A MECHANISTIC MODEL FOR AXISYMMETRIC CAVITY GROWTH DURING UNDERGROUND COAL GASIFICATION

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Underground coal gasification (UCG) is a process in which coal energy is recovered without mining by artificially enhancing gas permeability in a section of a coal seam, igniting the coal remotely, partially combusting and gasifying coal by means of injected oxygen-steam-air mixtures, and collecting the product gas for cleanup and processing for a variety of end uses. The technology has been the subject of active field, laboratory and modeling research in the U.S. and Europe for more than 15 years, and during this time significant advances have been made and the process is nearing commercialization.

The size of the cavity formed during UCG impacts directly the economic and environmental factors crucial to its success. Lateral dimensions influence resource recovery by determining the spacing between modules, and ultimate overall dimensions dictate the hydrological and subsidence response of the overburden. Field experiments of UCG are expensive, and unless the cavity can be excavated after the experiment, cavity geometry can only be approximately inferred from post-burn coring, thermowell responses, electromagnetic and seismic mapping data and material balance calculations. In 1986, normal coal mining operations at the site of an UCG field test performed in 1983 near Centralia, Washington, the Partial Seam CRIP or PSC test (1), offered a unique opportunity to excavate a cavity of near-commercial scale. This excavation (2,3) provided data on ultimate cavity shape and characteristics which have profoundly aided our understanding of the UCG process. However, the data provide only indirect information as to cavity growth dynamics, and it is clear that a reliable mechanistic model for UCG cavity evolution and gas production would be extremely useful for site characterization and process simulation. Previous cavity growth models (e.g. (4-7)) are of limited use since they rely on one or more of the following: arbitrary assumptions regarding oxidant flow distribution in the cavity, oversimplification of some crucial phenomena at the expense of detailed modeling of others, or boundary conditions on upward or outward cavity growth, either arbitrarily chosen or fitted to field data, which decouple growth rates from heat and mass balance constraints. Also, until now detailed data for full-scale cavity dimensions were not available to compare with model results.

The model described in this paper applies to flat-seam UCG of subbituminous or lower rank coals in which the oxidant injection point remains low in the coal seam, and has progressed, we feel, to the point where it has become a useful tool with predictive ability for these conditions. It is based on a few key assumptions which are difficult to verify fully at the scale of interest, but which seem to be justified by model comparisons with field data. The global cavity growth model integrates results of interacting submodels describing water influx from the coal aquifer, dispersion of injected reactants in a rubble bed at the cavity bottom, thermal degradation and chemical attack of rubble-covered coal sidewalls, and recession of cavity surfaces enclosing a void space in the upper cavity, caused by radiation-driven spalling and gasification. Also, a submodel which calculates the growth of an outflow channel through which hot product gas flows to the production wellhead, is included for cases in which a horizontal uncased production borehole is utilized. The global model is of course highly idealized in the interest of tractability, and all apparent geometrical and physicochemical symmetries have been exploited to simplify the problem, but it retains sufficient physics to describe very well leading order UCG process dynamics.

A mathematical description of the model and its many submodels would require far too many pages than allotted. The following sections describe briefly in words the submodels and their integration into the global cavity growth simulator, present comparisons of model results with results of two field experiments, and finish with a prediction of cavity characteristics for a proposed field test. Complete details of the model and its many parts can be found in (8-15).

MODEL FORMULATION

The model envisions upward and outward growth of a cavity with origin at the point of injection of gaseous reactants. Figure 1 shows typical cavity cross-sections at varying stages of development. The cavity itself consists of up to four zones of differing properties: an ash rubble pile at the bottom of the cavity, left by reacted coal; a rock rubble or slag pile which can exist on top of the ash rubble once the cavity has grown to incorporate overburden rock; and a void space at the top of the cavity through which radiative heat transfer from hot rubble surfaces drives reaction and/or rubblization of exposed coal and rock surfaces. Also, geometrical considerations based on surface area distribution of the coal-void interface and the location of the oxygen source, reinforced by early modeling results and observations of the aforementioned excavated cavity, suggest that a pile of pyrolyzed char rubble can accumulate around the edge of the cavity and is therefore modeled. Densities of the rubble in the various regions are specified and assumed constant. Dynamics of flow, heat and mass transfer, and chemical reaction in and across these zones and in the surrounding coal seam are described by the following submodels, and results incorporated into the global cavity growth simulator. Reaction chemistry is simplified by lumping $CO_2 + H_2O$ and $H_2 + CO$ into singlr gasification reactant and product species, respectively, with suitably defined heats of formation (15). This simplification is justified by the similar sthoichiometric and kinetic behavior of the individual species in the reactions of importance. By use of the assumption of equilibrium of the water-gas shift reaction at the calculated product gas trmperature and a carbon balance, detailed gas compositions can be calculated from model results. The model does not treat tar evolution or its secondary reactions.

Water Influx Submodel Water influx to a UCG reactor plays a major role in determining process efficiency. Water can enter the reactor through drying of overburden rock, gravity drainage, depressurization of the coal aquifer, and reflux of condensate from escaped product gas if gas losses to the formation occur. Although some water in the UCG reactor is essential as a gasification agent, often far more than desired enters the reactor, and the energy necessary to vaporize and heat it to the product gas temperature is essentially lost.

The water influx submodel used in the global simulation, described in detail in (8), calculates flow of free water through the (assumed) homogeneous aquifer of the coal seam by gravity drainage, which occurs independent of the reactor pressure, and depressurization of the coal seam, which occurs when the reactor is operated below the hydrostatic pressure. The model assumes that strata above and below the coal seam are impermeable. (Water from overburden drying is accounted for naturally in the roof recession submodel.) Reactor geometry in thr influx submodel is idealized as a cylinder extending the full height of the seam representing the cavity, and a noninteracting slot of variable width representing a horizontal outflow channel. Cylinder and slot volumes are specified by demanding equality with cavity and outflow channel volumes at each time step. We assume that gas displacing the water in the coal strata is of sufficiently high mobility that only the flow equations for the water-filled region need be considered. Also, capillary pressure effects are assumed negligible. These assumptions imply that the gas pressure on all water/gas interfaces are equal. The two-dimensional (radial and axial) flow problem for gravity drainage is reduced to a one-dimensional problem by use of the so-called Dupuit approximation (16) which considers Darcy flow only in the radial direction based on a radial gradient in piezometric head. This system has been solved numerically using a finite difference scheme to discretize the differential equation in the space dimension and integrating the resulting system of ODE's in time using a standard solver. In (8) it is shown that, except for very early times, the Dupuit approximation gives flowrate values in very close agreement with those calculated by solution of the full two-dimensional solution, for both stationary and uniformly expanding cylinder walls. Depressurization is included in this formulation by matching the drainage solution valid in the cone of depression with the solution for unsteady potential flow in the fully saturated far field aquifer, at the boundary where both solutions are valid.

In coupling the water influx submodel to the global cavity growth solution, the model equations are solved for a fixed geometry over a time interval equal to the time step of the full problem. At the start of each time step a new grid system is established with its inner boundary on outer edge of the cavity or outflow channel. Values of hydraulic head are obtained through interpolation of the previous solution. Drainage and depressurization water is assumed to enter the at the ash-rubble covered sidewall in the lower cavity. Values for parameters characterizing water influx, with the exception of flow porosity, can be obtained from standard well hydrology testing. One additional parameter, an initial pumping time, has been introduced to make allowance for the time during which the wells are pressurized or pumped down before initiating the UCG burn.

Injection Gas Flow Submodel At any instant flow through the ash rubble is quasi-steady, since the evolution of its geometry is over a much longer time scale than the flow residence time. The flow distribution is described by the compressible form of Darcy's law in the axisymmetric volume of the ash rubble pile (see Figure 1), with a source term at the origin, and an impermeable cavity floor. We assume a region of high permeability exists at the ash pile-coal sidewall boundary, since it is here that void space is being created by removal of carbon and volatiles from the coal. This assumption is critical to the success of the model. We also assume that the char rubble overlying the outer edges of the ash rubble is highly permeable. This is justified by observations of rubble characteristics of the excavated UCG cavity (3). These assumptions imply that the sides and top of the ash rubble are at the same sink pressure while the cavity remains in the coal seam. Once rock rubble enters the cavity, a resistance to upward flow through the central ash pile is added, proportional to the height of the rock rubble and the permeability ratio of rock to ash rubble. The system is solved by a finite difference method. A vertical half-plane with origin at the center of the axisymmetric rubble pile is mapped onto a grid rectangular in r and z coordinates, which is normalized at each time step to maximize the number of nodes lying inside the rubble pile. Permeability values at nodes lying on or outside the rubble pile are set very large, effectively tying the edge of the pile to the sink pressure P_s. The difference equations for the pressure at each node, linear in P^2, are solved iteratively using successive overrelaxation. The solution for the previous time step is used as the initial guess for the next step. Calculated fluxes at boundary nodes are smoothed with a polynomial fit for each of the interfaces adjacent to the coal sidewall, void and char bed. The integrated flow out of the entire boundary is normalized with the injection flow to remove errors introduced by the smoothing, and average flowrates to each of the three zones are computed.

Wall Recession Submodel The wall region is defined as the cavity boundary extending downward to the cavity floor from point d in Figure 1A. We assume the existence of a thin, highly permeable, char-filled zone between the ash and the solid coal wall. Here oxygen entering from the ash side combusts char, supplying heat to drive gasification reactions, vaporize and heat influxed water and dry, pyrolyze and degrade fresh coal to char rubble. The net effect of this rubblization, which involves relaxation of thermal and drying induced (shrinking) stresses coupled with overburden stresses at the solid wall, is to propagate this permeable reaction zone into the coal. We describe this failure mechanism in terms of a convective heat transfer rate from hot gas at temperature T_w to the coal wall at a specified failure temperature T_f, with the heat flux balanced by that required to dry and heat coal to temperature T_w at the rate of the sidewall recession. Also, settling of char and/or ash from above and upward flow of product gas is considered to occur in this layer. Solution of the fully-coupled two-dimensional heat and material flow problem described here is far beyond the scope of a module to be used in a global UCG simulation. A major simplification is the division of the wall into several discrete elements in the axial direction, and the assumption that the temperature is constant within a given segment. This temperature is presumed to be given by the formula for the effective extinction temperature of the steam/char reaction in a packed bed (12,13), subject to the constraints of energy and mass balances and the convective heat transfer conditions at the cold coal wall. This temperature is primarily a function of the Arrhenius kinetic parameters of the steam-char reaction and the local flux of the product gas in the layer. This formulation allows the computation of recession velocities and char conversion rates for each segment.

Void/Rubble Zone Submodel This submodel describes the interaction of the coal, overburden and rubble pile surfaces enclosing the void region at the top of the developing cavity. Competent coal or rock surfaces here are exposed to high temperatures, and thermally induced and lithostatic stresses interact in a fashion not completely understood to cause spalling (small scale failure) of material on the order of centimeters to occur. A one-dimensional transient model (14,15) has been developed to describe drying, pyrolysis, gasification and spalling of coal (or rock) exposed to a constant high temperature radiative heat source. Spalling behavior is empirically characterized by a failure length ℓ_f and a failure temperature T_f, in such a way that when the temperature a distance ℓ_f from the surface exceeds T_f, an element of this size is removed from the surface and the process repeated. Values of ℓ_f and T_f are obtained from analysis of one-dimensional transient heating experiments on overburden cores (17) when available, or appropriate values are chosen and regarded as model parameters. This model is used to calculate mean recession rates and related quantities, averaged over a series of spalls, as functions of the mean surface temperature. Heat transfer to the curved roof surface can be considered one-dimensional, since the thermal penetration depth is always much smaller than the local radius of curvature. The void space is assumed to be well-mixed.

The roof surface is divided into several conic sections. Oxygen exiting the top of the ash pile combusts with char which spalls onto this surface while the cavity is in the coal, and combusts product gas at the surface of the rock rubble when it is present, creating a hot surface which radiates to the other surfaces. Radiative exchange equations are written for the surfaces enclosing the void, in which the temperature of the roof surfaces determines their recession rates, and material and energy balances are solved (9,15) subject to two constraints, as discussed in a later section. While the cavity is in the coal seam, it is demanded that no char accumulate on the central surface of the ash rubble; all char arriving here must be reacted by combustion and gasification. When overburden rock is present, complete combustion of oxygen with product gas ($H_2 + CO$) at this surface is demanded. The char pile at the outer cavity edge is considered a one-dimensional packed bed modeled as in (13) in which oxygen and steam entering from below react with char, and the product gas exits into the void. Reaction chemistry is simplified in this region by considering $H_2 + CO$ as one chemical species, and $CO_2 + H_2O$ as another, as described in (15), with suitably defined reaction enthalpies.

Outflow Channel Model This model describes growth of an outflow channel, originally an open horizontal borehole in the coal seam, by thermally-induced rubblization of the coal as described above, driven by convective heat transfer from the hot product gas. Heat transfer is modeled in a semi-empirical fashion with constants fitted to the PSC excavation data (12). This channel is considered physically removed from the cavity such that no geometrical interaction occurs to break the symmetry of the cavity. Channel volumes calculated, and measured in the field, typically amount to about 10% of the main cavity volume.

Global Cavity Growth Module An initial cavity is defined as a series of line segments connecting points along one-half of a cavity cross section looking from the side. Initial cavities are defined as cylinders with unit height/diameter ratio and specified total, char and ash rubble volumes. (Parametric studies have shown that initial cavity configuration has a very small effect on late-time cavity characteristics.) This geometrical data is passed to the submodels which calculate temperatures, recession rates and chemical reaction rates for the various surface segments. The control segment then advances cavity segments over a time step, tentatively computes new cavity boundaries and rubble amounts. A unique cavity shape is calculated differently depending on whether the cavity interacts with overburden rock. When the cavity is contained in the coal, this shape is determined by noting that the amount of char which falls into the inner ash pile surface determines the upward growth of this surface, the temperature distribution in the enclosure and the amount of char remaining in the rubble bed. In other words, there is only one solution for the amount of char deposited on the ash-void interface, for which the location of point a in figure 1A simultaneously satisfies both char and ash material balances. When the cavity grows to encompass overburden rock, the ash pile ceases to grow upward and thus point b in Figure 1B is determined solely by the ash material balance. In this case the location of point a is fixed by simultaneous satisfaction of char and rock rubble material balances. Provision is made during late stages of cavity development for complete coverage of char by rock rubble, and also for the eventual depletion of the char rubble, by adjustment of point c in Figure 1D. The control algorithm also periodically performs various smoothing and point equalization operations on the calculated results. These are necessary since adjacent cavity points moving at significantly different velocities could cross paths if no intervention occurred, leading to highly irregular, multiply-connected cavity shapes numerically and physically unrealistic. Cavity volumes are computed before and after each smoothing operation and the errors incurred as a result of smoothing are recorded. For all cases considered, the cumulative smoothing error is about 3-6% of the total cavity volume. Time steps are constrained such that no point on the cavity surface can advance farther than a specified fraction of its distance from the cavity origin.

The present version of the code developed for this simulation requires relatively little memory and uses about 5 seconds per time step early on when an iteration on the void radiative exchange equations is required, decreasing to less than a second per time step for the latter stages of the calculation. Total cpu time on a Cray 1 computer needed for a 15 day simulation is about 3 minutes.

RESULTS AND COMPARISON WITH FIELD DATA

Partial Seam CRIP Field Test The parameter with the largest effect on model results is the ratio of permeability between the rock and ash rubble piles. This parameter controls the split of injected oxidant flow between the sidewalls and the void region once overburden is exposed, which occurs relatively early in the life of the burn. Generally, oxidant which is forced to the cavity sidewalls comes in intimate contact with coal, producing high quality gas, while oxidant passing into the void partially combusts product gas, heating overburden rock which represents an energy loss. A lower rock rubble permeability thus diverts more oxidant flow to the sidewalls, resulting in a wider, shorter ultimate cavity and enhanced energy recovery. This permeability ratio is very difficult to quantify. From observations of ash and rock rubble during the excavation of the PSC site (3) it was concluded that the rock rubble was probably somewhat less permeable than the ash, since much of it had fused, leaving an irregular network of fissures to conduct the gas, while the ash rubble clinker appeared relatively more porous. The effect of this permeability ratio is seen in Figure 2, which shows the molar ratio of produced hydrogen and carbon monoxide to injected oxygen, and excellent measure of process efficiency. Results using physical and process parameters given in Table 1A, corresponding to the PSC test conditions and with permeability ratios spanning three orders of magnitude, are here compared with test data. It is clearly seen that $\kappa_R/\kappa_A = 1$ gives the best agreement. This result, and the observation that past field tests also exhibited gradual declines in product gas quality, instead of consistent high values or precipitous declines when overburden was encountered, suggest that this ratio is of O(1) and we therefore specify a value of unity for all subsequent calculations.

The model calculation for $\kappa_R/\kappa_A = 1$ resulted in a final cavity shape which is compared in Figure 3 with that mapped during the excavation. The actual cavity was slightly asymmetric with respect to the injection point, but the agreement is quite good; both in sweep and the narrowing of the cavity midsection. This latter phenomenon occurs because this area of the cavity is covered for most of the burn with insulating char rubble, and is not exposed to direct oxidant attack as below, or high-efficiency radiative heat transfer as above. The simulation predicts total coal volume gasified to be 675 m^3. Analysis of the field data (1) suggest that about 700 m^3 of coal was gasified during the part of the test in which this cavity was formed. While the upper part of the actual cavity was destroyed by mining operations and cavity shape in the overburden cannot be directly compared, but the good agreement in produced gas quality shown in Figure 2 suggests that the simulation calculated reasonably the volume of overburden affected.

Rocky Mountain I Field Test The recently completed Rocky Mountain I (RMI) UCG field test provides another opportunity to test model results with a system in which oxidant injection remained low in the coal seam. Flow and pressure schedules used during the test and parameter values taken from a number of literature sources characterizing the Hanna coal, given in Table 1B, were used as inputs in the simulation. Day zero is defined as the beginning of forward gasification with steam and oxygen, and the initial cavity volume is specified by carbon removed during air gasification which occurred for about 3 days prior. Figure 4 compares model results of $(H_2 + CO)/O_2$ for these conditions with the test data. The agreement is striking. Figure 5 compares calculated cavity volumes with that calculated for the actual cavity by a material balance which assumes no char accumulation in the underground system. Also on this figure the product gas temperature is compared. Volumes agree quite well early but diverge by about 15% for later stages of the 40 day burn of the first cavity. Also, the predicted product gas temperature is somewhat higher than actual, though the slight upward trend with time is well-represented. The actual cavity shape is not reliably known, so no direct comparisons can be made. Qualitatively, the computed cavity shape is similar to that calculated for the PSC simulation, since this is largely determined by the proximate analysis of the coal, which is similar for these two coals.

Two weaknesses of the model are its neglect of the hydrogasification reaction ($2H_2 + C \rightarrow CH_4$) and its neglect of tar evolution and secondary tar reactions. The former may account for the discrepancy in CH_4 production between model and data (7% -vs- 11% respectively, on a dry gas basis). This reaction is endothermic and thus its inclusion in the model would serve to reduce product gas temperature. Tar cracking could produce a considerable amount of H_2 and CO, since tar amounts to as much as 15% by weight of the original coal (20). This could explain the equivalent $H_2 + CO$ production rates between model and data, when the model predicts up to 15% more coal was affected. One must keep in mind in interpreting this test data, however, that it is raw data; known errors have not yet been removed.

Proposed Brazilian UCG Field Test As part of the Lawrence Livermore Laboratory effort to provide technical support for a UCG feasability study in Brazil, cosponsored by the DOE, a simulation was performed using all available data concerning the coal and overburden at the proposed test site, near Porto Alegre in southern Brazil. This simulation provided estimates for sweep width and coal recovery used in planning link numbers and spacing for the two year demonstration test plan. Coal and overburden physical data specific to the site, as well as operating parameters are given in Table 1C. Rubble pile densities were adjusted from values measured at the PSC excavation based on the density differences in the original materials, and other necessary data unavailable for this site, such as coal and rock failure criteria, were taken as the same as for the PSC simulation. This test is of great interest because the characteristics of the coal, very dry, very impermeable and of a high ash content, represent conditions felt to be ideal for flat seam UCG.

Figure 6 shows the cavity shape produced by the simulation at approximately 11.5 days. The high ash content of this coal results in a larger volume of the cavity filled by ash rubble compared with coals previously studied. Thus, a larger fraction of the cavity surface is covered by rubble. The void region of the cavity is relatively small, such that the efficient radiative heat transfer mechanism dominant in the void is focused largely at the topmost part of the cavity, which gets quite hot and recedes rapidly. These factors combine to form a cavity wide at the bottom with a chimney-type upper end. The simulation was terminated when the void space became filled with bulked rubble, a situation that cannot be treated by the present model. The behavior of the system would not be expected to change substantially in the short term once the cavity is completely filled, however. The bed of pyrolyzed, unreacted char which persists in simulations of other UCG systems studied, disappears early on in this system. The volume of coal and rock affected by the cavity predicted by the simulation is 454 and 220 M^3, respectively. The results suggest that gas production efficiencies at sites such as this are expected to be quite good, but very hot product gas temperatures may be experienced.

CONCLUSIONS

A model for cavity growth and gas production during UCG, based on the assumption of cylindrical cavity symmetry and applicable for gasification of shrinking coals when injection low in the coal seam can be maintained, has been developed. The model is highly idealized, but treats includes all important factors impacting cavity growth such as water influx, porous media flow, heterogeneous and homogeneous chemical reactions, radiative and convective heat transfer, and rock mechanics. Model predictions have been shown to agree very well with available field data, and while detailed produced gas compositions cannot be estimated, it is felt quite adequate to describe in a semiquantitative fashion cavity evolution, energy recovery, aquifer response, and effects of process parameter changes, and therefore is a useful tool for UCG site characterization and module optimization.

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Table I. Physical and process parameters used in the simulations.

A. Partial Seam CRIP

coal specific gravity 1.39, 17% water, 21% ash, 28% fixed carbon
rock specific gravity 2.10, 12% water
coal failure temperature (K) 700 (roof) 850 (sidewalls)
rock failure temperature (K) 700 (roof) 850 (sidewalls)**
coal roof failure length (cm) 1; rock roof failure length (cm) 2
rubble specific gravities; ash 1.0, rock 1.3, char 0.8
permeabilities (mD); ash rubble 10000, rock rubble 10000, native coal 30
hydrostatic head (kPa)* 630, pumpdown time (days) 10
seam height 6 (m), initial cavity height & radius (m) 1.0 & 0.5
nominal gas flow (mol/s) 30, steam/oxygen ratio 2/1, ramp time (days) 5
injection temperature (K) 400, cavity pressure (kPa) 430
References: (1), (3), (8)

B. Rocky Mountain I

coal specific gravity 1.39, 9% water, 27% ash, 32% fixed carbon
rock specific gravity 2.10, 10% water
coal failure temperature (K) 700 (roof) 700 (sidewalls)
rock failure temperature (K) 660 (roof) 660 (sidewalls)
coal roof failure length (cm) 1; rock roof failure length (cm) 1.7
rubble specific gravities; ash 1.0, rock 1.3, char 0.8
permeabilities (mD); ash rubble 10000, rock rubble 10000, native coal 140
hydrostatic head (kPa) 990, pumpdown time (days) 12
seam height 7.6 (m), initial cavity height & radius (m) 3.6 & 1.8
gas flow schedule from actual data, injection temperature (K) 400
cavity pressure schedule from actual data
References: (17), (18), (19)

C. Brazil Test

coal specific gravity 1.78, 8% water, 46% ash, 28% fixed carbon
rock specific gravity 2.42, 4% water
coal failure temperature (K) 700 (roof) 850 (sidewalls)
rock failure temperature (K) 700 (roof) 850 (sidewalls)
coal roof failure length (cm) 1; rock roof failure length (cm) 2
rubble specific gravities; ash 1.1, rock 1.5, char 0.9
permeabilities (mD); ash rubble 10000, rock rubble 10000, native coal 0
seam height 3.7 (m), initial cavity height & radius (m) 1.0 & 0.5
nominal gas flow (mol/s) 30, steam/oxygen ratio 2/1, ramp time (days) 5
injection temperature (K) 400, cavity pressure (kPa) 1500
Reference: (20)

* measured from bottom of coal seam
** best fit to excavated outflow channel volume

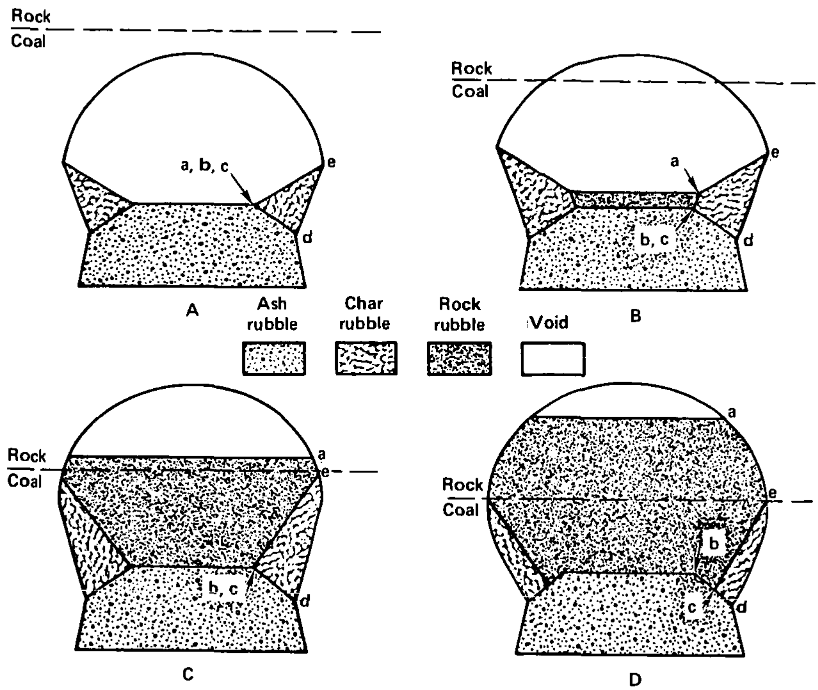

Figure 1 Generic cavity shapes constructed by the model.

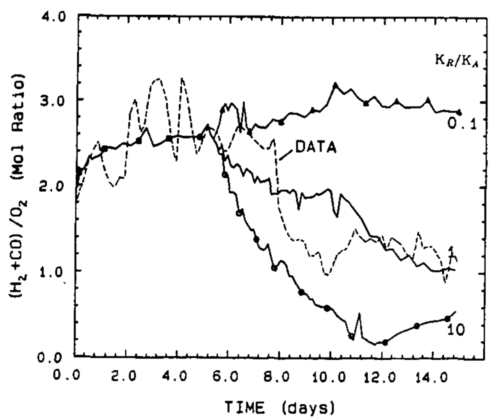

Figure 2 Effect of rock-to-ash rubble permeability ratio on the ratio of $H_2 + CO$ produced to O_2 injected. Conditions of Table 1A. Field data from PSC field test shown as dashed line

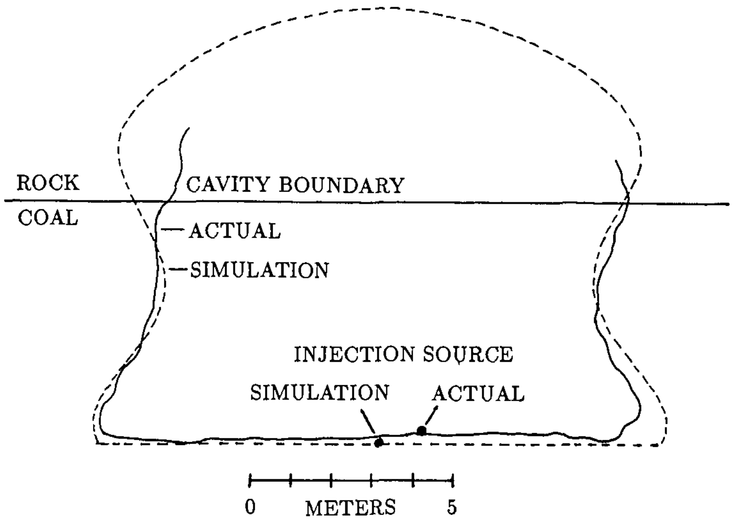

Figure 3 Comparison of actual and calculated cavity shapes in the plane perpendicular to the injection borehole at the injection point of the PSC CRIP cavity. Simulation used parameter values of Table 1A

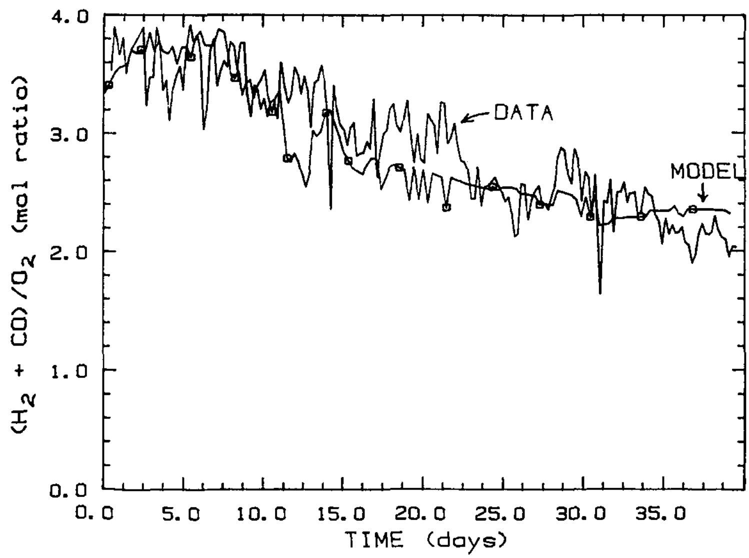

Figure 4 Ratio of $H_2 + CO$ produced to oxygen injected calculated for the simulation of the RMI field test compared with actual data. Conditions of Table 1B.

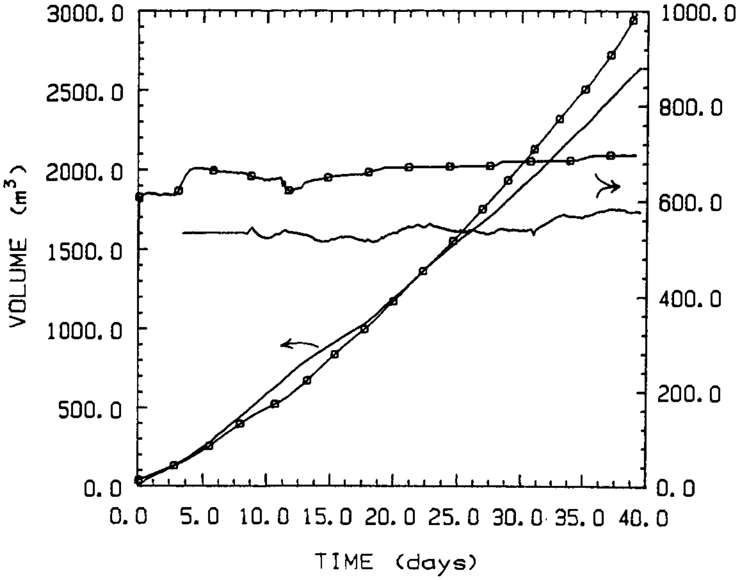

Figure 5 Cavity volumes and product gas temperature calculated by the model (marked lines), compared with material balance and temperature data from RMI CRIP side cavity.

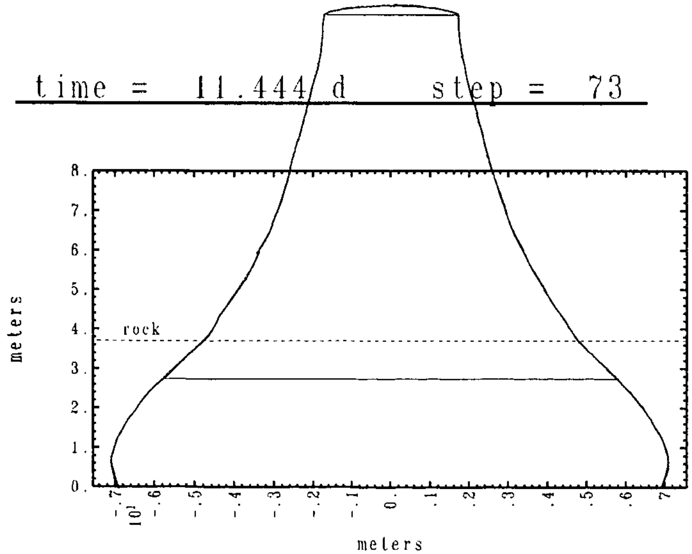

Figure 6 Cavity profile calculated at 11 days for simulation of the proposed UCG field test in Brazil. Simulation used parameter values given in Table IC.