.1 Instrumentation

The use of optical fibres as a temperature monitoring system inside the well worked very satisfactorily under the hostile and pressure conditions of the well even though they had never been tested under these conditions before.

The temperature of every metre of injection and production well was always available in the control room and was a considerable advance over the single point measurement of the thermocouple. In addition the fibre optic system was shown to be suitable, by monitoring the fibre burnout, of following and measuring the advance of the underground reactor.

The monitoring of the process, the remote control of the plant and the gas analysis unit for product gas composition all worked perfectly.

4.3.2 Underground Completion Equipment

The coiled tubing design, which used a single tube from top to bottom passed the reliability and performance tests. All CRIP manoeuvres were carried out without difficulty and the tubing break that necessitated termination of gasification could not be attributed to a coil tubing failure.

Moreover, the plant equipment for injecting the gasification agents, for controlling the underground pressure and handling the production gases operated successfully. The problems of water management, found during the first gasification period were a result of uncertainties in the hydrogeology, not of any installation failure.

The corrosion investigation indicated that the material selected for wells and surface pipelines met the design requirements, even though more extensive trials of longer duration would have been necessary for a complete materials evaluation.

Improvements are required in the security and monitoring of injection wells in order to avoid the underground failure that occurred. After the gasification operations, a detailed study was made of methods to detect abnormal flow in the injection well. Solutions to those problems were proposed but not tested in the current trial.

4.4 Operational Results

4.4.1 Measured Data

The measured data from the process are shown in the following two tables as aggregates for the two periods of gasification.

	1st Gasification Tons	2nd Gasification Tons	Total Tons
Injection			
Total Oxygen	31,4	58,5	89,9
Nitrogen used in wells	128,2	63,3	191,7
Production			
Total Gases at Surface	215,4	274,1	489,5
Gas from Reactor	177,4	265,8	443,2
Gas Losses to Strata	73,6	109,6	183,2

TABLE 1 Aggregate Process Data

Product Gas	1st Gasification Period		Total	Expected
	1st	2nd		
CO_2	43,4%	39,4%	41,0%	36,0%
CO	8,7%	15,6%	12,8%	16,6%
H_2	24,9%	24,7%	24,8%	21,0%
CH_4	14,3%	12,4%	13,2%	16,0%
H_2S	8,8%	7,9%	8,3%	4,6%
LHV (dry basis)	10 907 kJ/m^3	10 907 kJ/m^3	10 907 kJ/m^3	11 000 kJ/m^3
Av. Power at Surface	1,26MW	4,48 MW	3,19 MW	–
Peak Power (hr. average)	1,95 MW	7,90 MW	–	–

TABLE 2 Product Gas Composition

The expected gas composition column, are those made in the original estimation when the project was proposed.

4.4.2 Underground Mass Balance

The underground reaction between the injected gases and the coal seam are not known with certainty because the process of gasification depends on both temperature and the spatial growth of the reactor with time. These uncertainties were resolved by assuming an average char composition for the affected material left underground and undertaking a series of mass balances on the elemental compositions, as indicated in section 2.4. These calculations contain a certain margin of error, because the assumptions for unknown parameters have to be made. The results of the mass-balance calculation are as follows

	1st Gasification Tons	2nd Gasification Tons	Total Tons
Total Coal affected	94,1	199,3	293,4
Water influx to Strata	91,0	315,2	406,2
Gas losses to Strata	73,6	109,6	183,2
Char deposit left U/G	9,9	50,9	60,8

TABLE 3. Mass Balance Results

The coal affected is material that suffers any transformation process whether by gasification or pyrolysis. The difference is that gasification is a process of conversion of coal or char into gas, whereas in pyrolysis, the coal loses volatile components and forms char in the absence of oxygen when exposed to the increasing temperatures caused by coal combustion.

The water influx in the above table represents all the water that enters from the surrounding strata to the gasifier and takes into account, the moisture in the coal, the water required for gasification and the total water brought to surface. Some of the influx water will have passed through the reaction zone, but most of the water would have bypassed it and entered directly at the bottom of the recovery well.

The mass balance also allows an estimate to be made of the gas lost from the gasifier into the adjacent underground strata.

4.4.3 Observations and Conclusions from the Data

The composition of the product gases obtained during gasification lies within the predicted range for all the gaseous components. Figures 18 and 19 also show a remarkable stability in gas composition under all conditions.

During the second gasification stage, the output responded smoothly to changes in the oxygen injection flow without changing the gas quality. The process could be operated with stability and with a high degree of flexibility. Start-up was smooth and rapid.

The highest power outputs were reached during the second gasification and peaks of up to 8mW thermal output were observed after the process had stabilised.

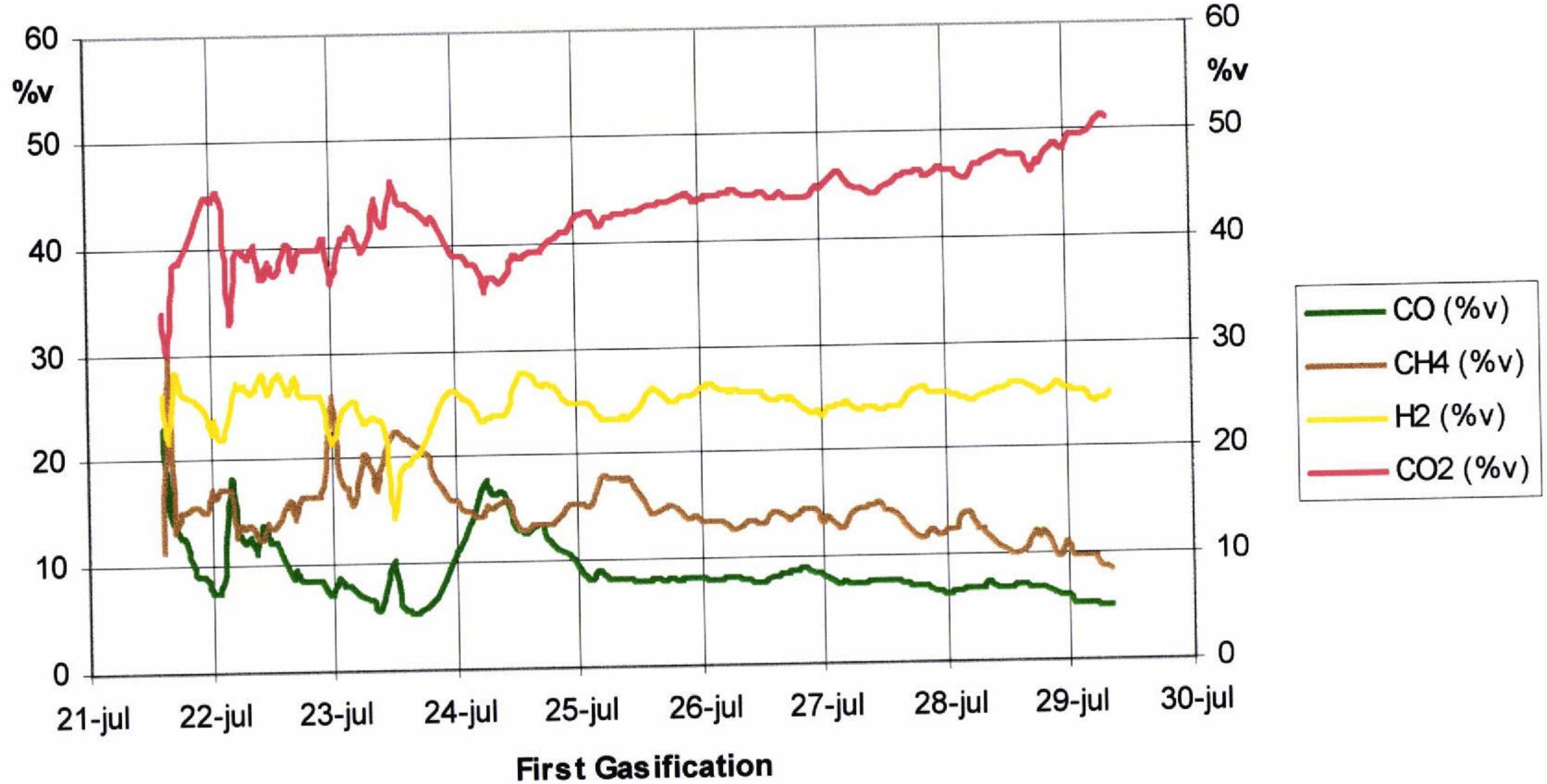


FIGURE 18 Gas Composition on Dry N2 Free – 1st Gasification

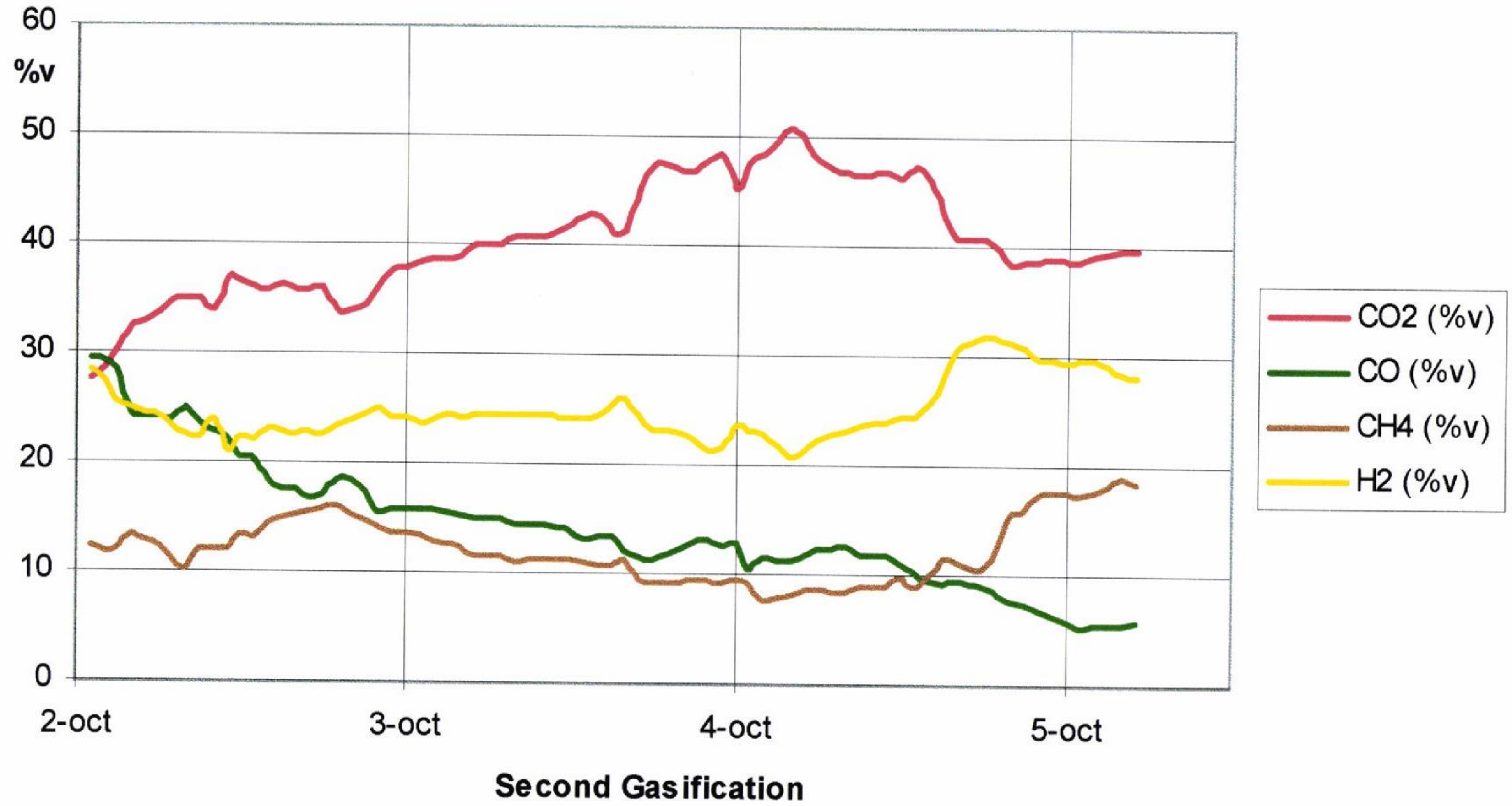


FIGURE 19 Gas Composition on Dry N2 Free – 2nd Gasification

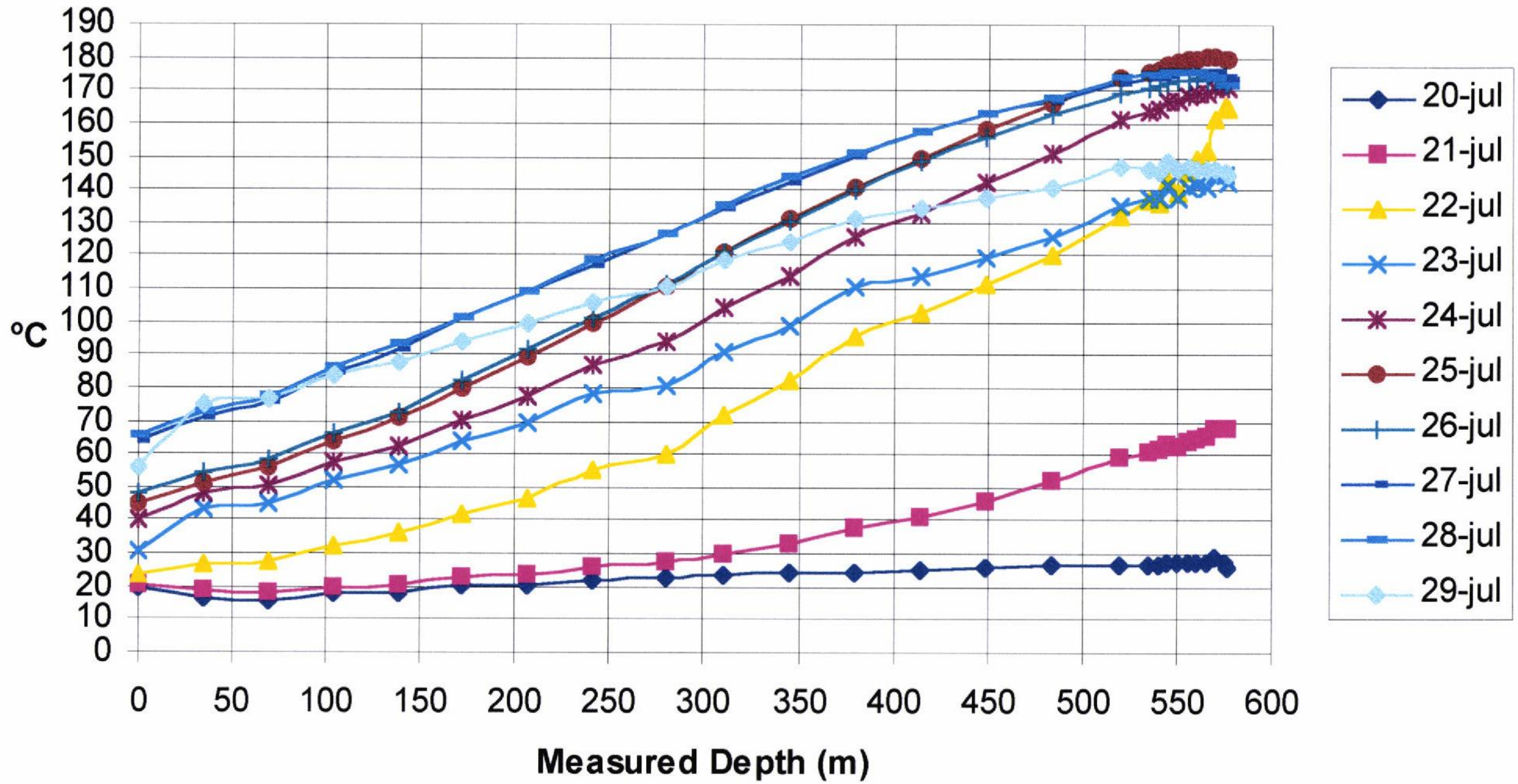


FIGURE 20 Optical Fibre inside 4.5" Recovery Well Pipe- 1st Gasification

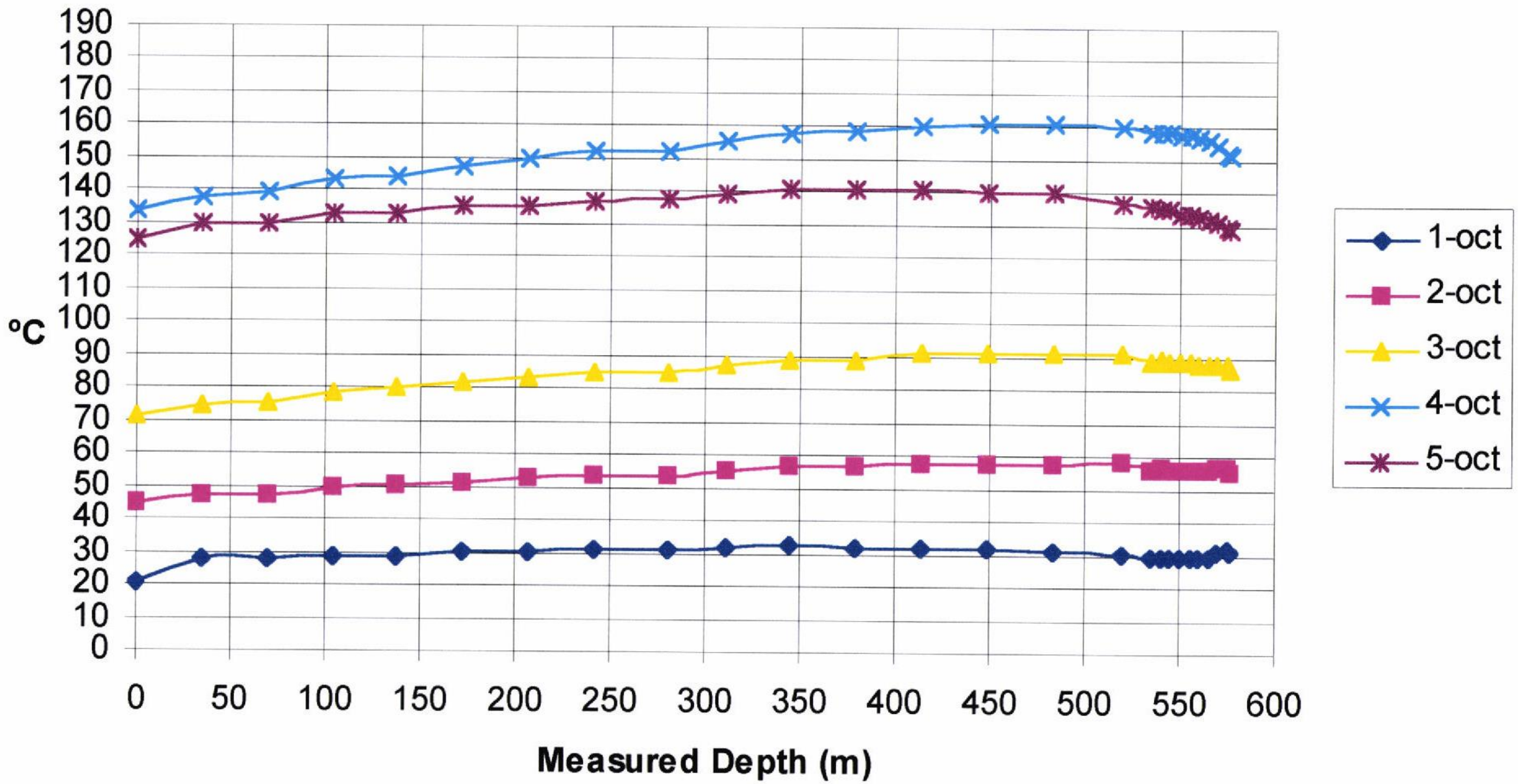


FIGURE 21 Optical Fibre inside 4.5" Recovery Well Pipe- 2nd Gasification

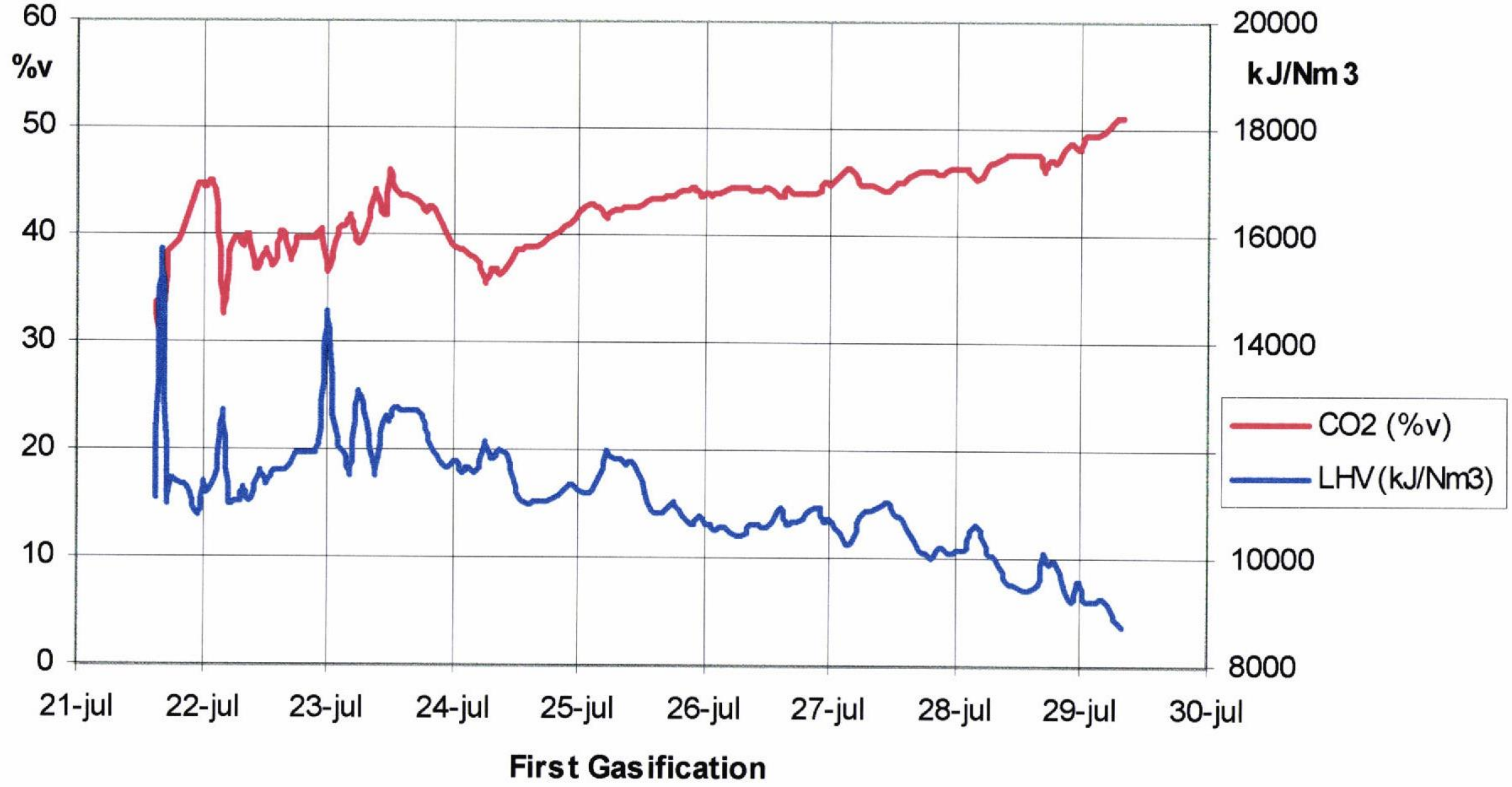


FIGURE 22 Gas Quality on Dry N2 Free Basis– 1st Gasification

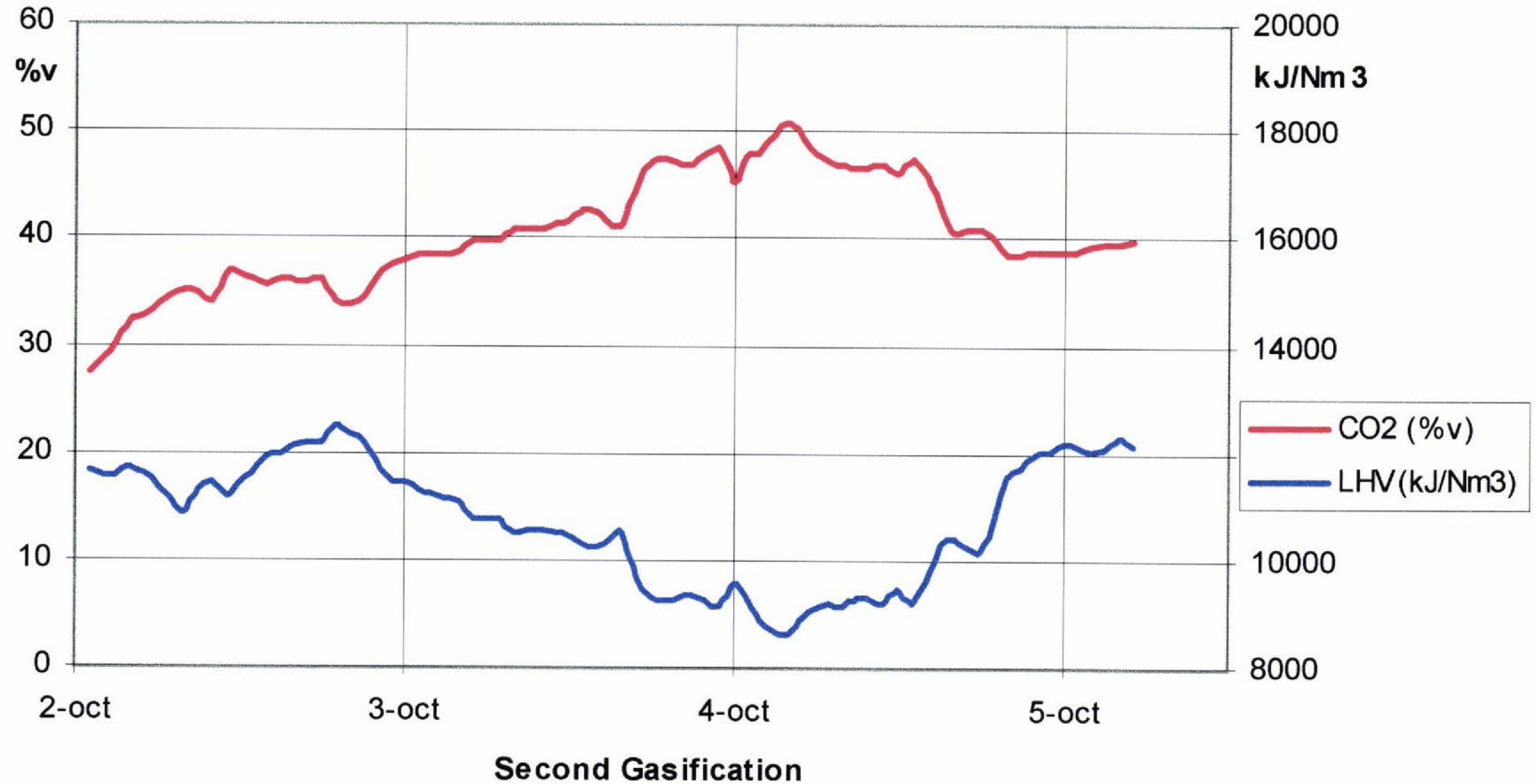


FIGURE 23 Gas Quality on Dry N2 Free Basis– 2nd Gasification

No water or foam was injected into the well during the whole of the trial. This was a consequence of the higher than expected underground water influx, which was sufficient to meet the requirements of the chemical reactions of gasification. On the other hand, this influx, which came from the permeable sand layer above the coal seam, was uncontrolled and created the risk of quenching the reactor.

Recovery wells temperatures were monitored for the two gasification periods and are shown in figure 20, 21. In the first gasification test, temperature did not exceed 65°C at the top of the well, and at the bottom the well, temperatures gradually rose from ambient to 180°C at the end of the ten day period. In the second series of gasification tests at much higher oxygen rate, the surface wellhead temperature reached 140°C, while the final temperature at the bottom well was similar to those in the first test.

Temperatures in all cases were well below the design limit for material selection.

Gas losses from the cavity into the permeable sand layer above were also high and caused both reductions in the efficiency of the process and a potential source of gas injection into the adjacent strata. Better geological conditions could have prevented or reduced this loss.

The heating value of the product gas, figures 22 and 23 on a dry nitrogen free basis lied between 10 000 kJ/Nm^3 and 13 000 kJ/Nm^3. The highest values occur just after the start of gasification.

The results indicate that although thermodynamic equilibrium had been reached for the main reactions, the high in-situ heat losses caused by excess water vaporisation would have lowered reactor temperatures and resulted in a lower energetic efficiency for the process.

A secondary effect of the low reactor temperature is that coal pyrolysis could have been enhanced at the expense of gasification especially during the start-up conditions. On the other hand, the ratios of CO/CO2 demonstrate that gasification, as opposed to pyrolysis took place under the conditions of the test and the probability remains that improved process management and better geological conditions will reduce the most significant losses of the underground gasifier.

4.4.4 Comparison with other Experiments and Process.

The gas quality results are compared with those obtained in the Centralia gasification trial at shallow depth in the United States.

The benefit of working under high pressure can be observed from these results. The lower heating value of the product gases from the UGE trial is better than that from Centralia and similar to surface coal gasification, where process efficiency has essentially been optimised and only limited scope for improvement remains.

	UGE Raw gas basis N_2 free	CENTRALIA Raw gas basis N_2 free	SURFACE After cleaning N_2 free
Operating Pressure (Bar)	53	4	25
Gas Composition			
CO2	41,0%	34,9%	4,48%
CO	12,8%	20,8%	69,98%
H2	24,8%	38,1%	25,53%
CH4	13,2%	4,7%	0,01%
H2S	8,3%	1,5%	0,00%
LHV (dry basis) (kJ/m3)	10 907	8 734	10 029

TABLE 4 Comparison of Current Results with Centralia

In situ gasification has a number of potential advantages:

- High pressures are technically and economically feasible in situ. Increasing the pressure raises the process efficiency and gas heating value.
- It obviates the problem of ash removal.
- It is flexible in operation since a wider variation in reactor pressure is potentially permissible provided it lies between the hydrostatic pressure and the formation fracture pressure.
- It is not necessary to match the injection and production rates at all times as an in situ gasifier also function as a storage system.
- An in situ gasifier has long time constants which facilitate process control.

4.5 Post-burn Activities

The EC proposal anticipated a series of post-burn activities to investigate, if possible, the shape of the cavity and the condition of the underground components.

The post-burn studies were in two parts:

- Drilling and coring

- Corrosion analysis

4.5.1 Drilling and Coring

The aim of postburn drilling was to obtain data on gasifier geometry and extract samples from the cavity for subsequent chemical and petrographic analysis.

Indications of cavity volume and position, at the end of the gasification tests, were available from both the underground temperature measurements and the mass balance. This information was used to design a programme of post-burn cavity drilling and coring.

The drilling programme consisted of constructing a single vertical well and then deviating from it with a series of boreholes, each of which entered vertically into the expected position of the cavity at different points as shown in figure 24. Three successful deviated boreholes were drilled as follows:

1. On the cavity axis, 7 metres from the production well bottom
2. 5 metres West of the cavity axis and 9 metres from the well bottom
3. On the cavity axis at the final injection point of 19 metres

Drilling of each well progressed satisfactorily to within a vertical distance of 5-7 metres of the cavity: thereafter, the resistance of the strata to the drill bit was lost. This indicated that the active caving zone extended upwards to this height, i.e. twice or more the seam thickness. It also proves that the edge of the cavity lies beyond the drill holes as shown in figure 25 and is consistent with the calculation of volume from the mass balance.

The width of the cavity is at least five times the coal seam thickness and the results verify that some backward growth has taken place with respect to the last injection point.

Coring of the three boreholes led to the recovery of some geological material from below the coal seam strata (carbonaceous clay and limestone). On the other hand, no material from the coal seam was found in the core barrel. It was assumed that either the coal had disappeared during gasification or the remaining material, char or ash was so unconsolidated that it could not be collected.

Microscopic and chemical analysis has been carried out on the small carbonaceous samples in the core samples but beyond some general indications of temperature changes and the presence of tar, the results have been inconclusive.

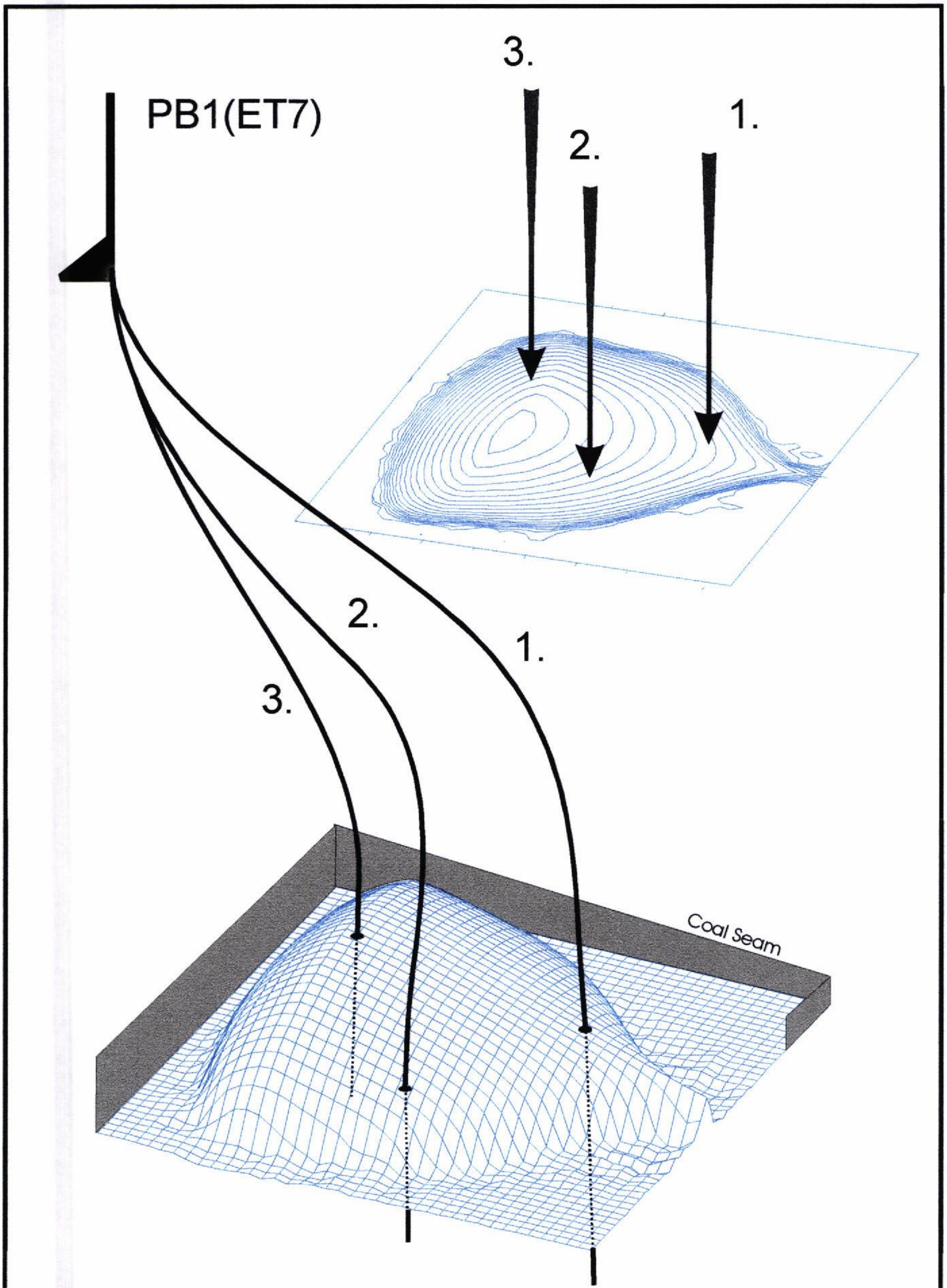


FIGURE 24 Postburn Coring Trajectories into the Cavity

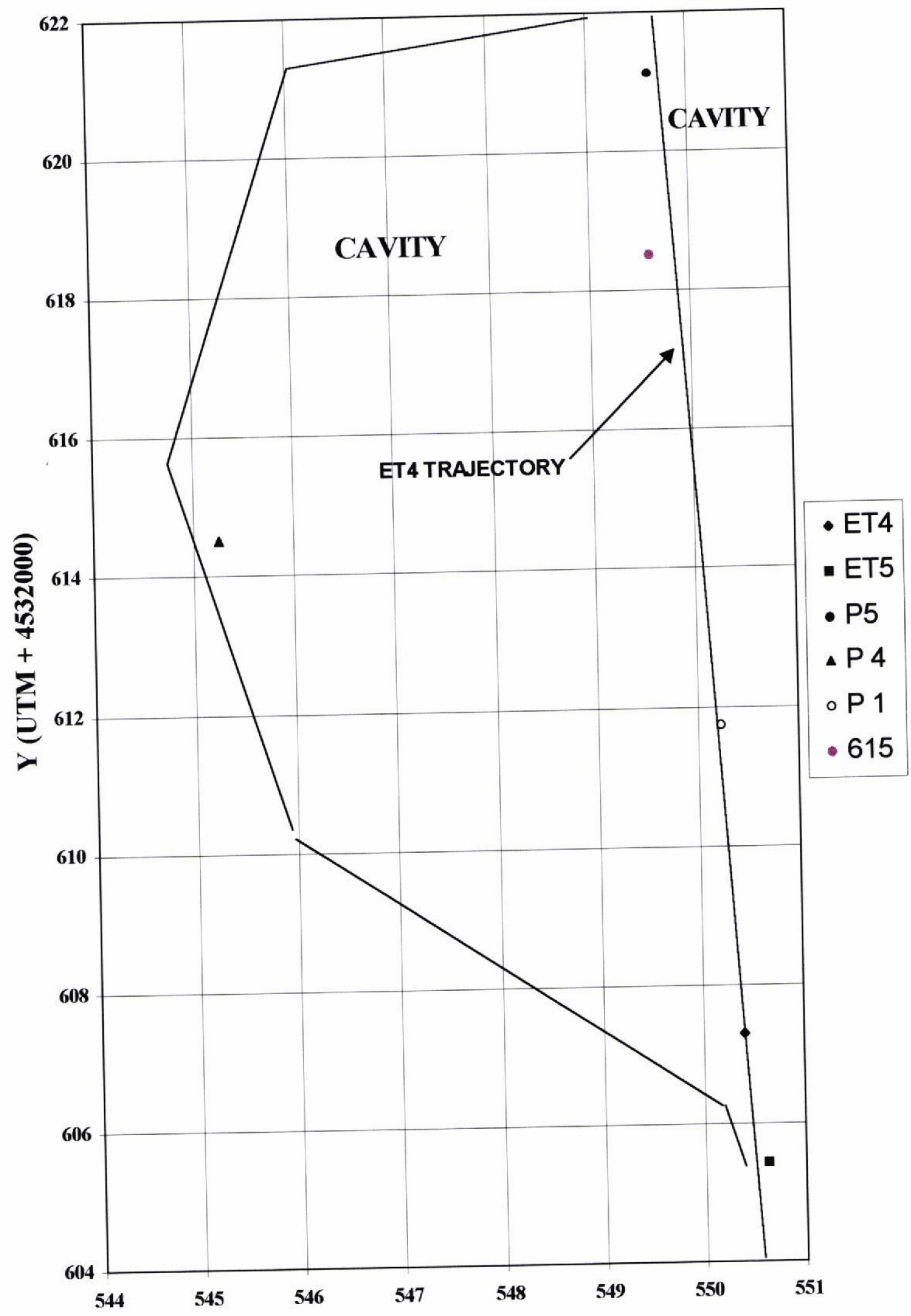


FIGURE 25 ET 4 and ET 5 Casing Shoes and Coring Points: Plan View

Much larger samples of char, ash and affected coal from the cavity were collected from the bottom of the production well, after the post burn drilling works. The analysis of these samples has shown that the majority of the recovered coal particles was strongly transformed by the process with evidence of high levels of pyrolysis. The measured porosity, in terms of specific surface, was similar to that for partially pyrolysed char from the Teruel area.

4.5.2 Corrosion Investigation

Metal samples from both the inner pipes of the production well and the surface production lines were analysed in order to determine if the alloys selected during the project design phase had been suitable.

The selection procedure for corrosion analysis was to sample those points which, according to the location, were subjected to the most hostile conditions of temperature, erosion, di-phasic flows or formed the welds between different alloys.

No corrosion attributable to poor material selection was found. Longer operation would, however have been necessary to obtain definitive conclusions.

4.6 "Sankey" Diagram.

The Sankey diagram in figure 26 shows the energy balance of the process. The chemical energy of the in situ coal is converted into chemical energy, sensible heat and potential energy within the product gas by virtue of its pressure.

A proportion of this energy is lost underground via product gas losses to adjacent strata and via sensible heat loss to the strata and to ground water. These losses were unusually high in the present experiment because of the high permeability of the roof strata, and of these strata being on an active aquifer. In this respect, it must be emphasised that the site was far from ideal, and the fact that the gasification was successful under these conditions gives confidence that the process has a wide potential utilisation.

The Sankey diagram averages the results obtained in the experiment. The share of the energy in the converted coal, which reached the surface in the form of chemical or pressure energy, was 68,7%.

This value would be improved in a 'good' and more typical deep European site with low permeability strata and zero or limited water ingress as follows;

- The gas losses would be drastically reduced
- The gasifier efficiency would be improved via optimised (higher) temperatures to a value of 85-90%; this would raise the heating value of the product gas and reduce the proportion of CO_2
- The heat losses to strata would be drastically reduced, since these losses are mainly a consequence of gas losses and the evaporation of groundwater.

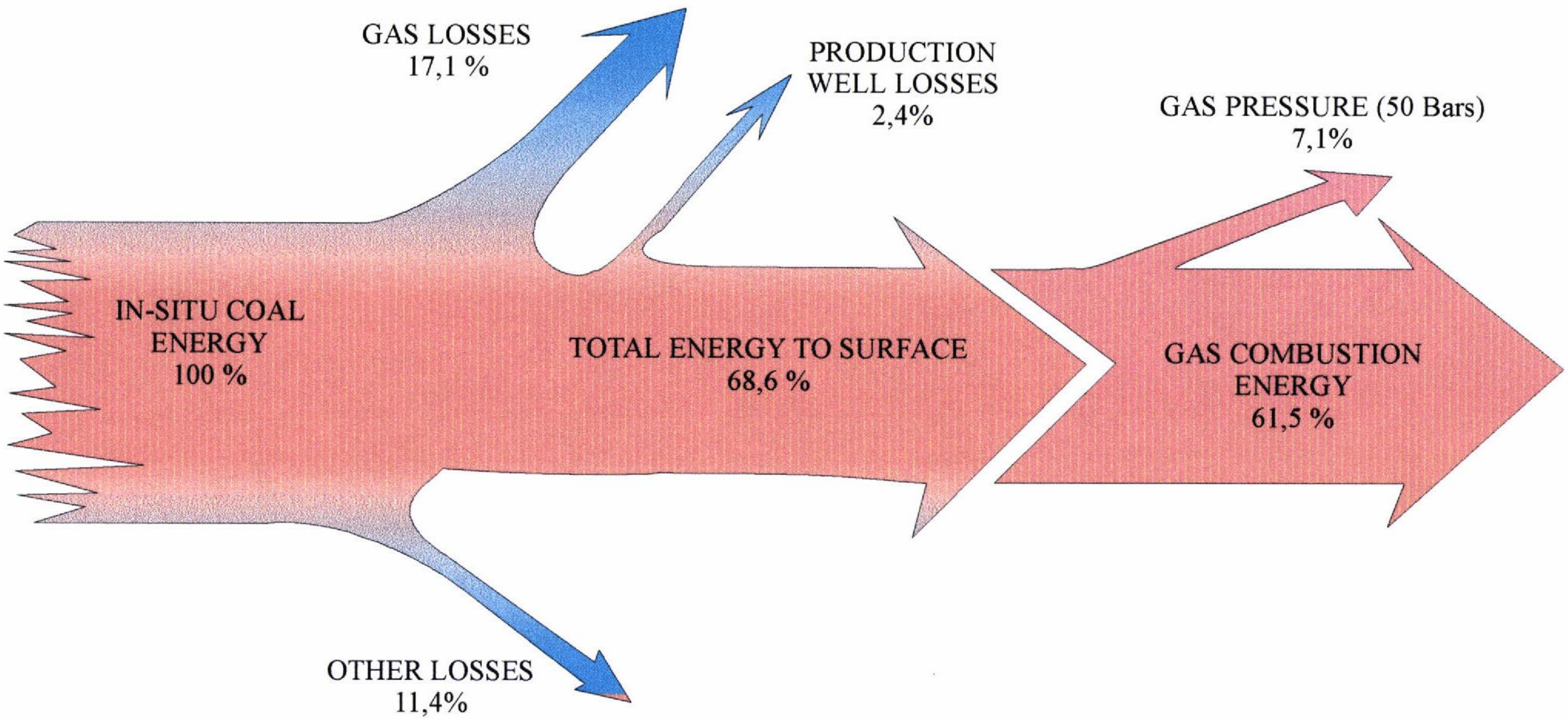


FIGURE 26 Energy from in-Situ Coal

5. ENVIRONMENTAL IMPACT

The environmental impact of the process is a key issue in the evaluation of underground gasification for future commercial chemical and energy production. At the strategic level, the impact has to be compared with the best energy generating processes, likely to be available in medium term, say 10 years. The environmental factors which have to be taken into account, include the atmospheric emissions, the underground effects, and other considerations such as the visual impact, subsidence and safety.

Figure 27 summarises the main environmental interactions of the gasification process. These are now considered in turn.

5.1 Emissions into the Atmosphere

The normal combustion of fossil fuels produces SO_2, NO_x, CO_2 and dust emissions which, in the absence of treatment, are released into the atmosphere.

The sulphur and organic nitrogen compounds, which exist in many coal reserves are converted under the reducing conditions of underground gasification to H_2S and NH_3 respectively. As the raw product gas is obtained at high pressure (53 bars in the UGE project), these pollutants can be separated at surface using proven commercial technologies.

Once eliminated from the gas, the production of electricity by UCG will be almost free of SO_2 emissions, and the chemical NO_x will be significantly reduced in comparison with a conventional coal combustion process. The use of "low emission" gas turbine combustors will further reduce the NO_x produced by reaction between the atmospheric nitrogen and oxygen.

In addition, the high pressure of the process can be used to facilitate the extraction of the product gas by physical or chemical processes. If the CO_2 is permanently removed from the atmosphere by reinjection into the well or other means, the emissions into the atmosphere is then substantially reduced. Reinjection of CO_2 into disused wells is a topic of current interest and research.

The average product gas composition from the trial, and a "best" case, based on the composition of previous UCG trials have been used to calculate the emissions from a conventional and combined cycle power plant operating on UCG gas. These are compared with alternative power generation systems in table 6.

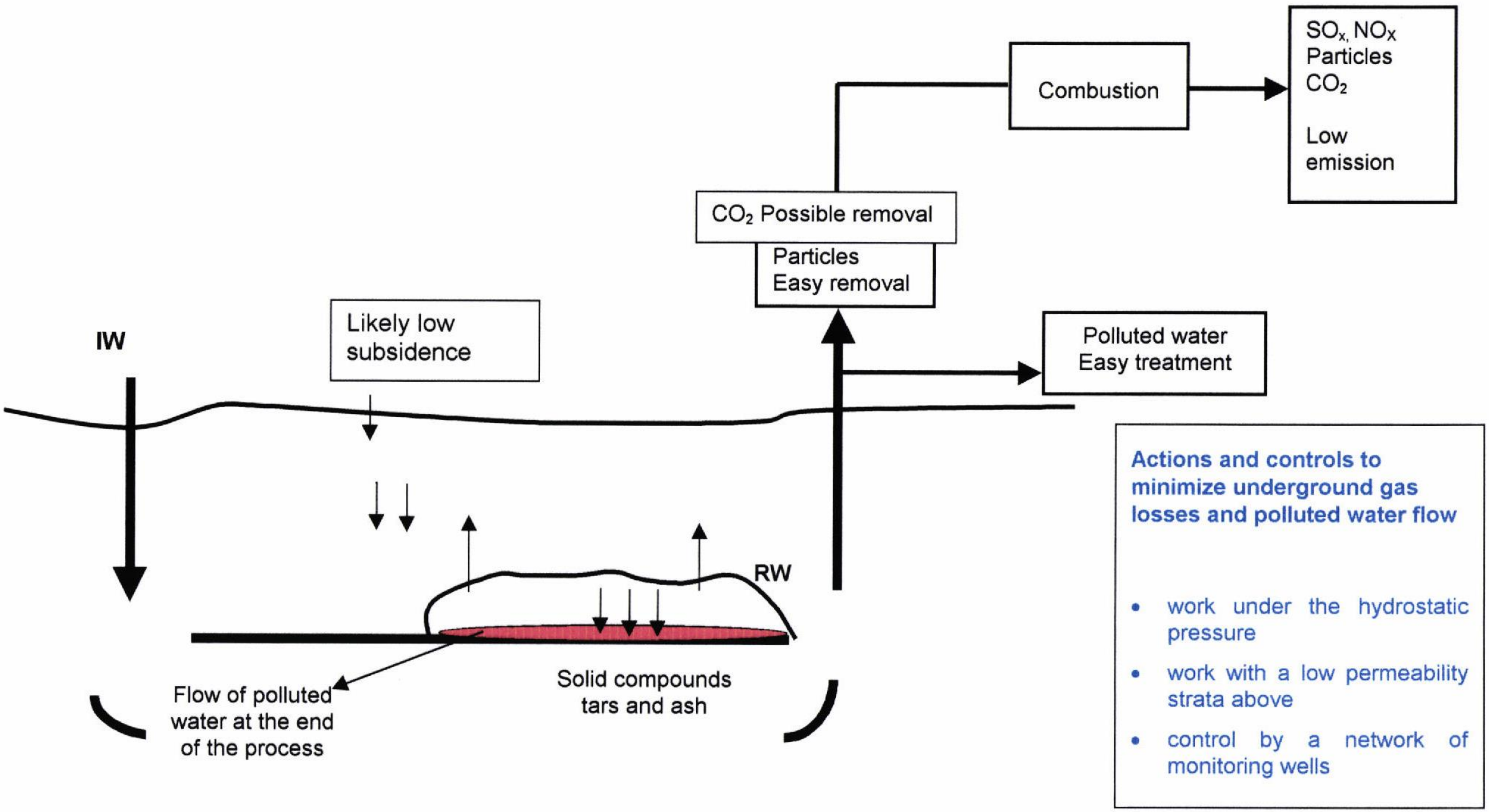


FIGURE 27 Summary of Environmental Interactions

Fuel	Process	Efficiency %	CO_2 Emission tons/MWh
Current UCG Trial Results			
UCG gas	Modern Steam Plant	38	1,14
UCG gas	Combined Cycle	46	0,94
UCGgas(CO_2Sep.)	Combined Cycle	46	0,44
"Best" UCG Gas -Previous Trials			
UCG Gas	Modern Steam Plant	38	1,00
UCG Gas	Combined Cycle	46	0,83
UCGGas(CO_2Sep.)	Combined Cycle	46	0,44
Natural Gas	IGCC	46	0,43
Coal (PF)	Modern Steam Plant	38	0,93

TABLE 6 Comparison of CO_2 Emissions

The table shows that the CO_2 emissions from plant powered by underground coal gasification compare favourably with modern PF coal plant for the same power output. CO_2 separation using proven technology reduces the CO_2 emission levels to those for natural gas powered plant.

5.2 Underground Environmental Impact

The effects of the process on the underground environment are caused by gas losses from the cavity and the possible flow of water pollution into the surrounding strata. Analysis of samples has shown that the pollutants from the gasifier are mainly phenols, and a small quantity of ammonia and sulphides. These also have the effect of raising the chemical and biological oxygen demand (COD & BOD) of the water and changing the pH levels.

If the underground gasifier is in contact with a permeable layer or aquifer, the correct selection of the operating pressure reduces the risk of underground water pollution and attenuates the gas losses. A pressure slightly below the local hydrostatic level encourages water to flow from the surroundings to the gasifier and tends to block the micro-pores, which hinders the escape of the gas through the strata.

Good geological and hydrogeological information of the zone is essential in order to set the operating parameters. At the same time, the proper selection of the site to be gasified may result in a low environmental impact.

During the gasification operations, monitoring of both the surrounding underground gasifier and the neighbouring surface water are required in order to detect any undesirable and uncontrolled occurrence.

The monitoring and analysis of the cavity water was undertaken at "El Tremedal" to evaluate the possible environmental impact of the gasification process. The studies showed that residual contamination was very low at the end of the process. It is believed that most of the phenols and the other pollutants were brought to the surface in the water extracted during the operations and, in fact, the high water ingress in the current trial favoured the removal of pollutants during gasification.

5.3 Subsidence

Surface subsidence, as in traditional mining, is a potential constraint on the selection of sites for UCG. No experimental data are available for evaluating the degree of subsidence for gasification at great depths, and the small dimensions of the cavity provides no useful information.

The factors that are likely to influence the degree of surface subsidence include:

- the depth and thickness of the coal seam
- the characteristics of the adjacent strata
- the mechanical properties of the char, ash and other remaining material in the gasified zone,
- The mechanisms related to the cavity roof collapse during gasification.

Subsidence damage is generally localised and is associated with the intersection of the shear/slip planes migrating from the boundary of a mined out area with the surface. These slip planes correspond to the direction of maximum shear stress, generally at 45^0 to the vertical.

At great depth and moderate coal seam thickness, the effect at surface is likely to be small. Nevertheless, in the future design of a commercial or semi-commercial project, which includes the development of several gasifiers, possible subsidence effects must be considered and, in the absence of data from UCG trials, the experience of traditional coal mining will need to be used.

5.4 Surface Impact

The visual and environmental impact at surface will be determined by the land requirements for drilling and surface plant, and the effect of plant operations.

In a commercial site, the drilling area and the plant itself could be widely separated and will have to be connected by piping systems, which relocate as the coal seam becomes exhausted. On the other hand, deviated drilling may allow the clustering of the surface well heads and a reduction in the surface impact.

The environmental impact of the surface facilities and the plant operation is less than conventional mining because the reactor is left underground and the non-gasified materials remain in situ. In comparison with other technologies, many process installations, coal storage, waste dump, tracks for transportation are not required.

5.5 Environmental Actions and Controls

The project was subjected to the full environmental requirements of Spanish law and met all the conditions. An important topic for the authorities was the water production at the surface which was classed as toxic material because of its phenol content. Estimates of likely concentrations and volumes had to be made from previous underground gasification tests.

The results and conclusions were submitted for environmental approval, which was granted on condition that suitable environmental insurance was obtained. The main difficulty was the lack of comparable data from previous experience because of the novelty of this process.

The composition of the product gas was exhaustively analysed before final incineration, both to study the process efficiency and to detect the presence of possible pollutants. No compounds, which could be considered environmentally dangerous, were found.

The additional actions carried out to control the underground water pollution were.

- A study of the hydrogeology of the zone. This allowed the velocity and direction of underground water flows to be calculated and an estimate of the possible dispersion of contaminates to be obtained.
- An analysis of water sources of the surrounding area. No interaction has been detected.

5.6 Environmental Conclusions

The main conclusions of the current trial are:

- No pollutant apart from the H_2S were detected in the raw product gas. This was a result of the high sulphur content of the particular coal seam.
- Full analysis of the produced water throughout the gasification period indicated that phenols reached concentrations of up to 550ppm but these quickly fell to very low levels when the process ceased.
- Residual concentrations of phenols in the cavity at the end of operations were less than 2ppm. It is believed that most of the pollutants were brought to the surface with the extracted water.

- The current trial experienced significant gas losses from the gasification zone to the surrounding strata. Factors which contributed to these losses were the presence of an upper permeable strata above the coal seam and a working pressure above the hydrostatic.
- Monitoring of the surrounding water sources, i.e. local wells and river, have shown that no interactions have occurred after two years of the monitoring programme. Monitoring will continue for an additional three years.
- The trial demonstrated that all legislative requirements can be fully satisfied and insurance companies will provide pollution cover for trials of underground gasification. This could be an important precedent for the future of UCG in Europe.

The environmental issues highlighted by the study are;

- Clean up of the sulphur and nitrogen compounds in the raw product gas can be carried out with proven commercial technologies. Removal of these constituents is more efficient at the high working pressures and concentrations of the product gas compared with the retrofit equipment of flue gases.
- Separation of CO_2 is technically possible at the working pressures of the process. Assuming the CO_2 is not then released to the atmosphere, the resultant emission levels from UCG fired generating plant are comparable with those of natural gas.
- The exhausted cavity of underground gasification and the surrounding affected coal are a possible location for re-injection. On-going research into reinjection into coal seams and exhausted oil wells may be applicable to UCG cavities in the future.
- The underground environmental impact is dependent on the geological and hydrogeological conditions, and site selection for future experimental and commercial projects must include a full analysis of the conditions which control the underground dispersal of both liquid and product gas. The impact of underground pollution decreases with depth, and the concerns during previous gasification trials in shallow coal fields will be diminished.
- Surface issues, such as subsidence, the lower visual impact of drilling operations and the simplicity of land reclamation are possible additional benefits of UCG.

6. SUCCESSES AND COMMERCIAL OUTLOOK

6.1 Success of the Project

The feasibility of underground coal gasification at intermediate depth, which was the project aim, has satisfactory been demonstrated. The project achieved most of the initial objectives and specifically achieved the successes listed below.

The major successes were:

- All the objectives related to the drilling were attained, both the execution of an in-seam deviated well and the linking between a deviated injection and a vertical production well.
- Two successful ignitions, in different points of the borehole, and seven manoeuvres of the coiled tube were performed. The coiled tubing operated perfectly satisfactorily on all occasions.
- The production gas had a quality and heating value consistent with the theoretical estimates and would appear to be suitable for industrial use in chemical and power production.
- Good process control and turndown was achieved and the wells were shown to be capable of high oxygen injection and gas production flows.
- Real data on cavity water composition were obtained for environmental impact evaluation.
- The engineering equipment, the control systems and the specially designed monitoring systems all operated well for an experimental plant.

The less successful aspects of the project were:

- The duration of the gasification phase was too short. The project had to be stopped without gasifying all the coal, due to well damage caused by the third ignition. It could not be repaired without major re-drilling.
- The filtration gasification test could not be performed, in spite of having the installation ready, because of the premature failure of the injection well.
- High water ingress into the cavity hindered the full development of the first gasification operation, required plant modification, and created both delays and extra costs. A thorough evaluation of the hydro-geological conditions is a requirement for any future trial.

6.2 Economic Viability

This first trial was never intended, on its own, to evaluate the economic viability of underground coal gasification. More data is required to reliably assess the operating economics but some comments can be made in relation to a previous economic evaluation made by the European Working Group in 1989.

The EWG report indicated that the technology could, under favourable circumstances, provide a competitive supply of synthetic gas for future energy or chemical needs. The basis of this assessment was a set of assumptions about the cost of drilling and operating process wells and the ability of a single gasification channel to extract energy from a section of the coalfield.

This trial has shown that at intermediate depth, the developed width of the cavity lies within the range assumed in the EWG study.

Significant investment costs are associated with geological investigation and drilling. Four separate drilling rigs were used to construct the exploratory, process, monitoring and postburn wells and a good deal of experience has been gathered about the costs of drilling and the scope of any future exploration programme for UCG. It is concluded that the overall estimates in the EWG report for drilling costs are still realistic and may even be improved upon as the technology develops.

6.3 Commercial Outlook

The technical outlook for underground gasification at intermediate depth has improved significantly as a result of this trial. A number of technical questions have been resolved, and the chances of success of any future project, experimental or semi- commercial, have been increased.

The advantages of working at great depth, in terms of gas quality and cavity growth, appear to be substantial and warrant a re-appraisal of the technology for future power and chemical production.

The current trial has indicated that the EWG technical assumptions were generally valid, and some factors such as drilling costs and the need for environmental processing are moving in favour of UCG. On the other hand, the availability of imported coal has increased, the cost is low, and conventional mining in Europe is on the decline.

UCG for small to medium scale power generation, say up to (50 MWe), could now be developed relatively quickly and could be an effective complement to the higher efficiency integrated power cycles now becoming available. Those which use coal as the primary fuel in Europe will increasingly rely on imported coal. The economic case for UCG is not proven but, if the remaining technical problems of UCG can be successfully solved and the economics are favourable, UCG offers a strategic option for power generation based on European domestic coal.

Furthermore it allows the possibility of extending the exploitation of currently unmineable indigenous reserves, particularly the reserves under the North Sea.

The environmental case for deep UCG is equally important. Production gas, which reaches the surface at very high pressure, allows efficient gas processing to be undertaken. Solvent extraction can be used under these conditions to remove the nitrogen and sulphur compounds before discharge into the atmosphere. The same techniques can be used to extract the CO_2, and thereby offer a process, which is comparable with the natural gas power generation cycles, in terms of its greenhouse potential. The CO_2 might also be re-injected into the cavity if not required for industrial purposes, although this needs further study.

7. CONCLUSIONS

- The feasibility of underground coal gasification at the intermediate depth of European coal (580 metres) has been demonstrated.

- The new deviated drilling techniques were particularly successful in establishing gas flow circuits through the coal seam. The same techniques were successfully applied to the post gasification investigation of the cavity.

- Valuable insights have been obtained into the gasification process at intermediate depth. Coal, at this depth, was found to be readily ignitable and the subsequent gasification is effective. Particularly important for the future is the apparent confirmation that cavity growth is enhanced with depth.

- The influence of the geological conditions has been observed at various stages throughout the trial. The thickness, position and dip of the coal seam, the presence of faults between injection and production wells and the high water ingress during gasification were all important factors. An important lesson for future projects is the need for detailed studies of the geological and hydrogeological conditions when projects of this type are undertaken.

- An important result has been the confirmation that the engineering completion of the injection and production wells operated satisfactorily. In addition, the CRIP manoeuvre was effective and important user experience has been acquired for the start up and control of the gasification process.

- With hindsight, additional safety devices should have been installed to prevent back flow in the injection well and the subsequent failure. Some re-engineering of the ignition system is also required.

- The gasification process appeared to be highly responsive. An increase in oxygen rate produced an almost immediate rise in power output, and decreases had the opposite effect. It is likely, although not proven in these tests, that the process could be stopped for a long period, perhaps several days or longer, and restarted immediately by oxygen injection. This feature, if proven, would be highly beneficial in power generation.

- Underground gasification has inherent environmental benefits in terms of gas processing and CO_2 removal. The cavity as a source of contamination is now better understood but dispersion of gases and liquids into the surrounding strata need further study.

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FIELD TRIAL OF UNDERGROUND COAL GASIFICATION

BY

UNDERGROUND GASIFICATION EUROPE (UGE)

TERUEL, SPAIN

SECOND PROGRESS REPORT
(ETSU Ref: Coal R032)

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THERMIE

participants

Instituto Tecnológico GeoMinero de España (ITGE), Madrid, Spain

Institution pour le Développement de la Gazéification Souterraine (IDGS),
Liège, Belgium

Energy Technology Support Unit (ETSU), Harwell, UK

This Progress Report has been prepared by

ETSU

Harwell

Oxfordshire, OX11 0RA

United Kingdom

dti
Department of Trade and Industry

INTRODUCTION

Underground coal gasification has considerable potential as a way of releasing the energy content of coal, in a form suitable for power generation and process uses, while avoiding the environmental problems associated with conventional mining.

The concept is not new; trials were carried out in the former USSR in the 1930s, and more recently in the USA and several other countries.

However, almost all this work was at comparatively shallow depths (250m or less). The current project in north-east Spain is being carried out at a greater depth (500m to 600m) and the intention is to develop techniques that will allow confident extrapolation to 1000m or more, since this is more typical of potential reserves in northern Europe.

The project is being undertaken by Underground Gasification Europe (UGE) a European Economic Interest Grouping (EEIG) involving Spain, Belgium and the UK, with funding from the European Commission under the THERMIE programme.

The rationale behind the trial, the basic theory involved and the progress up to January 1993 were covered in the first Progress Report (R009(P1)). This second report outlines the drilling work carried out since then, including the drilling of a third exploration borehole and the design, drilling and completion of the deviated injection well.

FURTHER EXPLORATION/ SEAM SELECTION

The First Progress Report covered the initial site development and the drilling of two exploration boreholes. It had been hoped that these two holes would be sufficient to establish the depths, dips and thicknesses of the two coal seams and to make the choice as to which should be the target seam.

In fact, when the data from the first two holes were analysed, there were some anomalies and some variations in coal quality and seam thickness. It was therefore decided to drill a third exploratory borehole. This served to clarify the position and also showed that the upper of the two seams was the more suitable for gasification. This was on the basis of it having better continuity, a good gamma marker at the bottom of the coal seam and a good limestone floor.

Although this third hole involved some extra cost and a delay to the project, this was not as significant as might be expected. Also its position, near to that of the proposed production well, means that it can be used, during the gasification stage, to give useful information about the linking zone.

THE DESIGN OF THE DEVIATED INJECTION WELL

The target seam dips at an angle of about 30°. The basic requirement therefore was to drill a hole consisting of three discrete parts: a vertical (or near vertical) section, a curved section which would divert the hole through an arc of about 60° and a final section within the coal seam. The start of the curved section (the 'kick-off point') would have to be determined from the predicted seam location, but there would be some scope to vary the radius of the arc as the seam was approached. There were some geological markers above the target seam, to assist in this. However, the best marker was the high natural-gamma emission band near the base of the target seam. It was envisaged that this could be used for guidance for the final portion of the hole.

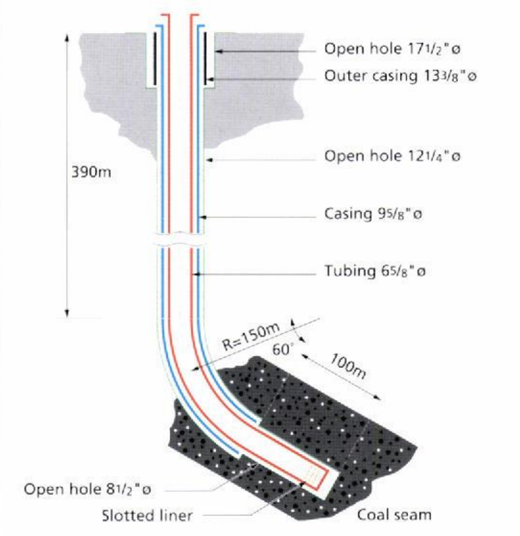

Figure 1 Diagrammatic side elevation of deviated well showing casing and tubing diameters

Deviated boreholes are now comparatively common in oil and gas exploitation. Down hole motors (DHMs) are available that allow comparatively accurate control of hole deviations and measurement while drilling (MWD) equipment is available to monitor and record the actual trajectories achieved.

The drilling depths involved in such exploitation are normally considerably greater than the 500m to 600m required for the UGE project. However, the absolute accuracies required to enter, and remain within, a coal seam about 2m thick are considerably greater than normally involved in oil and gas work.

As is so often the case with engineering projects, the design of the borehole had to be a compromise between several apparently conflicting criteria, namely:

- The minimum size of the injection tubing was governed by the flows expected during the trial.

- The cased portion of the borehole, above the coal seam, had to be of sufficient size to allow insertion of the injection tubing and the various instrumentation cables; but it should not be larger than necessary as hole and casing diameters are two key parameters governing the radius of the deviated portion of the hole.
- The maximum drilling diameter governed the size of the drill rig required, and hence the costs of the drilling operation.
- There were considerable benefits from using standard drill and casing sizes, not only to minimise costs and delivery times, but also so that additional tools or materials could be obtained at short notice if any problems occurred during the actual drilling programme. Such standard sizes are based on American Petroleum Institute (API) specifications, and explain the use of Imperial rather than SI units in the text which follows.
- The design had to be such that contingency options were available should any difficulties be encountered.

The final design choice was basically a 'bottom up' operation. The preferred option was to have a $6^5/_8$" diameter injection tubing. The 'in-seam' portion would generally be of an alloy steel, capable of withstanding the high reaction temperatures. The monitoring cables, consisting of four thermocouples and two fibre-optics cables, were all encapsulated into a single 'flat' cable which was designed to be clamped on to the outside of the injection tubing. This arrangement required the in-seam portion of the hole to be drilled at $8^1/_2$" diameter, and for the 'above seam' portion of the hole to be drilled at $12^1/_4$", to allow insertion of $9^5/_8$" casing. These are all standard drill and tubing sizes for the reason outlined above. In addition, the first 60m, through the superficial strata, was to be drilled at a still larger diameter ($17^1/_2$") to take $13^3/_8$" casing.

The minimum radius that can be satisfactorily achieved in a deviated borehole depends on a number of factors including the geology, the hole size, the casing size and flexibility and the capability of the DHM and associated drilling assembly. After discussions with various drilling companies, it was decided to drill the curved section of the well at 150m radius. This corresponds to a 'build rate' of about 12° per 100ft, which is the normal way that curvature is expressed in the oil industry.

In the event of problems being encountered in drilling the deviated portion of the hole, or while inserting the casing, contingency plans were prepared. These included the capability to drill all or part of the curved portion of the hole at a reduced diameter of $8^1/_2$". This would then be fitted with a 7" casing and the in-seam section drilled at 6", with a $4^1/_2$" injection tubing. Tools and materials for these alternatives were available on site during the drilling programme. These precautions, and the extra costs they entailed, were considered necessary given the high costs associated with the rig standing idle, should a key item of equipment or material not be available.

The basic plan then became to drill vertically to a depth of about 390m, followed by a 60° arc at a radius of 150m and finally a straight portion within the coal seam. This, together with the preferred casing and tubing diameters, is shown diagrammatically in Figure 1. A near-bit MWD system developed by Anadrill was considered for directional drilling but tools were not available when required. A conventional MWD system was therefore used in which the directional sensors were located some 14m behind the bit.

Part of the gasification trial is to attempt the 'Controlled Retraction Injection Point Technique' (CRIP). This requires the ability to perforate/burn the in-seam liner at pre-set points with the help of a downhole movable gas burner.

ACTUAL PROGRESS OF DRILLING

The first truckload of drilling equipment arrived on site on Saturday 16 October 1993. The main plant arrived on 20 October and drilling actually started on Saturday 23 October. Plate 1 shows the drill rig in position.

The initial vertical section was drilled by conventional rotary methods, generally as planned and the $13^3/_8$" casing inserted and cemented in.

It had been intended to drill all the $12^1/_4$" portion using a DHM, but as there was some delay in the arrival of this the first portion, down to about 300m, was drilled by rotary methods. Penetration rates were high and the associated high mud flow rates caused some problems with the screens.

Plate 1 Drill rig on site

At this point the drill string was extracted and the DHM was fitted, using a motor angle of 0.6°. This allowed the operation of the DHM and the MWD system to be proved prior to reaching the proposed deviated section. Verticality at the completion of this DHM drilled section was good. Initial advance was slow, due to the hardness of the Cenomanian marls, but this increased considerably when the Cenomanian/Albian boundary was crossed. Problems were again experienced with overloading of the screens at higher advance rates.

On reaching 393m, the string was withdrawn in order to change the well bottom equipment for the drilling of the deviated section. This included a change of motor angle to 2.42°. After about 50m of further drilling, no further advance was achieved. The drill string was withdrawn and when the tricone bit was found to be in good condition it was decided to change the DHM. The problem still persisted and after various experiments, it was deduced that the upper stabiliser was ledging in the hole with the result that insufficient weight was being transferred to the bit. The drill string was extracted, the stabiliser removed and normal drilling resumed.

Coal was reached at about 510m measured depth (MD, ie the length measured along the arc of the drill-string, as distinct from the true vertical depth) and drilling in coal continued to 556m MD, at which point drilling was stopped. The borehole was then cleaned and the string extracted. This was carried out without any problems, which suggested that the hole was in good condition. It was therefore decided to proceed with the insertion of the $9^5/_8$" pipe. This operation was carried out without any problems as far as 527m, when it became necessary to start mud circulation to clear the presumed accumulation of detritus at the bottom of the hole. The remaining three lengths of pipe were inserted with circulation in operation and without further problems. The pipe was then cemented in position.

After a 10 hour delay to allow the cement to harden, drilling was restarted using an $8^1/_2$" bit and a DHM. Drilling started with a dip 2° greater than the anticipated seam dip. The thinking was that the tool would 'rebound' when it reached the harder limestone that underlies the coal, and therefore naturally stay near the base of the coal. This did not occur in practice and the hole entered, and stayed in the limestone for a distance of about 50m, in spite of all efforts to deflect it upwards. It then entered the seam. The problem then became to reduce the inclination, so as to remain within the seam. This was also found to be difficult, the drill entering the strata above the seam at about 633m MD. Drilling continued with the toolface orientated down until 676m MD. Although inclination decreased the fall off was insufficient to bring the hole back into the coal.


Plate 2 Attaching the instrumentation cable

The difficulty of steering within the coal appeared to be a combination of two effects: the unpredictability of the behaviour of the DHM in coal and on crossing strata interfaces, and the distance between the drill bit and the MWD sensor. The latter meant that information was being received on 'what had occurred' rather than the current position and orientation of the drill bit. A near-bit MWD sensor would alleviate part of this problem, but it is something that needs further work if directional drilling is to be used for commercial UCG.

Although a significant part of the 'in-seam' section is below the coal it is considered to be sufficiently close (approximately 0.5m) to enable combustion to be sustained. This is bearing in mind that the limestone contains a percentage of carbonaceous material. Taking this into account, and also the length of larger diameter hole within the coal seam, there is an effective combustion length of about 90m. While this is less than the 100m target, it is considered acceptable. The option of trying to correct the trajectory by side-tracking was considered, but was rejected, due to possible difficulties when inserting the tubing.

The only design change made at this time was that the number of CRIP points was reduced from three to two. These were located, approximately, at the points where the hole crosses between the coal and the underlying limestone, the logic being that it could be difficult to achieve successful ignition at a CRIP location not actually within the coal.

On completion of drilling circulation was continued for a while to clean the borehole. The drill string was then extracted without any problems of sticking. The $6^5/_8$" tubing was then inserted, together with the instrumentation cable. The latter had to be fixed to the tubing using about 70 clamps. This made the operation comparatively slow, although no particular problems were encountered. The installation of the instrumentation cable is shown in Plate 2. Circulation was applied, as a precautionary measure, during the insertion of the last few lengths.

The well head was then fitted and the pipe and annulus filled with water containing an inhibitor. This operation was completed late on Saturday 6 November, the total time from start of drilling to closure being $14^1/_2$ days, which was within the planned schedule.

OTHER ONGOING ACTIVITIES

The gasification phase of the project will require a range of on-surface plant to:

- provide the oxygen, water and other fluids to be injected into the gasifier
- dispose of the gas produced in a safe and environmentally acceptable manner
- control and monitor the trial.

The outline design of these facilities has been completed and the detail design is now in hand. The site was originally sloping but has been re-contoured into three terraces to provide level areas for the drilling operations. These terraces lead to a layout based on the separation of the three functions outlined above.

Work has also been proceeding on the design of the product well. This requires the solution of a number of technical problems given the temperature and properties of the product gas.

It is intended to report on these aspects, in greater detail, in subsequent Progress Reports

CONTACT ADDRESSES

The office of UGE is located at:
Calle Hermanos Nadal, 27 - 1°
44550 ALCORISA (Teruel)
Spain
Tel: +34 (78) 88 33 04 Fax: +34 (78) 88 33 18

Further information can be obtained from UGE, or from one of the participating organisations listed below. Versions of this document are available in Flemish, French and Spanish.

Instituto Tecnológico GeoMinero de España (ITGE)
Ríos Rosas, 23
28003 Madrid
Spain

Institution pour le Développment de la Gazéification Souterraine (IDGS)
rue du Chéra, 200
B-4000 Liège
Belgium

Manager, Coal R&D programme
ETSU
Harwell
Oxfordshire OX11 0RA

SUMMARY

A field trial of underground coal gasification is being carried out in north-east Spain. The work is being undertaken by Underground Gasification Europe (UGE) a European Economic Interest Grouping involving Spain, Belgium and the UK, with European Commision funding under the THERMIE programme.

This Progress Report, the second in the series, concentrates on one key step in the project - the design and drilling of the deviated injection well. This well started vertically and was subsequently deviated through an angle of 60° to enter the coal seam, reaching a final depth of nearly 600m.