SYSTEM FOR CULTIVATION AND PROCESSING OF MICROORGANISMS AND PRODUCTS THEREFROM

Field of the Invention

This specification relates to processes and apparatus and systems for cultivating and processing microorganisms, particularly microalgae or diatoms, to processing or extracting products from such cultivation to processing other organic materials and organic wastes and organic chemicals, and to particular parts of and systems useful in the foregoing fields.

Background

There have been proposed and sometimes implemented in the past, at least in experimental installations, systems, apparatuses and processes for cultivating microorganisms particularly microalgae to produce useful by-products such as lipids potentially useful as a source of fuels. There have been two broad approaches to such microorganism cultivation on a large scale, the first using large open ponds, raceways, vats or the like in which the microorganisms such as microalgae are grown and subsequently harvested, and the second involving closed vessels or passages in which the microorganisms are moved in a nutrient medium while being exposed to incident radiation, either solar or artificial radiation, to promote the growth and propagation of the microorganism culture. The open systems are particularly vulnerable to contamination by other organisms which can either predate the desired species or become more dominant in the population of microorganisms thus degrading the productive output and commercial viability or, at the very least, requiring continual measures to inhibit or remove the contaminating population. The closed system designs have been far too costly to be commercially viable for commercial fuel production. Both have tended to use land with high alternative use value.

In most of the above systems, the aqueous nutrient medium carrying the microorganism culture has been agitated or moved at flow velocities to nutrify the medium with CO_2 to maintain turbulent conditions for the purposes of preventing or minimising settling of microorganisms, coagulation or flocculating of microorganism clusters limiting optimum growth within the culture, and to continuously mix nutrients and microorganisms and to remove waste products so as to ensure that all receive adequate nutrition, space and insolation to optimise growth and reproduction. However, such turbulent flow can require substantial energy inputs to pump the nutrient and microorganism soup and maintain the required turbulence.

There have been many other limitations and drawbacks of particular large scale microorganism cultivating and processing systems which will be mentioned in this specification where relevant in the particular context of the description of parts of the present applicant's method, apparatus and system.

The above and following references, including references in the Appendix of the present specification, to and descriptions of prior proposals or products are not intended to be, and are not to be construed as, statements or admissions of common general knowledge in the art.

Throughout the specification, including the claims, the present applicant's overall system, process, and apparatus, many individual aspects of which are not in themselves essential and may be omitted or varied in particular implementations of the applicant's system, will be referred to as the "Winwick system", "Winwick process", "Winwick apparatus", etc. This is for convenient reference but it is to be understood that the particular aspect of the system, method or apparatus being described, or indeed the references to the system, method and apparatus as a whole are not to be construed as being necessarily essential to the present invention.

Summary of the Invention

According to a first aspect of the invention there is provided a method of cultivating phototropic microorganisms, particularly microalgae or diatoms, in a bioreactor comprising the steps of:

entraining a culture of the microorganisms in a tenuous, gelated, thixotropic carrier medium having nutrients therefor and moving the medium along a passage which in cross section is closed and which has transparent walls through which the culture is irradiated to enable photosynthesis;

providing process parameter control means associated with the passage; and

selectively varying the process parameter control means to thereby selectively control parameters or conditions of the cultivation and photosynthetic activity of the microorganisms moving within the passage.

The method of the first aspect may further include the steps of:

moving the carrier medium at a sufficiently slow speed to enable laminar flow thereof along the passage; and

effecting convective turnover of the culture and medium as they flow along the passage by differentially heating the medium laterally relative to the flow direction so as to produce a generally helical flow of the culture and medium. Preferably the carrier medium has a viscosity or tenuous structure sufficient to impede gravitational settling, surface scumming, or deposition onto solid surfaces by the microorganisms, at the same time as prolonging the residence time in the medium of the gaseous phase nutrient and impeding clumping of the microorganisms into less productive clusters.

Preferably the viscosity, structure and composition of the medium and culture are monitored and are controlled to promote an optimal concentration of active microorganisms. The viscosity and thixotropicity may be increased by addition of a gel substance (e.g. a water swellable, or hygroscopic, organic polymer gel with high water absorptivity) to increase the impedance to gravitational settling and to the passage of gaseous phase nutrient up through the medium (except at locations of designated medium agitation, where the viscosity is deliberately reduced to enable gas liberation, algal harvesting and sparging with nutrient gas to proceed) but without preventing access by the microorganisms to nutrients in the medium nor preventing removal of excreta of the microorganisms in a gas liberation process.

In a preferred embodiment of the method of the first aspect, the convective turnover is promoted by exposing one lateral side of the passage to greater radiant, conductive or convective heat than the opposite lateral

side. Preferably the radiant heat comprises angled incident solar radiation, or alternatively, the heat differential from heating or cooling is applied via a thermal element running longitudinally and next to the passage.

A heating or cooling mechanism may extend along one lateral side of the passage so that heat transfers promote convective turnover in the medium to expose otherwise shaded microorganisms to radiation. The heating (or cooling) mechanism preferably comprises a pipe in which is circulated fluid at a temperature greater or less than the culture and medium.

In the preferred embodiment of the method of the first aspect the process parameter control means includes at least one envelope located around part or all of the closed passage (or, where multiple co-extending adjacent passages are provided, the envelope(s) surround part or all of the grouped, multiple, closed passages). The closed passage is preferably enclosed within the envelope (and preferably multiple further passages also being enclosed side by side within the same envelope) and the process parameter control means includes a control space defined between the outside of the wall of the passage and the inside of the wall of the envelope, the control space being provided with an insulating material, the method including the step of selectively controlling radiation conduction and convection passing heat between envelope and passage, either way by selectively varying a property (such as the quantity, dispersion or quality) of the insulating material.

In this embodiment the insulating material preferably comprises a foam formed or maintained by selectively variably bubbling a control gas into a control liquid provided within the envelope adjacent the passage. The composition, state, pressure, volume and/or temperature of the control liquid and control gas media that provide the insulating bubbles or foam in the insulating envelope when required may be selectively varied. The foam provides a control of insolation and of insulation for the passage in which the microorganism bearing medium is moving by altering the amount of heat passing through the control space, and wherein the selective variation of the bubbling of the gas includes selectively varying at least one of the following: gas composition, gas volume, gas pressure, control liquid temperature, control liquid composition, and control liquid state.

Preferably both the microorganism bearing medium within the passage and the control space are pressurised separately at greater than atmospheric pressure. The pressure differential of gas and/or liquid between the passage and the control space may be selectively varied so as to control the cross sectional shapes of the passage and the control space, and optimise the shape and depth of the medium in the passage to suit changing external parameters or cultivation requirements. In this embodiment the control liquid within the control space provides hydraulic support to the side walls of the passage which are flexible and thereby promotes adoption by the walls of the passage of a more optimal cross-sectional shape for the microorganism bearing medium.

The envelope may be provided with condensate collection channels extending longitudinally partway along the inside of the envelope walls, the channels being arranged gently sloping to collect water condensing inside the envelope, the collected water being capable of providing sterile distilled water for use in the cultivation, harvesting and processing of the microorganisms, such as by enabling the replacement of water removed during harvesting

with a safe, local equivalent.

The preferred process parameter control means (preferably the envelope) has provided externally thereof a base sheet or groundsheet sub-assembly providing an upper light reflecting surface located under and on both lateral sides of the passage and in proximity thereto so as to reflect incident photosynthetically active radiation (PAR) into the medium through the transparent walls and base of the passage, and to provide physical protective properties beneath the envelope when being located on, moved on, or removed from a supporting ground surface.

The passage is preferably defined by a flexible polymeric material composed of the material of the transparent wall and the envelope also comprises a tube composed of a flexible polymeric material of greater dimensions than the passage so as to enclose the same, the passage and envelope being initially flattened and provided in a form of a roll, being deployed by unwinding the roll, and thereafter being expanded to their operative configurations by supplying them with fluids. This preferred embodiment further includes servicing ducting or pipes through which fluids flow to support processes occurring in the bioreactor. The flexible polymeric tube constituting the envelope also encloses the servicing ducting or pipes, and the servicing ducting or pipes are composed of flexible materials and being in the roll and being deployed by unwinding the roll along with the passage, envelope, and any attachments. The passage when deployed from the roll and expanded preferably adopts a shape when the medium is moving therein of rounded cross sectional shape having a greater width than depth.

Preferably the microorganism bearing medium is moved through alternating zones of relatively higher and relatively lower insolation so that microorganisms are exposed to PAR in a pulsed manner, preferably for PAR exposure periods substantially less than one second and preferably somewhat greater recovery times of relative darkness whereby radiation can most efficiently be photosynthesised by microorganisms and reducing the likelihood or effect of photoinhibition in the microorganisms. The transparent outer envelope top surface may be provided with bands or stripes having PAR attenuating or excluding properties relative to the transparent parts of the envelope between successive bands, the bands extending generally transverse to the direction of flow of the medium, whereby the bands, their adaptive width and their relative placement define the width and separation of the alternating zones of relatively higher and relatively lower insolation within the passage.

In this preferred embodiment, the bands are composed of photovoltaic (PV) material electrically connected whereby incident solar radiation can be utilised by the PV bands to generate electricity for use in performing the method or for use in associated operations (or for sale) and, in the zones intermediate between successive bands or beyond them, the incident radiation can be used in photosynthesis by the microorganisms. The bands may be located within fluting made largely of transparent polymer film enabling airflow therethrough, so as to promote passive PV air-cooling to improve PV conversion efficiency and to help maintain the microorganisms within their most productive temperature range, the PV material comprising ribbons of transverse-curved material, attached to and/or acting as part or all of the support members within the fluting and projecting into the airflow passages of the fluting, the fluting being affixed to the top surface of the envelope of the bioreactor. The fluting, comprised of the

envelope, the outer film of the fluting, and the support members of PV ribbon and other material are preferably able to be compressed in thickness, along with the bioreactor tubes, to improve transportability.

In one possible embodiment the ribbons, bands, strips or stripes are provided by bodies having shapes or configurations that are thermally responsive so as to provide relatively greater areas to intercept incident radiation upon being heated above a certain threshold. In one possible configuration, the bodies may comprise transverse-curled or rolled material having the property of progressively uncurling or unrolling upon exposure to a threshold and higher temperatures by incident radiant energy or increasing ambient temperature. The exposure of the transverse-curled ribbons, bands or stripes to a threshold temperature preferably commences uncurling by utilising differential coefficients of expansion of different materials forming part of the ribbon material, thereby reducing excessive insolation that would otherwise enter the medium and increasing the amount of electric power produced, and conversely, when lower insolation or ambient temperatures cool the strips, they curl up transversely, allowing more light to the medium and producing less power.

In this possible embodiment, the transverse-curled ribbons, bands or stripes are preferably generally S-shaped in transverse section when in the curled condition and wherein the different materials include a material with different (higher or lower) thermal coefficient of expansion to the PV or to another layer in the ribbon on one surface section of the S-shaped ribbon so as partly or wholly to uncurl that section upon being heated to or beyond the threshold temperature by incident radiation.

In an alternative possible construction, the bodies are movable from retracted positions towards extended positions in which they present greater surface area to incident radiation and hence greater interception of incident radiation upon exposure to a threshold and higher temperatures by incident radiant energy or increasing ambient temperature. The bodies may comprise wings and exposure of the bodies to the threshold temperature commences raising of the wings from retracted positions towards their extended positions by utilising differential coefficients of expansion of different materials forming mountings of the wings, thereby reducing excessive insolation that would otherwise enter the medium and increasing the amount of electric power produced, and conversely, when lower insolation or ambient temperatures cool the mountings, they lower the wings towards their retracted positions, allowing more light to the medium and producing less power. The mountings of the wings may form hinges to which the respective wings are mounted and the hinges may be each composed of different materials in laminar form with different (higher or lower) thermal coefficients of expansion so as to progressively open out and raise the wings mounted thereto upon being heated to or beyond the threshold temperature by incident radiation or ambient temperature increase. The mountings of the wings are preferably located on supports within an air space between transparent polymer films, the supports being initially in a collapsed condition for storage and, upon being installed, adopt an erected condition and ratchet arrangements prevent return to the collapsed condition.

Preferably the gaseous nutrients in the carrier medium are introduced, at least in part, to the medium by introducing gas by way of sparged microbubbles to the medium. The step of introducing gas preferably includes

introducing carbon dioxide gas into the medium before the medium enters and moves in the tubular passage. The step of introducing gas to the medium may be performed at a processing station through which the microorganism bearing medium is circulated and from which medium flows into the passage and into which the medium after having passed through the passage and its return passage is returned, the step of introducing gas being performed in a treatment zone of the processing station by bubbling carbon dioxide in fine bubbles into the medium within the treatment zone. The step of bubbling carbon dioxide in fine bubbles into the medium within the treatment zone may be performed by a sparging member having raised-edge perforations through which carbon dioxide gas bubbles are introduced into the medium, the sparging member or plate being vibrated (e.g. by a piezoelectric or magnetostrictive transducer mechanism associated with the sparger) at a frequency, preferably a sonic frequency, to promote the ready release of carbon dioxide bubbles from the perforations enabling smaller or microbubbles to be generated.

The method may further include the step of releasing waste gas from the medium performed at a waste release zone of the processing station, and the waste release zone may be downstream of the point where the medium and microorganisms therein return from the passage and enter the processing station and may be upstream of both the treatment zone where carbon dioxide gas is introduced into the medium and of the zone where harvesting of the microorganisms occurs. At the waste release zone preferably there is performed a fluidising step in which the medium and microorganisms therein are agitated by an agitator which reduces viscosity or dethixotropises the medium and thereby to promote the release of gaseous waste (oxygen) from the medium into the gas body above it.

In the preferred embodiment a gas phase exists within the closed passage above the level of the carrier medium, the gas phase within the passage accepting oxygen from the photosynthetic process in the medium below which oxygen is progressively collected in the treatment zone along with microorganisms for recovery and processing.

Preferably, the step of moving the medium along the passage comprises impelling the medium by an impeller at the processing station which propels the medium into which nutrient gas has been introduced at the processing station in a manner to promote laminar flow of the medium along the passage, and preferably the impeller and the agitator are coupled together so as to operate synchronously. The agitator has a vigorous action upon the medium and the impeller has a gentler impelling action.

A gas phase exists within the closed passage above the level of the carrier medium, the gas phase within the passage accepting oxygen from the photosynthetic process in the medium below which oxygen is progressively collected in the treatment zone along with microorganisms for recovery and processing.

Preferably the processing station includes a harvesting zone in which microorganism bearing medium is sparged with a flow of harvesting gas which promotes froth flotation and concentration in the froth of microorganisms, the sparging gas being taken renewably from that immediately above the medium in the processing station and typically comprising an oxygen and carbon dioxide mixture of around a 90:10 ratio, together with lesser

component gases such as water vapour and nitrogen. Preferably, the harvest sparger is vibrated at a suitable power level and/or frequency by a transducer for short time periods, preferably less than 60 seconds per day in total, so as to limit adverse effects on the microorganisms so that the vibration serves to clean the harvest sparging member and immersed surfaces within the processing station.

According to a second aspect of the invention there is provided a method of cultivating phototropic microorganisms, particularly microalgae or diatoms, in a bioreactor comprising the steps of:

entraining a culture of the microorganisms in a carrier medium having nutrients therefor and moving the medium along a closed passage at a sufficiently slow speed to enable laminar flow thereof along the passage, the passage having transparent walls through which the culture is irradiated to enable photosynthesis;

effecting convective turnover of the culture and medium as they flow along the passage by differentially heating the medium laterally relative to the flow direction so as to produce a generally helical flow of the culture and medium;

providing process parameter control means associated with the passage; and

selectively varying the process parameter control means to thereby selectively control parameters or conditions of the cultivation and photosynthetic activity of the microorganisms moving within the passage and the processing centre.

According to a third aspect of the invention there is provided a method of cultivating phototropic microorganisms, particularly microalgae or diatoms, in a bioreactor comprising the steps of:

entraining a culture of the microorganisms in a carrier medium having nutrients therefor and moving the medium along a closed passage having transparent walls through which the culture is irradiated to enable photosynthesis, the transparent walls having externally thereof multiple bands or strips or ribbons of material having PAR attenuating properties relative to the transparent walls between successive bands, the bands, strips or ribbons extending generally transverse to the direction of flow of the medium, whereby the bands, strips or ribbons, their effective width and their relative placement define the width and separation of the alternating zones of relatively higher and relatively lower insolation within the passage;

providing process parameter control means associated with the passage; and

selectively varying the process parameter control means to thereby selectively control parameters or conditions of the cultivation and photosynthetic activity of the microorganisms moving within the passage.

In this third aspect, the microorganism bearing medium is preferably moved through the alternating zones of relatively higher and relatively lower insolation so that microorganisms are exposed to PAR in a pulsed manner, preferably with the duration of each complete cycle of higher and lower PAR exposure being less than one second and preferably with somewhat greater recovery time of relative darkness than the PAR exposure time of each cycle whereby radiation can most efficiently be photosynthesised by microorganisms and reducing the likelihood or effect of photoinhibition.

The bands, strips or ribbons are preferably composed mainly of photovoltaic (PV) material electrically connected whereby incident solar radiation can be utilised by the PV material to generate electricity for use in performing the method or for use in associated operations (or for sale) and, in the zones intermediate between successive bands, strips or ribbons, the incident radiation can be used in photosynthesis by the microorganisms.

According to a fourth aspect of the invention there is provided a method of cultivating phototropic microorganisms, particularly microalgae or diatoms, in a bioreactor comprising the steps of:

entraining a culture of the microorganisms in a carrier medium having nutrients therefor and

moving the medium along a closed passage having transparent walls through which the culture is irradiated to enable photosynthesis, the transparent top surfaces having externally thereof multiple bands or strips or ribbons having PAR shielding properties relative to the transparent areas between successive bands or ribbons, the bands or ribbons extending generally transverse to the direction of flow of the medium, whereby the bands or ribbons, their effective width and their relative placement define the width and separation of the alternating zones of relatively higher and relatively lower insolation within the passage, and wherein the bands or strips or ribbons are provided by bodies having shapes or configurations that are thermally responsive so as to provide relatively greater area to intercept incident radiation upon being heated significantly.

In this fourth aspect, the bodies preferably comprise curled or rolled bands, strips or ribbons of material having the property of progressively uncurling or unrolling upon exposure to a threshold temperature and higher temperatures by incident radiant energy. The exposure of the curled or rolled bands, strips or ribbons to a threshold heating effect of insolation preferably commences uncurling by utilising differential thermal coefficients of expansion of different materials forming part of the material, thereby reducing excessive insolation that would otherwise enter the medium. Alternatively, the bodies may be movable from retracted positions towards extended positions in which they present greater horizontal surface area to incident radiation and hence greater interception of incident radiation upon exposure to a threshold and higher temperatures by incident radiant energy or increasing ambient temperature. The bodies may comprise wings and exposure of the bodies to the threshold temperature commences raising of the wings from retracted positions towards their extended positions by utilising differential coefficients of expansion of different materials forming mountings of the wings, thereby reducing excessive insolation and heat that would otherwise enter the medium, and conversely, when lower insolation or ambient temperatures cool the mountings, they lower the wings towards their retracted positions, allowing more light and heat to the medium.

According to a fifth aspect of the invention there is provided a method of performing processing operations on a flowable feed material, the method comprising the steps of:

flowing the feed material from an initial level down a confined path or drill hole which descends underground by a substantial vertical distance to a working depth so that the pressure experienced by the feed material at that working depth is substantially greater than the initial level;

providing working conditions for the flowing feed material at the working depth to utilise the

relatively high pressure in performing the processing operations on the feed material; and

returning the flowable feed material by a return passage having undergone the processing operations at the working depth from the working depth at least a substantial vertical distance away from the working depth so as to conduct further processing operations on the reaction products within the flowable media.

The processing operations carried out on the flowable feed material preferably include at least one physical change of the flowable medium and reactants therein, the physical change being brought about by the effects of the pressurisation of the feed material descending from the initial level to the working depth as well as the working conditions provided at the working depth which include conditions to effect mixing, decavitation, and depressurisation.

For example, the reactants may comprise microalgae or diatoms from which valuable substances are to be recovered, the method comprising the steps of:

flowing a slurry of the microorganisms, flowable medium and gases from a ground surface level down the path to the working depth so that the pressure at that depth is substantially greater than at the ground surface level whereby the microorganisms are exposed to substantially increased pressure and osmotic gas transfer into their cells but without incurring the cost of active pressurisation and subsequent depressurisation;

providing conditions at the working depth to utilise highly-localised decavitation energy and rapidly changing pressures by means of choking and decompression as a result of ascent in the fluid column to induce lysis of the microorganisms; and

returning to the ground surface level the slurry of lysed microorganisms and substances released by the lysis for processing and separation of released valuable substances. Preferably the step of providing conditions to induce lysis comprises flowing the slurry in a closed and profiled passage or loop, typically formed by a profiled pipe within an outer pipe, with a series of expansion and compression zones where the partly gas-bubble-filled microorganism slurry undergoes abrupt pressure changes thereby inducing lysis of the microorganisms via ruptures of cells and vesicles caused by explosive decompression and the microimplosions and microjets resulting from decavitation. The passage has multiple restrictions arranged in series so that the slurry passes through the restrictions sequentially, each of the restrictions being followed in the flow path in the passage by an abrupt increase in cross-sectional area of the passage to thereby define the respective expansion zone of relatively lower pressure. The passage or bore may descend underground by at least 100 metres for pressurisation sufficient for a microorganism lysis process.

Preferably, the processing operations also include chemical reactions induced to occur within the flowable feed material, the chemical reactions being initiated, caused, accelerated, or enhanced as a result of the increase in pressure to which the feed material is subjected in descending from the initial level to the working level or experienced at the working level.

In one possible chemical process, the path preferably comprises a passage or bore which descends

underground by at least 100 metres, and preferably by some thousands of metres, so that the pressure in the fluid at that depth is of the order of 1,000 atmospheres, and wherein the feed material comprises a heated mixture of reactant fluids (typically heated via heat exchangers located on the ground surface level) which are entrained typically as bubbles in a fast moving, catalyst bearing high boiling point liquid such as residual fuel oil as carrier, and at the working depth in the passage or bore there is generated methanol from stoichiometric volumes of methane, steam, oxygen and carbon dioxide. The methane is preferably sourced from anaerobic digestion of algal cell walls from the processing of microorganisms, or from waste material, or from hydrocarbon deposits, and wherein the oxygen is sourced from photosynthesis by microorganisms.

Another chemical process reaction comprises synthesis of a syngas comprising a mixture of carbon monoxide (CO) and hydrogen (H_2), the feed material comprising bubbles of a mix of oxygen and carbon dioxide and steam in an aqueous slurry if carbon based substances including carbon based substances, and wherein the slurry at least upon reaching the working level achieves supercritical water conditions. The slurry may be flowed down the path from the initial level includes a proportion of gaseous material wherein pressurisation of the slurry as it flows downwardly to the working level is compressed and the slurry thereby experiences adiabatic heating. The carbon based reactants preferably include micro-organisms or diatoms which have undergone lysis so as to release lipids which have been recovered and removed therefrom.

Another possible chemical process comprises a Haber ammonia synthesis and the feed material include suitable catalyst substances added to the reactants to promote the Haber process.

Another possible chemical process comprises a Fischer-Tropsch alkane synthesis and wherein feed material include suitable catalyst substances added to the reactants to promote the Fischer-Tropsch process. In this process, the reactants comprise syngas derived from the method as described herein and the production of syngas is carried out at a first working depth, and the Fischer-Tropsch synthesis is carried out at a second working depth to which the products from the syngas synthesis (after removal from the aqueous carrier and mixed with the oil carrier for the Fischer-Tropsch process) are transferred to produce the required working pressure in the flowable medium suitable for the Fischer-Tropsch process. For the Haber and Fischer-Tropsch processes, the reactants and catalysts are entrained in an oil carrier medium and small bubbles therein provide surface conditions for the chemical processes to progress.

Preferably heat from exothermic reactions is transferred to raise the temperature of feed material flowing downwardly to undergo the chemical reaction at the working level, the feed material being heated comprising at least one of:

- the feed material in the method described to undergo lysis of the micro-organisms,
- the feed material in the method described flowing down in the path to undergo the chemical reaction producing methanol,
- the feed material in the method described flowing down the path to undergo the syngas synthesis

process,

- the feed material in the method described flowing down in the path to undergo the Haber reaction,
- the feed material in the method described flowing down in the path to undergo the Fischer-Tropsch reaction.

In a preferred embodiment, in which the slurry comprises the aqueous carrier medium and the lysed micro-organisms resulting from the reaction at the working level includes lipids released upon lysis of the micro-organisms, the method includes the further steps of separating or at least concentrating the lipids by gravitational or centrifugal separation, and reacting the lipids in a transesterification reaction conducted under controlled temperature and pressure conditions at a predetermined level in the underground facility where moderately elevated pressures are experienced sufficient for the transesterification reaction.

Preferably the steps of the various methods are at least partially performed underground in a deep drill hole so that the elevated pressures experienced by the flowable feed material comprising flowable medium and reactants result from the ambient pressure experienced at substantial depths below ground surface level, the depth of the drill hole preferably being at least 100 metres and most preferably being in the range of from 1,000 to several thousand metres. Preferably, heat for promoting the processing operations carried out at depth is in part derived from elevated temperatures of the ground in which the drill hole is provided. For example, the drill hole is provided at a hot fractured rock geologic formation utilising at least one deep drill hole created to access the hot rock formations deep below ground surface level, the processing operations being carried out within processing apparatus lowered from ground level into the drill hole to the required depth for achieving the desired temperature and/or pressure conditions for the respective processing operations.

Brief introduction to the drawings

Possible and preferred features of the present invention will now be described with particular reference to the accompanying drawings. However it is to be understood that the features illustrated in and described with reference to the drawings are not to be construed as limiting on the scope of the invention. In the drawings:

Fig. 1 is a schematic perspective view of a bioreactor embodying aspects of the present invention;

Fig. 2 is a simplified perspective view of a processing station embodying some aspects of the present invention;

Fig. 3 is a cross-section through a portion of the processing station showing arrangement and action of the impeller and agitator;

Fig. 4 is a cross-section through a pipe bundle for supply of working fluids and off takes in a system embodying some aspects of the present invention;

Fig. 5 is a perspective view of a pipe bundle joiner for use with the pipe bundle of Fig. 4;

Fig. 6 is a sectional view through one version of a fluting passage overlying the phytotubes;

Fig. 7 is a sectional view through the fluting of Fig. 6 when compressed;

Fig. 8 is a sectional view through an alternative system for shading medium in the bioreactor responsive to radiation intensity or ambient temperature;

Fig. 9 is a schematic vertical sectional view through a system for processing microorganisms embodying aspects of the present invention; and

Fig. 10 is a schematic vertical sectional view through a system for producing methanol or other fuels and chemicals embodying aspects of the present invention.

Description of possible embodiments of the invention

BIOREACTOR DESIGN

Winwick bioreactors and their associated impeller/harvester units, are designed to be mass produced as complete assemblies in a factory environment. The bioreactors are designed to be transported in flattened form on reels, together with their enclosed piping. Reels are unwound or rewound on-site using high, wheel-base tractors with reel management attachments. A bioreactor body 10 (see Fig. 1) comprises four, suitably separated, clear plastic film phytotubes 11-14 (the tubular containers for growing the microalgae, diatoms or other or phytoplankton in aqueous, growth media with room 16 for exhaust gas above), within a protective and insulating, outer envelope 21 and solar-adaptive fluting 45. All the tubes are produced by standard blow-moulding or extrusion techniques. The envelope 21 is temporarily sliced open lengthwise to facilitate the placement and fixing of the tubular contents, the fluting 45, the photovoltaic (PV) 41, the supporting members, and the protective/reflective groundsheet 29, prior to re-sealing.

The PV 41 is formed into complex, centrally-vented (to permit the exit of cooling air), transverse bands or strips of PV running inside fluting 45, crosswise along the bioreactor 10. In one version, two PV strips are attached edgewise to a third, non-PV supporting strip. These together form a combination strip that holds apart the external film or face of the fluting that is thus produced with the envelope forming or located at its lower part. When cold, the strips 41 in Fig. 6 are transversely curled to expose more of the algal medium to insolation. When warmed by progressively hotter sunlight, they uncurl to shade more of the medium. The uncurling is mediated by differential thermal expansion of the two sides of each strip, one side being composed of metal foil and/or dense, polymer foam or other material with different expansion coefficients to the other PV layer. In the alternative embodiment of Fig. 8, the PV strips or bodies 41 comprise wings and exposure of the bodies to the threshold temperature commences raising of the wings from retracted positions towards their extended positions by utilising differential coefficients of expansion of different materials forming mountings of the wings. The wings 41 are mounted on support walls or struts 150.

The shading caused by the strips means that each alga in the algal soup, moving along the bioreactor, under the motivational force of the rotating impeller blades, experiences rapid changes of dark and light. When these changes occur at sub-second frequency, i.e. the total dark – light cycle duration, the algae use the incident light most efficiently in photosynthesis and are less subject to photoinhibition caused by excessive light. The

flashing effect appears to increase light-usage efficiency by nearly double, so less light is required for photosynthesis and more can be diverted to daytime power generation.

The striping solution is also one that is adaptable to different conditions and algal strains. Given flexibility in PV dimensions, both the PV strips and the spacings between them can easily be set differently at envelope assembly, whilst the frequency of light variation to each algal strain can be varied for a given spacing simply by changing the variable impeller speed.

The recently discovered antenna-reduction effect helps make the unusually large cross-section of the Winwick phytotubes efficient at biomass production, without requiring high turbulence, even for moderately high algal concentrations.

The elevated pressure in the phytotubes also serves to increase the concentration of nutrient gas in the soup , leading to increased productivity for most algal species.

The phytotubes contain the growing microalgae, nutrient media and gases. They are encased by a clear, outer plastic film tube, the envelope, that lies on, and is affixed to, the groundsheet. The gas in the envelope is chosen from CO_2, O_2/ CO_2 or other filtered gas, whichever represents the best site choice when the factors of: heat retention, fire risk, maintenance workers, pests, lichen/mould growth and bubblemix contamination are considered together. The envelope encloses, and is fixed to, the phytotubes and to the internal piping, to keep them in place. Following deployment, it also encloses the bubblemix, gases, algae and algal growth media.

The separation distance between the inflated phytotubes 11-14, within the inflated envelope 21, is important for two reasons. First, it allows sunlight to penetrate the algal media 15 from several directions, thereby permitting the algal soup to be either denser in algae or the soup deeper. Second, as it allows sunlight (or the bed heating mechanism in cooler times) to warm one or other side of each phytotube 11-14, this results in slow, convective, circumferential flow or turnover in the soup as it passes along the phytotube passages. Combined with the low-energy, laminar flow lengthwise in the phytotubes 11-14 that is provided by the energy-efficient, rotating impeller blades 32, the resulting slow, helical flow along the bioreactor passages results in all the algae being periodically exposed to suitable amounts of photosynthetically active radiation (PAR). The periodicity, when combined with the striping effect of PV and possibly antennae-reduction, is designed to be sufficient for most algae in the soup to survive, grow and reproduce optimally, without the need for rapid, energy-intensive agitation, turbulent flow, costly artificial illumination, or the high, pipe resistance involved in small-bore, enclosed tubular bioreactors.

Selected, thixotropic (i.e. having the property of becoming less viscous upon agitation) gelators added to the soup 15 mean that the algae are grown in a thin, tenuous thixotropic gel. This or these additions have several major benefits. First, suspension in even a weak gel means that a far wider range of algal strains can be used - not just the few that remain well-dispersed and suspended in aqueous media. Therefore, algal strains with superior growth and lipid-producing abilities can be used, without the need for the turbulent flow and costly agitation required by prior proposed methods. Second, even a weak gel will tend to prevent dead or flocculating algae from either

scumming at the surface or precipitating, under which latter action they become less available for harvesting. Third, it means that individual algae are less likely to be occluded from nutrients or sunlight and the effective exchange of gases that is necessary for their optimal growth. Fourth, use of a gel means that the energy used for agitation and propulsion can be very significantly reduced, principally because agitation for the purpose of aeration, mixing and dispersion is much less necessary. Fifth, vigorous or violent agitation is no longer required to ensure that algae do not plate, or scum out, on interfaces, thereby involving costly material losses, downtime and/or cleaning operations. And sixth, because using a gel and allowing additional, sunset-time oxidation of the soup, by means of reducing carbonation and/or aeration means that the high energy cost of impulsion, agitation and sparging at night-time, required by prior proposed methods, may be omitted entirely, or else very significantly reduced. This only-daytime power requirement also fits in nicely with the timing of solar electric power delivery from the local PVs.

Although sparging (generating bubbles of gas to travel up through the algal soup) happens at two places, at different rates, and for two different purposes in the impeller/harvester unit 30 (Figs. 2 and 3), they both affect the productivity and dispersion of the algae, nutrients and waste products travelling in the soup in the phytotubes 11-14 and impeller/harvester unit 30. Small-bubble introduction is done by sparging means 33 in a treatment zone 31 to provide the algal stock with a sufficient amount of carbon dioxide nutrient to feed it during its passage through the length of one of two outgoing phytotubes 12, 14 and return phytotubes 11, 13 (until another active sparge plate is reached). The sparging in zone 31 also helps to remove the photosynthetic waste product of oxygen, which can otherwise retard algal growth. A gel that slows upward bubble movement to almost any desired extent, also helps to ensure that there is high utilisation of the (initially nearly pure) carbon dioxide content of the sparged bubbles by the algae, before the gas is largely lost to that above the soup, which is pumped off (typically, as a 90:10 oxygen:carbon dioxide mixture). Slow, small-bubble movement upwards in the weak gel also helps to ensure that, in the absence of turbulence, there are continuous micro-exchanges of small, transient groups of algae and of materials amongst different levels in the soup, thereby contributing to productivity. The helical motion of the soup in the phytotube also helps to prolong bubble residence time and hence gas interchange in the soup.

The bubbling of carbon dioxide in fine bubbles into the medium within the treatment zone 31 is performed by a sparging member 33 having raised-edge perforations through which carbon dioxide gas bubbles are introduced into the medium. The sparging member or plate 33 is vibrated (e.g. by piezoelectric or magnetostrictive transducer mechanism - not shown but incorporated in the small-bubble sparge plate) at a sonic frequency to promote the ready release of carbon dioxide bubbles from the perforations enabling smaller or microbubbles to be generated than would otherwise emerge naturally from perforations of such diameter in such a medium. Piezoelectric or magnetostrictive transducer produced vibration at higher power settings and/or frequencies or with the use of different transducers integrated with a harvest sparge plate 51 also serve to clean nearby surfaces and components of the impeller/harvester unit 30. The processing station includes a harvesting zone 50 in which microorganism bearing medium is sparged with a flow of harvesting gas through a harvest sparger 51, the flow of harvesting gas

promoting froth flotation and concentration in the froth of microorganisms, the sparging gas being taken renewably from that immediately above the medium in the processing station 30 and typically comprising an oxygen and carbon dioxide mixture of around a 90:10 ratio, together with lesser component gases such as water vapour and nitrogen. The harvest sparger 51 is vibrated at a suitable power level and/or frequency for short time periods so as to limit adverse effects on the microorganisms so that the vibration serves to clean the harvest sparging member and immersed surfaces within the processing station.The processing station 30 also has a waste release zone 36 where waste gas is released from the medium. The waste release zone 36 is immediately downstream of the points where the medium 15 and microorganisms therein returns from the return passages 11, 13 and enters the processing station 30 and is upstream of both the treatment zone 31 where carbon dioxide gas is introduced into the medium and of the harvesting zone 50 where harvesting of the microorganisms occurs.

At the waste release zone 36 there is performed a fluidising step in which the medium and microorganisms therein are agitated by agitators 37 which both impel the medium and agitate it to reduce viscosity or dethixothropise the medium and thereby to promote the release of gaseous waste (oxygen) from the medium into the gas body above it. The agitators 37 are on shaft 38 which is slave coupled to the shaft 35 by gears 39 so as to counter-rotate. In Figs. 1 and 3 the agitators 37 are shown as having elongated blades but they may have multiple paddles or fingers to more effectively break up the gel and promote release of the gaseous oxygen.

Large-bubble sparging at a harvesting zone 50 may only occur at intervals when algal harvesting is desired, though continuous harvesting is also possible. Whilst small bubble sparging in treatment zone 31 uses CO_2, large-bubble sparging will recycle the O_2/CO_2 mix above the algal soup for its gas supply. This serves four purposes: it conserves CO_2; it ensures an adequate gas supply for harvesting for all bioreactors, even when many are harvesting at once; it maintains the relative purity of the gases; and it means that correct pressures are easier to maintain in the system. Large-bubble sparging only has a minor effect upon the dissolved or small bubbles of gas remaining after agitation in the soup. Most of these remain in the soup after passing the harvester 50. CO_2 thereby continues to nutrify the algae until the microbubbles dissolve, rise to the surface and burst, or are conveyed away with the harvested algal slurry. Typically, by the time the microbubbles reach the surface, the algae and aqueous soup solution will have extracted most of their CO_2 content, replacing it with oxygen.

Large-bubble production by sparging means 51 is more vigorous or violent than small-bubble sparging. This is so because it is designed to maintain the agitators' break down of the somewhat crystalline or ordered, thixotropic soup structure. A thin harvesting fluid is desirable to allow large bubbles to move easily and algae to be exposed to frequent gas-liquid bubble interfaces, to which they may loosely adhere and thus be carried upwards with the bubble to form a froth or algae-rich slurry that can readily be harvested. Another beneficial effect of this froth-flotation process is that the algal content of the froth, after the larger bubbles have preferentially burst, is many times greater than that in the original algal soup. Large-bubble sparging also has the effect of breaking up undesirable agglomerations of algae and of lipid, of providing additional macro-scale mixing, and even of partially

cleaning the equipment. In metallurgical froth-flotation, surfactants are usually needed to ensure that the valuable mineral particles are selectively captured by the bubble surfaces, leaving behind the dross. As algae tend to have a natural attraction to bubble surfaces, the addition of surfactant may not be required. However, if its use does deliver a net benefit for harvesting a given algal strain, then the surfactant(s) chosen may be able to be one that has a secondary use as algal macronutrient or catalyst.

Similar, sparge plates 33, 51 in stainless steel are used to produce both small and large bubble sparging. The main differences being: the internal diameter and number of the sparge holes; the pressure and composition of the gas; the presence in 33 of piezoelectric transducers to vibrate the plate at sonic frequencies and promote release of microbubbles; the sparge plate locations; and transducers of the harvest sparger 51 that are vibrated at a higher power level and/or frequency for short time periods so as to limit adverse effects on the microorganisms.

To a reasonable maximum extent possible, the plant and other constructed elements are designed to be made from a single, cheap, available, adaptable, easily-formed, long-lasting and non-reactive thermoplastic. This maximises opportunities for economical re-use, recycling and transportation - and minimises material separation difficulty and other environmental issues and costs. Most plastic elements forming the bioreactor farm are currently designed to be made of endlessly-recyclable and cheap polythene. However, another polymer or polymers may end up replacing this, without adversely affecting the concept.

In Figs. 6 and 7, attached to the top of the envelope 21 are bands or (broken) strips 41 of semi-flexible photovoltaic film, mounted in the airspace of two lengthwise sheets 46, 47 of fluted, transparent polymer 45. The slightly inclined, transverse fluting serves passively to air-cool the curved top of the envelope and the PV, thereby increasing its solar conversion efficiencyThe PV strips are fixed to the supporting member to project into the air between the fluting film or coating 46 above and the envelope 21, or lower sheet 47 below to keep the strips relatively cool and thereby reasonably efficient. The air cooled fluting also serves to reduce unwanted heating to the bioreactor phytotubes 11-14 and the algal medium 15. When cold, the strips 41 are curled up to a fraction of their fully deployed width. However, as their surfaces are laminated with a different coefficient of expansion materials (e.g. a dense, foam polymer, glass ceramic or metal foil), when the composite strip is warmed by the sun, it uncurls proportionately in response to the heating, thereby increasing the depth of the fluting 45 (raising the upper surface to the level 46A) to allow more air to circulate and increasing the extension of the PV thereby to shade more of the algal media 15 from excessive insolation and heat, and producing more PV electric power.

Referring particularly to Figs. 6 and 7, the fluting 45 includes in the air space between the upper sheet 46 and the lower sheet 47, ribbons or bands or strips of curled S-shaped PV and supporting materials. The PV material 42 on one part of the S has a lower thermal coefficient of expansion to 43 of the bi-layered support material 40, 43 and a higher one than 44 on the other part of the S. Material 43 has a higher coefficient of expansion than does 40 on the same supporting member. These differences mean that the ribbons uncurl and the fluting expands at the same time under increasing temperature, and vice versa. In this heated condition, the uncurled strip 41 intercepts a

greater proportion of the incident radiation thus shielding the medium moving beneath the lower sheet 47. The space between the end 41B of the strip 41 and the next adjacent end 41AA of an adjacent strip remains as a window for incident PAR to irradiate the medium and microorganisms moving past that space. Conversely, when there is less incident radiation and consequently less solar heating, the ends 41A, 41B of the strip 41 progressively curl up towards the S-shaped configuration shown in Fig. 6, thus allowing greater insolation of the medium moving beneath sheet 47. The width and positioning of adjacent strips and the extent by which they uncurl are the factors that principally determine the proportion of the insolation transmitted to the algae and that is used to produce power.

In Fig. 7, the fluting 45 is shown compressed (which would be effected when the strips 41 are heated and in their uncurled condition) so as to enable the fluting to be formed into a roll, desirably with the sheet 47 already attached as the upper surface of the envelope 21.

In Fig. 8, the PV strips or bodies 41 comprise wings 142, 143 shown in solid line in retracted positions . Exposure of the bodies to a threshold temperature commences raising of the wings 142, 143 from their retracted positions towards their extended positions 142a, 142b and 143a, 143b by utilising differential coefficients of expansion of different materials 144, 145 forming mountings of the wings. The raised positions 142a and b, 143a and b of the wings shown in broken lines intercept incident radiation that would otherwise enter the medium and also increase the amount of electric power produced. Conversely, when lower insolation or ambient temperatures cool the mountings 144, 145, they lower the wings 142, 143 towards their retracted positions, allowing more light to the medium and producing less power. The mountings 144, 145 of the wings form hinges to which the respective wings are mounted. The hinges are each composed of different materials in laminar form with different (higher or lower) thermal coefficients of expansion so as to progressively open out and raise the wings mounted thereto upon being heated to or beyond the threshold temperature by incident radiation or ambient temperature increase.

The fluting 45 in Fig. 8 can be initially flat for transport or storage The central support 150 shown erected is composed of a hexagonal section 151 of plastics material with flexible hinged corners 152 and strap 155 with a ratchet bearing face 156. When initially collapsed, the section 151 has a low height and walls 46, 47 are close together. When the fluting 45 is first deployed e.g. from a rolled up condition, an airfoil effect over the top face 47 lifts the face 47, the hexagonal section 151 erects and passes through a partially erected condition shown in broken line at 151a in Fig. 8 to its fully deployed position shown in solid line at 151. During erection the strap 155 passes through an aperture 157 in the centre of the section 151, and the ratchet teeth 156 prevent the central support 150 from collapsing again, thus making the fluting 45 effectively self-erecting.

Commercial, anti-condensation coatings are provided to appropriate surfaces of the envelope 21, phytotubes 11-14 and even fluting 45, with the coatings being selected from ones having little effect on PAR transmission and (for the internal surface of the phytotubes) do not encourage algal adhesion. A Teflon ™ or FEP coating may be used to reduce such adhesion where a given algal strain in use or prospect has that tendency.

Should potential conditions make it advisable, the open ends of the flutes 45 may be covered with strips of

transparent, thermoplastic flywire mesh the better to secure the fluting to the adjacent fluting and to the envelope at the other open end and to hinder the ingress of detritus and insects.

The PV fluting system serves a fourfold purpose: shielding the algae and plastic tubes from excessive or damaging heat and insolation (sunlight); producing solar electric power to run the machinery and to generate excess power for sale; strengthening the envelope around its area of prime, near-horizontal exposure to radiation and weathering; and providing the alternation of light and dark to the moving algal soup that is necessary to gain optimal radiation usage, without photo-inhibition. The width of the strips 41 and the intervals between them is so calculated as to provide the required, sub-second light and longer dark-recovery intervals between light exposures that result from the modest velocity of the soup 15 along the bioreactor 11-14 that is, in turn, provided by the relatively slow-spinning impeller blades 32.

Any of several existing commercial or near-commercial brands of flexible, preferably thermoplastic polymer, PVs may be employed. The width and spacing of PV strips 41 along the envelope 21 would be selected at assembly time in order to suit the climatic conditions of the site and the algal strains for which the bioreactor 10 was being built.

Inside, attached to one (or to each) side of the envelope 21 and sloping down towards the impeller/harvester unit 30 are narrow plastic channels 48 to collect and conduct water that condenses on the internal, upper surface of the envelope 21 to valves (not shown) which, when open, remove the water so distilled from the protective, salty bubblemix 22 lying in the bottom of the envelope tube. When the valves are shut, the distillate simply overflows back into the bubblemix 22. Water for the original bubblemix mixture will usually be sourced from local, possibly brackish bore water. This, like the water for the algal media 15 itself, if desirable, be sterilised by one of the heat sources, such as heat from a nearby solar pond, or geothermal or hot fractured rock power generating facilities (known as HFR), to ensure that no unwanted, living organisms or spores remain viable. The bubblemix 22 develops its wildlife-repellent, briny nature from the distillation process that concentrates the brine. Its long-lasting, bubble-forming properties are given it by the addition of bubblemix concentrate, which may be a form of detergent and/or gel. A biocide will normally be another component of the bubblemix, to keep it transparent and free of organisms.

Distilled water from the distillate channels 48 that is not recycled to the bubblemix 22 is directed to the impeller box 55, 56 or can be pumped into the fresh/distilled water main. Water from this main pipe can be used to increase or replace phytotube liquid volume removed by harvesting and/or to reduce the salinity of the algal media 15, or the bubblemix 22. The distillate channels 48 and valves therefore act as essentially passive, solar-powered salinity controllers and as economic producers of distilled water for the algal soup or other purposes. The condensation process also serves as a mechanism to transfer excess heat from the bioreactor contents to the envelope, from whence it moves readily to the atmosphere.

Distilled water for a variety of uses may also be stored locally by the system, typically within a double hull of

the impeller/harvester casing, should that be desirable. A sensor and pump may be activated to remove such an accumulation of distilled water to a central, sealed reservoir. Alternatively, the double hull can be used to hold brine or concentrated nutrient solution to deter wildlife seeking fresh water. Such a water ballast would also serve to stabilise the impeller/harvester unit 30 when otherwise empty. It could be useful when new bioreactors were being set up, as water ballast might avoid undesirable movement of the impeller/harvester unit when a bioreactor 10 was being unrolled from it.

Changing the salinity, sodicity, pH, temperature, level, pressure, algal strain or nutrient concentration of the algal media 15 or bubblemix 22 may be done by pumping the relevant material from or to a mains pipe - an action that is usually mediated by the local microcomputer and implemented by equipment in the impeller/harvester unit 30. Initiation for this is directed by locally-stored program or is done remotely from the facility control centre, either by pre-set computer program or over-riding human intervention, possibly requested on location by the installation or maintenance staff.

Four types of tube reside within the envelope 21: the phytotubes 11-14, distillation channels 48, bubblers 18 and warming tubes 19. The three, porous bubbler tubes 18 are used to produce masses of bubbles from the briny bubblemix 22 in order to create a semi-stable foam that fills the control space 25 of the envelope 21, thereby insulating the algal soup from excessive heat, cold or insolation. The warming tubes 19 bring (typically waste) warm water from either: industry; hot fractured rock (HFR) geothermal sources (typically, after its steamy, higher temperatures have already been used for other purposes); ordinary geothermoclines; warm bores; or solar ponds. When the warm (or else cold, if bioreactor cooling is required) water pumps and/or valves are actuated, warm water flows in two pipes 19, through the bubblemix 22, in the envelope 21, between each of the two pairs 11, 12 and 13, 14 of phytotubes. This both warms (or cools) the bed of the bioreactor and maintains algal, temperature-dependent activation levels. At the same time, it sets up circumferential convection currents in the algal soup 15, thereby replicating the beneficial effect of warm-season, angled sunlight during cold or overcast times. The two warming tubes 19 are joined at their far ends, to form a U-shaped loop. Local, microcomputer controls can reverse the flow periodically in these to ensure that the different pairs 11-12 and 13-14 and sections of phytotube are warmed approximately equally. Afterwards, the now-cooled water is pumped by return pipe to the original heating or cooling facility for re-use.

The far end 10a of the bioreactor 10 is made of hollow, rotomoulded polythene. Its form is roughly that of a flaccid ellipse, freestanding on its long, flatter edge and supported on stability supports projecting from its lower, long edge. Its cross-section resembles a thin “witches hat” with five extra protrusions on one side, by which to attach the envelope 21 and the four, phytotube 11-14 elliptical ends. Subsequent to the rotomoulding operation, the centres of the phytotube formers on the rotomoulded item are cut out to allow lengthwise and transverse passage of the algal soup. The barcode of the impeller/harvester unit, plus an endpiece code, are heat embossed in large characters on the exposed side of the bioreactor endpiece for identification and navigation purposes. The central database

associates each barcode with the farm, access road, rectangle, layout, kytail, sequence, impeller/harvester, bioreactor, GPS location, age, contents and status of the unit. This information is remotely available to maintenance workers, as are their team members' GPS positions, schedules, timing, tech information, guidance and communications.

The bioreactors 10 in one production-scale embodiment envisaged can be initially designed as being 100m long, 2.5m wide and 0.55m high at the slightly curved apex. The bubblemix 22 is normally only around 0.13m deep, but this can be increased to as much as 0.30m in order to cope with less-level terrain, or to help resist overheating or damaging bioreactor movement by way of floodwater or cyclone The depth of the bubblemix 22 is what allows the phytotubes 11-14 to be filled as deep as they are with soup, and to become as round in cross-section as they are, without the enclosing membrane of which the tubes 11-14 are composed coming under unnecessarily high stress. It also means that the phytotube membrane only has to withstand a pressure of water from 0.27 less 0.13 equals 0.14m depth, rather than the full 0.27m depth of the soup 15 in the phytotube 11-14. Each phytotube 11-14 has a similar, though rounder, cross-sectional shape to the envelope and has dimensions 100x0.5x0.4m. When inflated, phytotubes have spacing between them of around 0.12m. This allows sunlight to penetrate between them and perhaps sideways into the phytotubes. Some rays are reflected from the underlying, aluminised groundsheet 29 and penetrate into the lower, outer levels of the algal soup 15 on both sides. Normal operating depth for the algal soup in the phytotubes is 0.27m. However, they can still operate from between depths ranging from 0.15-0.37m. The normal operating depth has sufficient leeway as to be able to accommodate minor land surface irregularities that occur along the contour of the flat, natural (or possibly levelled) surface on which the bioreactor is laid, whilst still providing an adequate channel depth for soup transport. The extended range of depth allows accommodation to somewhat greater landform variations. At normal operating depth, there is a space 16 of around 0.13m above the algal soup 15 in the phytotube 11-14 for gas accumulation and transport. The gas in space 25 of the envelope 21 and phytotubes is lightly pressurised to create the desired shape by means of the gas pumps (not shown) in the impeller/harvester unit 30 or that of the pressure in the inlet and outlet pipes. The pressure in the phytotubes 11-14 is maintained slightly higher than that of the envelope 21, in order to maintain the desired cross-sectional shape. This also serves slightly to increase the CO_2 concentration in the soup, and thereby to increase algal productivity.

The volume of gas in each type of tube 11-14 and 21 can be altered temporarily, to allow easier, or less potentially damaging, access for repairs, maintenance and replacement. On partly deflating the bioreactor envelope 21 and/or phytotubes 11-14, weighted, padded bars placed across them is usually sufficient temporarily to isolate the bulk of their contents, with little chance of rupture or wrinkle formation. When replacing a bioreactor 10, the tubes 11-14, 21, 18, 19 may be rolled up from the far end 10a, pumping off the contents, until they can be tied and cut like umbilical cords. The replacement tubes can then be attached over the nubs of the previous ones, or replacing them. Whereupon the nubs can mainly be cut away and removed via the inside the impeller/harvester unit 30.

IMPELLER/HARVESTER DESIGN

Each impeller/harvester unit 30 (see Figs. 2 and 3) has a bioreactor 10 attached to both ends. There are four, distinct, internal chambers in an impeller/harvester unit, two of which 55, 56 each share the algal soup and gases with its own bioreactor, a third 57 for the drive box containing shared machinery, and a fourth 58 as the shared internal conduit located over the external pipe bundle 70 that transports external fluids and which conduit is sealed by a plastic board embossed with the unit's barcode 61 for easy aerial and ground-level identification. The unit also has a trapezium-shaped tunnel 59 running under its middle. This straddles the pipe bundle 70. Pipe-bundle offtakes typically lead through holes in the roof of the tunnel 59 to the relevant chamber and item of equipment. The tunnel 59 is also used to connect services to a surveillance pole and part-buried computer post (neither shown).

The housing or body 60 of the impeller/harvester 30 is made of rotomoulded, hollow polythene or similar, thermoplastic polymer, which may be of recycled bioreactor or impeller/harvester material. It is tank-like and has a rectangular base and a curved, openable top 57 which is covered by the barcode plank 61 and twin, separately removable, clear plastic covers, sealed at their edges by strapping, fasteners and seals. The impeller/harvester body's outer dimensions are approximately 2.5x2.2x0.9m.

Each chamber 55, 56 that connects to a bioreactor 10 has two injection-moulded polythene, drive shafts 35 and 38, one say 35 being slave-driven from the other 38 by gear cogs 39. The shaft 35 mounts a spaced pair of multi-bladed, polythene impellers in the form of paddlewheels 32, having paddles or blades shaped rather like some curved turbine blades. The shaft 38 mounts a spaced pair of multi-bladed, polythene agitators 37 in the form of drums with knife-like radial protrusions shaped to create agitation in the medium without splashing. Each paddlewheel impeller 32 and agitator 37 is located non-adjacently at the mouth of a respective one of the four phytotubes 11-14. Underneath almost the entire length of the impellers 32 and agitators 37 is a flat, small-bubble, sparge plate 33 made of stainless steel (see Figs. 2 and 3) and incorporating piezoelectric transducers. This sparge plate 33 provides tiny, carbonating bubbles to the algal soup.

At a waste release zone there is performed a fluidising step in which the medium and microorganisms therein are agitated by the agitator 37 which reduces viscosity of the medium or dethixotropises it and thereby promotes the release of gaseous waste (oxygen) from the medium into the gas body above it. The movement of the medium along the phytotubes 12,14 is caused by the two impellers 32 which propel the medium into which nutrient gas has been introduced by sparger 33 in a manner to promote laminar flow of the medium along the passage. The impellers 32 and the agitators 37 are coupled together so as to operate synchronously, with the agitators 37 having a vigorous action upon the medium and the impellers 32 having a gentler impelling action.

Baffles 34 permit only soup from the lower half of the soup body in chamber 55, 56 to reach the two expelling impellers 32. This ensures that little of the froth produced by the large-bubble harvesting sparger 51, set further back, is destroyed before it can bubble over into the open Archimedes screw channel 52 above, which does the harvesting. Two drive belts (not shown), powered by either or both of twin electric motors (not shown) in the

common drive box in the machinery chamber 57 power all drive shafts in the unit. Solenoids controlled by the unit's microcomputer, and over-ridable by central control, engage individual valves, pumps, drives and devices.

The sparge plates 33, 51 type have dimensions approximately 2.3x0.018m with widths of 0.6 and 0.3 respectively. They are constructed of two sheets of approximately 0.5mm thick stainless steel sheet, welded together at the down-tapered edges and spot welded at points where the lower sheet is dimpled upwards to maintain a separation of 15-20mm between the plates. In the small-bubble sparge plates 33, piezoelectric transducers are sealed into some of the dimples. Transducer height may require some protrusion of the upper plate surface. One or more reinforced plugholes admit a removable nozzle that is joined to an offtake pipe containing pressurised carbon dioxide gas. Prior to welding, the upper sheet of the sparge plate has many holes of controlled diameter and pattern made in its surface, with raised and smoothed edges round the holes. This is done so as to minimise the chance of algae and grit clogging the holes. In the small-bubble sparge plates 33, the holes are preferably smaller than the smallest algal strain used. The large-bubble sparge plates 51 tend to be self-cleaning. Electrically-driven ultrasonic piezoelectric transducers in the large-bubble sparge plate 51, vibrating at about 42kHz, perform regular, computer-controlled cleaning of plates, nearby equipment and impeller box. The small-bubble sparge mounts a low power, low frequency sonic transducer that facilitates the formation and detachment of microbubbles from sparger 33.

In the machinery chamber 57 drive box are located motors, pumps, and valves. If feasible using commercially-available equipment, all gas is to be directed through a universal gas valve and pumped, if pumping is necessary to increase the pressure, by a single gas pump. Similarly, all liquids, except the algal slurry, are to be directed through a universal liquid valve and pumped, if necessary, through a single liquid pump. The flushing of pumps and valves to keep them clean and the materials they convey uncontaminated, is controlled by the microcomputer.

PIPE BUNDLE

For purposes of easier management, neatness, standardisation, mutual protection, cost and insulation, the different pipes, fibres and wires required to service the bioreactors 10 are combined in their own cluster or pipe bundle 70 - see Figs. 3 and 4. The general-purpose bundle connector plate 95 in Fig. 5 is used to connect both standard pipe bundle 70 lengths together, as well as offtake bundles to standard pipe bundles. The connector 95 takes the form of a connection plate 96 having some fifteen, joined, hollow, male, pipe connectors 97 on both sides. It is formed by injection moulding high-density polythene (HDPE). The ordinary pipe bundles 70 are simply pushed against their matching plate 96 and over the male connectors 97.

The contents of the fifteen pipes in the pipe bundle 70 are as follows. The three largest diameters contain: hot water in 71 within covering 72, cooled return water in 78 , and algal slurry in 79. The eight middle-sized pipes contain: algal soup in 80; nitrogenous algal soup in 81; sterilised, typically-brackish bore water in 82; carbon dioxide (CO_2) gas in 83; 90:10 oxygen O2/ CO_2 gas mix in 84; distilled or sterilised fresh water in 85; nutrient water from the

anaerobic digester (possibly plus some replacement gel mix) that has subsequently been sterilised in 86; and brine or bubblemix brine in 87. The four smallest diameter pipes 88-91 contain: nutrient mixes #1, 2, 3 or 4; or inoculants of seasonal or replacement algal strains that temporarily replace the contents of one or more of the nutrient mixes. Any replacement may if required be preceded by a flushing process with distilled water. The nutrient mixes themselves are so specified that they can be combined in various ways to make many different, algal media, nutrient mixes. Each can also be temporarily replaced to address a particular situation. The contents of the conduit 75 include any insulated wire, fibreoptic or other cable that is necessary to conduct power or communications.

PROCESSING PLANT

Processing plant includes various, relatively standard, chemical engineering units, such as liquid, slurry and gas pipes, heat exchangers, filtration plant, centrifuges, pumps, valves, sensors, actuators, fractional distillation towers, an anaerobic digestor, and storage reservoirs or tanks. The presence of gelators will tend to improve slurry piping mechanics.

Novel plant comes about from newly perceived opportunities (described in connection with Figs. 9 and 10):

- to implement chemical and physical processing methods underground in a deep drill hole so that the elevated pressures experienced by a flowable feed material comprising flowable carrier medium, reactants, catalysts and promoters result from the ambient pressure experienced at substantial depths below ground surface level,
- the use of heat for promoting the processing operations carried out at depth being in part derived from geothermal heat derived typically from hot fractured rock (HFR) geologic formation utilising other deep drill holes created to access the hot rock formations deep below ground surface level. The processing operations are carried out within processing apparatus lowered from ground level into processing drill holes to the required depth for achieving the desired temperature and/or pressure conditions for the respective processing operations;
- use of HFR, hydrocarbon extraction and solar resources and infrastructure for chemical process engineering and algacultural purposes;
- use of the cultivation of algae to produce a 90:10 O_2: CO_2 gas mix that can be combined with local methane to produce methanol most economically for on-site transesterification of algal lipids or sale. Any excess oxygen may also be separately saleable for piped industrial use particularly where exchanges for carbon dioxide are both feasible and desirable;
- use of fast moving high boiling point liquid such as residual fuel oil as carrier for reactant bubbles and catalysts, and to use the high pressures at working depth in the drill hole to generate methanol from stoichiometric volumes of methane, steam, oxygen and carbon dioxide;
- use of an aqueous slurry of reactants including algal cell or biomass and other carbon based substances and oxygen, so that when the slurry reaches the working level in the drill hole reactor, supercritical conditions enable synthesis of syngas comprising a mixture of carbon monoxide (CO) and hydrogen (H_2);

- use of the pressure experienced deep underground to carry out Haber ammonia synthesis in a drill hole reactor using a feed material of suitable catalytic substances added to the reactants comprising suitable mixed gas in bubbles in an oil carrier to achieve a variant of the Haber synthesis of ammonia from hydrogen and nitrogen;
- use of the pressure experienced deep underground in a twin pipe to carry out Fischer-Tropsch syntheses using a feed material of suitable catalytic substances added to the gas bubble reagents to promote any of several Fischer-Tropsch processes includes ones for alkane production from syngas.

PROCESS ENGINEERING USING HFR

Extracting heat from HFR typically requires making deep, and consequently high-pressure drill holes into hot, fractured rock formations. The same heat and/or pressure, when combined with input reactants, suitable catalysts and processing steps, can be utilised to produce desirable physical and chemical changes in materials, such as lysis of algal cell walls and the consequent release of lipids or the production of methanol or other compounds requiring the application of heat and/or pressure for their synthesis. Processing steps using HFR are likely to be far more economical and friendly to the environment than are traditional methods that rely on fossil fuel and high-pressure pumps to achieve elevated temperatures and/or pressures.

Processing microalgal cells to produce biofuels and co-products involves overcoming several physical and economic problems. These include the high costs involved in: rupturing the tough algal cell walls; heating; dewatering; chemically transforming the viscous, algal lipids into suitable transport fuels and the non-lipid fractions into other useful materials; producing the methanol to make lipid transesterification possible; and separating the output components into valuable products and recyclable material. Brute force methods have traditionally been used to address these problems. However, these are increasingly costly, unsustainable and typically involve serious greenhouse emissions. The novel method proposed, bypasses the step of removing water from the algae by processing the algae in aqueous phase, thereby facilitating oil/water phase separation. It also rationalises the number of separate processing steps, making use of carbon-neutral and economical HFR resources.

A developed HFR resource has two useful components: accessible pressure and carbon-neutral heat. These components can separately be replicated away from an HFR resource, but at typically much greater financial and environmental cost. In the present process, pressure and heat are used successively to produce the desired transformations in the algal slurry, and later to separate the individual fractions. They can also be used to produce methanol, syngas from biomass, alkanes from syngas and ammonia from hydrogen and nitrogen.

Referring to Fig. 9 a flowable feed material 102 is caused to undergo at least one physical change brought about by the effects of the pressurisation of the feed material descending from the initial level to the working depth 110 as well as the working conditions provided at the working depth which include conditions to effect depressurisation. In particular, a gas-rich aqueous slurry of microalgae or diatoms such as from the impeller/harvester units 30 is flowed e.g. by pumping deep down a closed-ended drill-hole 100 to a working depth

110, via a profiled pipe 105, set inside the casing 101 of the drill-hole. The closed and profiled passage, typically formed by the profiled pipe 105 within an outer pipe in this case being casing 101, has a series of expansion and compression zones where the partly gas-bubble-filled microorganism slurry undergoes abrupt pressure changes thereby inducing lysis of the microorganisms. HFR resources are usually located a few kilometres below the surface 103, however a much lesser depth, for example of the order of about 100 metres , (and hence lesser pressure) may still be adequate. The increasing pressure progressively dissolves most of the gas bubbles into the algal media water and, by osmosis, into the algal cells and their inner vesicles.

The microorganisms are caused by explosive decompression along down and up their flow paths to lyse. A second beneficial effect is caused by de-cavitation. As the bubbles of gas implode as their last vestiges dissolve, tiny and highly-localised, but highly energetic, shock waves and penetrating microjets occur and very high, very localised, instantaneous temperatures result. The energy of these jets and shockwaves is often sufficient to rupture nearby algal cell walls and to progress chemical reactions.

The profiling of the inner pipe 105 is such that at points within it, and on the upward return slurry journey in the surrounding zone 106 outside it, there are created regions 105a, 106a of relative compression and regions 105b, 106b of decompression, as well as different velocities and degrees of turbulent mixing. When gases are involved, compression and decompression also result in significant adiabatic local heating and cooling. At decompression regions105b, 106b, gas tends to come out of solution. When it comes out of solution suddenly within a vesicle or alga, the sudden increase in gas pressure inside tends to rupture the container (the vesicle or algal cell wall), releasing its contents into the main, aqueous solution with minimal damage to its contents. Thus, the algal lipids and other cell contents are freed, unharmed to take part in further transformational processes.

As lipids are hydrophobic, they tend naturally to aggregate and to separate from the aqueous phase with only minimal subsequent de-watering effort being necessary.

At this stage, desirable co-products, such as some nutraceuticals and proteins, that would be deleteriously affected by the higher temperatures occurring later, may, if desired, be extracted. However, as the algal lipids are somewhat viscous at ambient temperature, the mixture may first be passed through a heat exchanger akin to the one at 108, using waste HFR heat or other sourced heat, to bring its temperature up to a modest 60^0C. This is sufficient to reduce the viscosity of the lipids significantly, making physical separation easier, less costly, and more complete, whilst not usually being high enough to damage fragile co-products.

The four main phases: the solid components (chiefly the ruptured cell walls comprised of glycoproteins and polysaccharides); the aqueous phase; the immiscible, oily lipid phase; and the gaseous phase are then coarsely separated by means of centrifuging at 115, using an inline, vortex centrifuge and near ambient pressure. It should be noted that it is far easier to separate ruptured cell walls from water than it is to separate complete algae from water - particularly when the cell walls can remain wet. After removal of lipids and the more valuable proteins and sugars, the wet slurry of remaining solids is piped to a biomass to syngas drill hole reactor or to an anaerobic

digester, where the action of anaerobic bacteria converts it mainly to methane, CO_2 and free macronutrients. These are all recycled. Alternatively, if economical sources of macronutrients can be made available (e.g. treated sewage, agribusiness or industrial waste), the cell walls can readily be turned into high-protein, human food or stockfeed. Note also, that for algae and diatoms having cell walls of silicic acid, the digester's action will produce less methane and may require special treatment to free the silicic acid for recycling. The methane can be used to synthesise methanol as described later in relation to Fig. 10.

Following the algal lysis process, the aqueous phase, that contains the bulk of the macronutrients, may be treated to extract its more valuable components by electrophoresis, adsorption or other methods. Its residues may then be piped to either a biomass to syngas drill hole reactor or the digester both of which release nutrients and water for recycling back to the bioreactors, or some residues may be sent directly back to the bioreactors to make up most of the material that had been removed during harvesting.

As the presence of water deleteriously affects transesterification (it can cause undesirable saponification), the lipid-rich liquid from the rupture process is heated and any residual water is allowed to boil off as steam at atmospheric pressure when the lipid-rich mixture is heated to over 100°C. The resulting steam itself is condensed and returned to the system. After the steam has been removed from the lipids, they are pumped through a heat exchanger to bring them to 107°C and thence pumped into a sealed reaction vessel or HFR drill hole where there is 5atm pressure. Where HFR heat is not available, this heat may be produced by any other economical means. In warm to hot climates, this may best be done using solar ponds. Otherwise, ordinary geothermal heat may be used or waste heat from industry. Because the triglycerides that make up the algal lipids have boiling points well above these temperatures, they are not lost earlier on.

The viscous lipids in the lipid-rich liquid are then transesterified in the reaction vessel. This is done by mixing one or more of the many recognised catalysts, together with six moles of methanol for every mole of triglyceride in the lipids to be transesterified and adding the mixture to the lipids. Although only three moles of methanol are required to react stoichiometrically, the excess methanol is added so as to drive the equilibrium reaction to transform methanol and triglyceride into methyl esters and glycerine. Due to the pressure applied, the methanol at this temperature remains liquid so that it reacts in close contact with the lipids to produce fatty acid methyl esters (FAMES, which together may be used to produce several different types of biofuel) and glycerine. With the possible use of ultrasonics to hasten the reaction, and the right selection of vessels, pumping and catalysts, the whole process can be made a continuous one, rather than a batch one. Alternatively, and probably more cost-effectively for this purpose, the mixing, cavitation and decavitation produced when the reactants are pumped hot through a (this time modestly) deep, pressurised, profiled pipe 105 may be used to replace the function and cost of ultrasonic irradiation in transesterification, or else the reaction can just be left to take its time.

When the transesterification reaction has occurred, the heavier glycerine may be drawn off from the bottom of the containing vessel or centrifuged. The lighter fractions may then be fractionally distilled (fractionation) using

additional HFR heat to produce the various fuel products: methanol (the excess), petrol, jet turbine fuel, biodiesel and residual fuel oil (RFO). Now, HFR temperatures of 250°C are not unknown. However, as only the C8:0 and C10:0 long FAMES have lower boiling points than this at atmospheric pressure, the C12, 14 and 16 FAMES will require either partial-vacuum distillation, or else the application of higher temperatures from a different, hotter heat source.

The partial vacuum distillation route is probably the most economical here. Particularly, as the bulk of the FAMES can be separated using atmospheric pressure distillation at less than maximum HFR temperatures. Furthermore, as most of the remaining FAMES can be separated using vacuum distillation at these temperatures, no extra high temperature heat source should be required. The smallest, least valuable, fraction is RFO which is left behind undistilled with possibly some of the catalysts and other impurities. Unless catalytic recovery is economical, this may be sold as fuel oil or cracked, possibly with the use of HFR or solar resources to form more valuable hydrocarbons, together with possibly carbon char and free catalysts.

Should high temperature distillation be required to produce any product, the availability of gas/oil well methane and oxygen, or the development of local solar concentrators for this and other purposes at some facilities, makes these obvious and reasonably economical sources of such incremental heat energy.

Any heat recovered from these processes might be: fully utilised in the lower temperature processes of the process; used to generate power; used in nearby agribusiness, factories and towns; or returned to the cooled, HFR fluid. Waste heat from the higher temperature processes is re-used in the lower temperature ones in cascade. The heat waste from the lowest temperature process may be employed to warm the bioreactors during cold or dark periods or for growing thermophilic strains of algae.

Due to the availability of economical heat sources at the facility, the crude glycerine will usually be: distilled to pharmaceutical grade; used as raw material to produce more fuel; or used elsewhere in the biorefinery or in associated agribusinesses.

At cool times, the waste heat resulting from the cascading of heat reuse and production in these processing steps, and/or other HFR heat, is used to improve algal insolation (exposure to sunlight) by convection and to warm the algae sufficiently to keep them at high activation and productivity. Cool times may also be a signal to introduce cool-climate algal inoculant into the bioreactors, and vice versa in warm or hot times.

The catalysts from the transesterification process may be recovered from the residue after fractionation. These may or may not be reusable or recyclable, depending on their nature and whether or not they have been neutralised or otherwise affected. The methanol is recycled.

The methane from the anaerobic digestion processes described in relation to Fig. 9 is used, possibly with impure methane from other sources (typically from gas/oil wells and coal mines), and combined with the O_2/ CO_2 mix from the bioreactors and steam as bubbles in an entraining liquid to form methanol via catalysis in the drill-hole 100 and may be used later in the transesterification of the algal lipids as previously described. Any catalysts used

would either be included with the entraining, high boiling point liquid and/or be coated onto the wall of the pipes, thereby providing them with close contact to the turbulent reactant gases.

The apparatus schematically illustrated in Fig. 10 can be used to implement chemical reactions induced to occur within the flowable feed material 102, the chemical reactions being initiated, caused, accelerated, or enhanced as a result of the increase in pressure to which the feed material is subjected in descending from the initial level to the working level 110 or experienced at the working level 110. The apparatus in Fig. 10 can be used in the methanol production process. This can be done by forming and if desired preheating the mixture of methane, O_2/ CO_2 mix, steam and catalysts in heat exchanger 108, prior to liquid carrier entrainment of gas mixture bubbles in mixer 109, and pumping by pump 111 to descend by at least 300 metres and preferably by a few thousand metres to create further compression heating to reaction promoting temperatures and pressures. Heavy finely divided catalysts can help increase the density of the carrier fluid which can be important in drill hole reactors and processes. The reaction products returning upwardly in the annular return passage 106 reach the head space 107 from which the gaseous products are output to the condenser or other separation stage 116 where methanol in particular can be separated through line 117 and from whence unreacted materials can be recycled through line 118 to mixer 109. As methanol is typically produced by employing pressures of up to 1,000 atm and modest to high temperatures (80-800^{0}C), depending on the intermediates and catalysts used, it may also be produced, with very substantial economies, using HFR or other drill holes, where the pressures can exceed 1000atm and the unimproved temperatures can exceed 250^{0}C at 4,200 metres depth. Even higher temperatures may be achieved as entrained gases heat up under high gravitational compression in drill-holes or by pre-heating.

Other chemical engineering processes may similarly be facilitated with this drill hole technology. Although Fig. 10 schematically depicts only a single down flow path 105 and single inflow path 106, the drill hole can accommodate multiple down flow paths or pipes for conveying reactants and carrier substances to various working depths and respective return paths or pipes, or even using multiple down flow paths or pipes and a shared or common upflow path for reaction products. Many of the possible processes utilise heating and instead of, or in addition to, heat exchangers on the surface or adiabatic heating effect of gas bubbles in the fluid being compressed, control of fluid temperature may be achieved by the use of superheated steam or chilled water introduced to the fluid by means of a long, hollow metal pipe or lance, typically running centrally down the drill hole pipe, e.g. 30-300m. Alternatively, steam may be introduced by means of one or more hollow, split collars around the drillhole casing at selected depths. A separate drill hole located adjacent to the reactor hole may be used for the steam pipe for insulation purposes. These constructions are described in more detail in the Appendix in the section DRILLHOLE REACTOR CONSTRUCTION.

In one further use, the chemical reaction comprises synthesis of a syngas comprising a mixture of carbon monoxide (CO) and hydrogen (H_2). The feed material 102 comprises an aqueous slurry of reactants including oxygen in sufficient quantity to ensure partial oxidation of the organic material substances which may comprise

biomass such as organic matter from the processing of microorganisms as described herein (i.e. the carbon based reactants include micro-organisms or diatoms which have undergone lysis so as to release lipids which have been recovered and removed therefrom), agri-wastes (e.g. lignocellulose products, crop wastes or by-products), sewage or pulp mill waste or other waste water processing products, and may comprise carbon based products from industrial processes or waste recycling collections, e.g. plastics materials, rubber wastes, etc. The slurry at least upon reaching the working level 110 achieves supercritical water conditions. Under supercritical conditions of temperature and pressure, the reactants can produce syngas by chemical reactions which are known in the chemical industry. The slurry being flowed down the path 105 from the initial level may include a proportion of gaseous material so that pressurisation of the slurry as it flows downwardly to the working level 110 is compressed and the slurry thereby experiences adiabatic heating.

In another further use, the chemical reaction comprises a Haber ammonia synthesis. For this chemical reaction, the feed material 102 includes suitable catalyst substances added to the reactants (hydrogen and nitrogen gas) to promote the Haber synthesis of ammonia.

In another further use, the chemical reaction comprises a Fischer-Tropsch alkane synthesis. The feed material 102 includes suitable catalyst substances added to the reactants to promote the Fischer-Tropsch process. In this process, the reactants in the feed material 102 may comprise syngas derived from the chemical processing method described above with the production of syngas being carried out at a first working depth, and the Fischer-Tropsch synthesis is carried out at a second working depth 110 to which the products from the syngas synthesis are transferred to achieve the required working pressure in the flowable medium suitable for the Fischer-Tropsch process. The syngas is produced in a process using an aqueous carrier so the syngas is separated before being fed to and mixed with the oil carrier for the Fischer-Tropsch process. The Fischer-Tropsch and the syngas production processes may be performed in separate but proximate drill holes because of their different process parameter requirements.

In the Haber and in the Fischer-Tropsch processes, the reactants and catalysts are entrained in an oil carrier medium and small bubbles therein provide surface conditions for the chemical processes to progress.

In performing any of these processes, heat can be available from the exothermic reactions and this can be transferred to raise the temperature of any one or more of the feed materials flowing downwardly to undergo the any of the chemical reactions in the underground processes. For example, the feed material being heated from one of the exothermic processes may comprise at least one of:

- the feed material to undergo lysis of the micro-organisms,
- the feed material flowing down in the path to undergo the chemical reaction producing methanol,
- the feed material flowing down the path to undergo the syngas synthesis process,
- the feed material flowing down in the path to undergo the Haber reaction,
- and indeed the feed material flowing down in the path to undergo the Fischer-Tropsch reaction

itself.

Also it will be understood that a useful cooling action can occur when employing regenerative heat utilisation in some processes. For example heat transfer from exothermic chemical reactions, e.g. to heat the reactants in the syngas production, can be useful to maintain desired temperature and avoid excessive temperature rises.

LOW-NITROGEN OXYGEN FROM ALGAE FOR INDUSTRY

Many industries use oxygen in their processes. Typically, the majority content of nitrogen in air reduces the efficiency, and increases the cost, of these noticeably. Those that extract oxygen from air, typically by membrane techniques, pay a cost for the process. However, if algae are provided with nearly pure carbon dioxide, such as is available as a waste product from several industries, including hydrocarbon extraction ones, algae can produce very low-cost, carbon-negative oxygen.

The Appendix at the end of the present description provides further background information, including sources of technical data, and provides descriptions and examples of the processes according to various aspects of the Winwick systems and inventions. The disclosures of that Appendix therefore constitute part of the disclosure of the present patent specification.

It can be seen from the foregoing description and from the Appendix that the Winwick systems, methods and apparatus can provide an integrated process by which microalgae can be grown on low-cost land, then harvested, transported and processed economically to produce carbon-neutral biofuels and co-products. Co-products include solar electricity, where the bioreactors form an economical, low, highly-accessible and standardised platform for photovoltaic films covering potentially thousands of square kilometres of otherwise unproductive land.

Although novel concepts are proposed for several individual processes, there are also novel combinations of several, hitherto unrelated, resources and methods.

The technology is somewhat dependent upon the availability of concentrated sources of CO_2 (though less concentrated sources can also be used). However, these are less expensive to deliver to areas where flat, non-arable land is available than are most other materials. This is so for several reasons: CO_2 is often available as a waste product from other industries and widespread deposits; as a gas, CO_2 is less costly to pump over mountains, up elevations, or over long distances than are other forms of matter; several industries, including power generation and metal refining, can benefit doubly by exchanging their CO_2 emissions for algal-produced oxygen using pipelines sharing the same trench; and liquid CO_2 may readily and economically be back-loaded in cryotankers or pipelines from LPG and LNG transporting operations. Furthermore, CO_2 may even be extracted from industry sources or the atmosphere itself using zeolitic imidazolate frameworks (ZIFs) or quicklime (CaO) to absorb it, provided there is an economical source of high temperature, such as solar concentrators located on non-arable land, to regenerate the quicklime from limestone, $CaCO_3$.

Whilst the initial application is to produce biofuels, the same technology is equally applicable to the production of algal biomass for other purposes. The main difference is that more nutrients need to be added for non-biofuels, as biomass takes all its macronutrients with it, whereas biofuel production allows most of them to be recycled endlessly. In turn, the biomass can be used to produce many different products, including: human food, stockfeed for a wide variety of organisms, nutraceuticals, pharmaceuticals, chemicals, fertilisers, plastics, raw materials and many other items.

As the Winwick process is land intensive, it is best located on land with little in the way of alternative, productive use and value. Whilst the production of biofuels from algae by the Winwick process may be most economic when located beside or on top of a geothermal resource, the production of biomass from algae using the process is best located sufficiently near (or at least not much higher in elevation than) sources of cheap macronutrients, such as sewage plants, agribusiness, or coal-fired power plants, so that the waste macronutrients from them (including CO_2) can be piped (as the most efficient transport means) to the bioreactors at modest or negative, net triple-bottom-line cost.

The great variety of organisms that are supportable from food chains that start with very large volumes of cheap, pumpable, microalgal slurry, at biofarm locations on otherwise unproductive land, when combined with the co-production of cheap, solar electric power, leads to opportunities for integration with large-scale agribusinesses and chemical engineering plants. Moreover, being collocated, these can benefit from vertical and cross-industry flows of recyclable waste, energy and by-products.

It is to be understood that alterations, modifications and/or additions may be made to the features of the embodiment(s) of the invention as herein described without departing from the scope of the invention.

APPENDIX

WINWICK SYSTEM FOR CULTIVATION AND PROCESSING OF MICROORGANISMS AND PRODUCTS

INVENTOR: CLARKE, William Severn

ASSIGNEE: Winwick Business Solutions Pty. Ltd

ABSTRACT

This paper describes the technology for a new and integrated renewable energy industry. It discloses processes, methods and designs to grow, harvest and process biofuels, and to produce solar electricity and other co-products from the aquacultivation of microalgae in enclosed, water-conserving photobioreactors, of low capital and operating cost, on otherwise unproductive, flat land. The economics of cultivation are improved by means of several novel steps, including the use of: photovoltaic films; light/dark striping; gelled or thixotropic media; low agitation; passive convective turnover; differential sparging; water conservation; nutrient recycling; slurry/piping technology; heat, solar and salinity control; and active, fine control of algal growing conditions, growth media and strain change. In addition, novel methods are proposed for some of the biomass processing methods, for mechanical handling, access, construction, security, logistics, and for the control of operations.

The algal cultivation process involves the use of sunlight and water, together with waste carbon dioxide sourced from oil/gas wells, industry and/or carbon dioxide captured from the atmosphere by other means. Other nutrients incorporated by the algae are typically recovered and recycled, though some may be produced on-site using novel, drillhole or deep hole reactor technology. Algal processing is made economical by: the avoidance of traditional de-watering steps; the creative use of geothermal heat and pressure; and an innovative combination of processing technologies.

The concept incorporates that of an integrated biorefinery, where not only the waste products from individual

processes are re-used, but also the heat from processing and the materials from which the plant and associated structures are built. The biorefinery can also accept other forms of biomass besides algal biomass, such as lignocellulose, agricultural wastes, sewage, polymer, medical or other organic waste, for processing into biofuels with similar economy. These can be processed with but small footprint even in locations or climates where algal bioreactors themselves may not be economical. As a valuable by-product, water from sewage and pulpmill wastes is upgraded by the supercritical drillhole process to a quality suitable for irrigation and industrial uses, or as a cost-effective input to desalination plants.

Extracting heat from hot fractured rock (HFR) typically requires making deep, and consequently high-pressure drillholes into rock formations. The same pressure, even when present only in drillholes that have been sealed off from the HFR resource, and when combined with heat from HFR heat exchangers, input reactants, suitable catalysts and processing steps, can be utilised to produce desirable physical and chemical changes in materials, such as algae and lipids.

Methods are divulged how piggy-backing on the existing infrastructure and under-utilised resources of associated industries can be used to improve the economics and reduce the developmental risks of establishing operations at some bioreactor sites, markedly.

The construction and operation of the bioreactor farm is designed such that its deployment and extension (scale-up) is relatively easy and of low-cost. This is so because the actual bioreactor units are simply replicated as many times as is required, on a dendritic layout, that is akin to that of leaves on a tree or, more accurately, on a ground-hugging vine. Only the size of the vine stem and processing plant require scaling.

Farm construction and operation have been designed to have minimal impact on the environment. Whilst the bioreactor design has been crafted to suit flat, temperate desert locations, it is also designed to be adaptable to many other environments, including flat: mid-latitude, arid tropical, high plain, rangeland, salt or clay pan, barren, degraded or highly polluted ones. Production may even be possible using Winwick bioreactors floating on calm water, with fish, shrimp, molluscs or other forms of aquaculture occurring beneath or beside them. Indeed, the algae from the bioreactors can be used as a secure and plentiful source of premium-quality food for the other creatures, thereby avoiding the algal harvesting and processing steps.

Provided the temperature is within their growing range, most microalgae require only modest amounts of insolation – typically 10-25% of the incident insolation (sunlight or radiation) in mid latitudes in summer. Moreover, many microalgal strains use angled and sub-second flashing light more efficiently than they use near-vertical, strong and continuous light. The Winwick design makes use of both these effects to increase the efficiency and to extend the latitudes and altitudes suitable for the commercial production of algae using enclosed photobioreactors in the field.

Using the Winwick system, some of what have until now been regarded as unsuitable climatic and insolation conditions for growing algae no longer pose insuperable constraints. With suitable adaptations to the standard Winwick system, microalgae may now be grown commercially at higher altitudes and in cooler and hotter climates than ever before. Cooler temperatures are addressed using bed heating and/or additional, insulating envelopes. At the other extreme, excessive insolation and temperature is addressed: by increasing the proportion of the bioreactor covered by photovoltaics to provide increased solar screening and energy conversion; by providing passive, air-cooled transparent, fluting on the upper surface of the bioreactor envelope; by using photo-antenna-reduced algae to increase the light path into the algal soup; by controlling the amount of insulation provided by a temporary foam ‘blanket’; by using algal adaptation and acclimation and algal extremophiles; by varying the cross-section of the bioreactor; and/or by using genetic selection, breeding or modification of algal and diatom strains to suit different operating conditions.

The novel methods of economically processing the algal biomass are equally important to viable Winwick operations. Key to these is the novel use of deep (up to 5km) drillholes, typically drilled to extract geothermal heat or hydrocarbons, and typically lined with thick, steel drill casing inside concrete. When no longer useful for resource extraction, these can be sealed at the bottom and transformed into hyperbaric (high-pressure) reactors for processing biomass and hydrocarbons into biofuels and other useful chemicals.

Winwick technology (WT) is an umbrella term that incorporates several different processes and methods. Some of these are entirely novel, some are developments on, or variants of, current and even old technology. For ease of reference, each of the different technologies is given a name and a Winwick acronym as follows:

- Winwick Microalgal Growth (WMG) technology
- Winwick Solar Power (WSP) technology
- Winwick Cell Rupture (WCR) process
- Winwick Syngas Synthesis (WSS)
- Winwick Methanol Synthesis (WMS)
- Winwick Ammonia Synthesis (WAS)
- Winwick Fischer-Tropsch Alkane Synthesis (WFTAS)
- Winwick Lipid Esterification (WLE) process
- Winwick Oil Fractionation (WOF) process

DESCRIPTION OF THE INVENTED INDUSTRY

The inventions provide an integrated process by which microalgae can be grown on low-cost land, then be harvested, transported and processed economically to produce carbon-neutral biofuels and co-products. Co-products include nutraceuticals, glycerine, methanol, ammonia and solar electricity, for which the bioreactors form an economical, low, highly-accessible and standardised platform for nanopolymer photovoltaic films covering potentially thousands of square kilometres of otherwise unproductive land.

Although novel concepts are proposed for several processes and structures, the single most inventive step lies in the novel combination of several, hitherto unrelated, resources and methods.

Excepting perhaps the PV nanopolymer and possible genetic modification to algal strains, none of the technology involves more advanced technology than is used in standard engineering practice. The above two advanced technologies proposed for use are now in commercial production and under further rapid development in a number of organizations.

Thus, the level of technical risk in Winwick technology development is not that high, though the integration risk is probably at least moderate. Nor is there substantial social or environmental risk. Indeed, insofar as the technology, if deployed successfully, reduces the risk of oil depletion and global warming, it should reduce the overall risk to life on Earth. As far as global equity is concerned, excepting developed nations possessing flat, temperate deserts, most of the countries to benefit most from implementing the Winwick technologies are those belonging to the less-developed world, including many of the poorest nations. The level of financial risk is thought to be low for many site locations and markets; and anyway is manageable using standard business techniques. Sovereign risk is another matter, but one that may best be addressed via franchising, on-going development, logistic support and marketing arrangements, rather than by entire reliance upon facility ownership, patent law and licensing.

Whilst the initial Winwick application is to produce biofuels and hydrocarbon chemicals, the same technology is equally applicable to the production of algal biomass for other purposes. The main difference is that more nutrients need to be added for non-biofuel production, as biomass takes all its nutrients with it, whereas biofuel production allows most of them to be recycled endlessly. In turn, the biomass can be used to produce many different products, including: human food, stockfeed for a wide variety of organisms, nutraceuticals, vitamins, pharmaceuticals, chemicals, fertilisers, plastics, biochar, and other organic raw materials. Some of these materials, such as biochar, can biosequestrate carbon in the soil for thousands of years without risk, with additional beneficial results upon soil fertility and moisture retention.

As Winwick technology is both land extensive and intensive, it is best located on land with little in the way of alternative, productive use and value. Whilst the production of biofuels from algae by the Winwick process is likely to be most economic when located beside, or on top of, a geothermal resource, the production of biomass from algae using the Winwick process may best be located sufficiently near (or at least not much higher in elevation than) sources of cheap macronutrients, such as sewage plants, agribusiness, or coal-fired power plants, so that the waste macronutrients from them (including CO_2) can be piped (as the most efficient transport means) to the bioreactors at modest or negative, net triple-bottom-line cost. CO_2 for biosequestration might also be sourced from backloaded, LNG cryotankers delivering to the coastal end of connecting pipelines or grids. That way, even countries without suitable areas or climates for Winwick bioreactor farms would also benefit from Winwick's low-cost, biosequestration capability. This is particularly so, as Winwick technology is likely to be commercially-ready and widely deployed long before geosequestration using carbon capture and storage (CCS) from burning coal is

sufficiently well-proven and substantially deployed, if it ever is. Moreover, the Winwick solution is also likely to be available at considerably lower cost and environmental risk than is CCS.

Many countries already have pipeline networks carrying methane or natural gas, often piped from distant sources, sometimes passing through several countries and going underseas or across mountain ranges. Sometimes the gases are transported by cryotanker (where gases are cooled and compressed to a compact, easily-pumped liquid form). Recently, geosequestration protagonists in several countries have suggested that there be developed national networks of pipelines carrying CO_2 for sequestration. This concept is hereby extended and complemented to include pipeline networks for oxygen and possibly ones for biofuels and hydrogen.

There exist already international gas, oil and electric power networks spanning continents. Soon, large quantities of oxygen may be produced as a by-product of hydrogen fuel production from the direct splitting of water by solar and other means. Even larger quantities are forecast to be produced of the roughly 90:10 O_2/CO_2 mixture generated by microalgae in bioreactors using mined and industrial CO_2 waste. Now, to limit climate change, carbon emissions, carbon taxes and costs, the worldwide community, governments and industry are going to wish to collect and sequester whatever CO_2 emissions are easiest and cheapest to collect in bulk. As well, industry will want to improve the burning efficiency of fossil fuels by burning them in oxygen, rather than in air. Plus, there is an increasing need for large amounts of oxygen for use in underground coal gasification (UCG) to produce relatively clean syngas. Both of the aforementioned uses are unlikely to be troubled by the presence of a 10% CO_2 component in Winwick-generated oxygen. However, such uses cannot usefully accept the inefficiency of using air that has 78% of its content as deadweight nitrogen (N_2). The more we can keep nitrogen apart from burning operations, the more efficient they will be, and the less greenhouse gases (GHG) and pollutants (NO_x) will they emit per unit of beneficial output. A complementary network of pipes for a mixture of predominantly oxygen and a little CO_2, laid in the same trench and complementing the existing supply of hydrocarbon gas would address this concern. Thus, a firm would draw on its fuel source and the oxygen pipe for burning, and send the resulting nearly pure CO_2 to the other pipeline for sequestration (of either bio or geo type).

Fuel sources would be drawn upon for ore reduction and refining, the oxygen source for steel-making and other forms of oxidation. Cement works and aluminium refineries would produce relatively pure CO_2 by their own means and pump them into the CO_2 network to share in the carbon sequestration benefits, or at least reduce their carbon costs. Algal bioreactor farms would do the reverse, producing oxygen from the CO_2 whilst biosequestrating the carbon – thus completing the cycle. Each pipeline network would double as a pressurised storage system. Time- or demand-set price change management for each resource, pumps, and exchanges with non-pipeline storage systems would tend to keep each gas pressure within the preferred range.

A simplistic analysis might indicate that saving the cost of heating the 78% deadweight nitrogen in a burning operation would save 78% of the cost. In fact, many other factors come into the equation. Amongst these are included: the cost of the oxygen; the amortisation and operating costs of the pipelines; some carbon costs; taxes; metering & inspection costs; gas impurity premiums; exhaust gas handling and cooling costs; pressurisation costs; contaminant allowances & penalties; process efficiency benefits; and pollution reduction credits (particularly of the GHG oxides of nitrogen, which would be virtually eliminated). The actual savings to industry might still be a useful 20-40% of fuel costs.

Regarding gas cooling costs in transporting gas, considerable economies may be achieved at one or both ends of cryotanker voyages when there is backloading of CO_2. This can be achieved by using the low temperature of one liquefied gas in the cycle to help chill another via a heat exchanger, and vice versa. Thus, methane/natural gas coming from an oil/gas well or extracted from a coal seam could be chilled by the cold, liquid CO_2 being off-loaded from a ship coming in the other direction and before, or as, the methane enters the cryotanker as LNG (liquefied natural gas or ~methane). At the other end, the cold LNG might be used to chill outbound CO_2, depending on whether the LNG and CO_2 were to be piped overland as gases, rather than to be transported as cryogenic liquids.

Many industries use oxygen in their processes. Typically, the majority content of nitrogen in air reduces the efficiency, creates polluting nitrogen oxides, and increases the cost, of these processes markedly. Using air-burned moist brown coal to generate power is a notorious example of such inefficiency. Those processes that seek to improve efficiency by first extracting oxygen from air, typically by membrane separation techniques, pay a substantial cost penalty. However, if algae are provided with nearly pure carbon dioxide, such as is available as a

waste product from several industries, including hydrocarbon extraction ones, algae can produce very low-cost, carbon-negative oxygen. The Winwick process may be the first to be registered as a process designed to do this.

The great variety of organisms that are supportable from food chains that start with very large volumes of cheap, pumpable, microalgal slurry at bioreactor farm locations on otherwise unproductive land, when combined with the co-production of cheap, solar electric power and Winwick drillhole reactor technology, leads to opportunities for integration with large-scale agribusinesses and biorefinery/chemical engineering plants. Moreover, being collocated, these could benefit from vertical and cross-industry flows of recyclable waste, heat, water, chemicals, energy and by-products.

BIOREACTOR DESIGN

Winwick bioreactors and their associated impeller/harvestor units are designed to be mass produced cheaply as complete assemblies in a factory environment. A material flow design for bioreactor construction has been drafted. The bioreactors are designed to be transported in flattened form on reels, together with their enclosed, but collapsed tubing, piping, and groundsheet assemblies. Reels are unwound or rewound in the field using high-wheel-base tractors with reel management attachments.

To a reasonable maximum extent possible, the bioreactor plant and other constructed elements are designed to be made from one or two cheap, available, adaptable, easily-formed, long-lasting and non-reactive thermoplastics. This maximises opportunities for economical re-use, recycling and transportation – and minimises material separation, environmental problems and costs. Most plastic elements forming the bioreactor farm are currently designed to be made of endlessly-recyclable and cheap polythene and/or PET (polyethylene terephthalate). However, other polymers may end up replacing these, without adversely affecting the concept.

A bioreactor body comprises four, suitably separated, clear plastic film phytotubes (the tubular containers for growing the microalgae, diatoms, cyanobacteria or other or phytoplankton in aqueous, growth media with room for exhaust gas above), within a protective and insulating, outer tube called the envelope. All the tubes and pipes are produced by standard blow-moulding or extrusion techniques. All tubes are coated with anti-condensation coatings, the phytotubes being coated both inside and out. The blown envelope tube is temporarily sliced open lengthwise to facilitate the placement and fixing of the tubular contents, together with possibly the fluting, the photovoltaic (PV) strips and the protective/reflective groundsheets, prior to re-sealing.

The bioreactors are initially designed as being 100m long, 2.5m wide and 0.55m high at the slightly curved apex. The bubblemix liquid in the envelope is normally only around 0.13m deep, but this can be increased to as much as 0.35m in order to cope with less-level terrain, or to help resist overheating or damaging bioreactor movement by way of floodwater or cyclone The depth of the bubblemix is what allows the phytotubes to be filled as deep as they are with algal soup, and to become as round in cross-section as they are, without the enclosing membrane coming under unnecessarily high stress. It also means that the phytotube membrane only has to withstand a pressure of water from 0.27 less 0.13 equals 0.14m depth, rather than the full 0.27m depth of the algal soup in the phytotube. Each phytotube has a similar, though rounder, cross-sectional shape to the envelope and has dimensions approximately 100x0.5x0.4m. When inflated, phytotubes have spacing between them of around 0.12m, less at the outside edges. These spaces allow sunlight to penetrate between the phytotubes and sideways into them. Some rays are reflected from the underlying, aluminised groundsheet and penetrate into the lower, outer levels of the algal soup on both sides. Normal operating depth for the algal soup in the phytotubes is 0.27m. However, they can still operate from between depths ranging from 0.15-0.35m. The normal operating depth has sufficient leeway as to be able to accommodate minor land surface irregularities that occur along the contour of the flat, natural (or possibly levelled) contour surface on which the bioreactor is laid, whilst still providing an adequate channel depth for soup transport. The extended range of depth allows accommodation to somewhat greater landform variations. At normal operating depth, there is a space of around 0.13m above the algal soup in the phytotube for gas accumulation and transport. The gas in both envelope and phytotubes is lightly pressurised to create the desired shape by means of the gas pumps in the impeller/harvestor unit or that of the pressure in the main CO_2 inlet pipe, mediated by the solenoid-operated entry valve. Outlet valves, pipes and pumps relieve excess pressure. The pressure in the phytotubes is maintained slightly higher than that of the envelope, in order to maintain the desired cross-sectional shape. This also serves slightly to increase the CO_2 concentration in the soup, and thereby possibly to increase algal productivity.

The volume of gas in each type of tube can be altered temporarily to allow easier, or less potentially damaging, access for repairs, maintenance and replacement. On partly deflating the envelope and/or phytotubes, weighted bars placed across them is usually sufficient to isolate the bulk of their contents, with little chance of rupture or wrinkle formation. When replacing a bioreactor body, the tubes may be rolled up from the far end, pumping off the contents to the paired bioreactor or mains piping, until they can be tied and cut like umbilical cords. The replacement tubes can then be attached over the nubs of the previous ones, or replacing them, whereupon the nubs can mainly be cut away and removed from inside the impeller/harvestor unit.

Four types of tube reside within the envelope: the phytotubes, distillation channels, bubblers and warming tubes. The three, porous bubbler tubes are used to produce masses of bubbles from the briny bubblemix in order to create a semi-stable foam that fills the envelope, thereby insulating the algal soup from excessive heat, cold or insolation. The warming tubes bring (typically waste) warm water from either: industry; hot fractured rock (HFR) geothermal sources (typically, after its steamy, higher temperatures have already been used for other purposes); from ordinary geothermoclines; warm bores; or solar ponds. When the warm (or else cold, if bioreactor cooling is required) water pumps and/or valves are actuated, water flows in two pipes lying in the bubblemix in the envelope, one between each of the two pairs of phytotubes. This warms (or cools) the bed of the bioreactor to maintain algal, temperature-dependent activation levels. At the same time, it sets up circumferential convection currents in the algal soup, thereby replicating the beneficial effect of warm-season, angled sunlight during cold or overcast times. The two warming tubes are joined at their far ends, to form a U-shaped bend. Local, microcomputer controls can reverse the flow periodically to ensure that the different pairs and sections of phytotube are warmed approximately equally. Afterwards, the now-cooled water is pumped by return pipe to the original heating facility for re-use.

The phytotubes contain the growing microalgae, nutrient media and gases. They are encased by a clear, outer plastic film tube, the envelope, that lies on, and is affixed to, the reflective groundsheet. Bonding of polymer films is achieved typically by the application of heat and pressure (thermal bonding), ultrasonic welding, plasma activation or hotmelt glue.

Winwick phytotubes are of substantial cross-section relative to most other closed bioreactors. Therefore they incur less wall friction. This, together with laminar flow and no aeration/turbulence requirement, contributes to Winwick's low energy usage. The recently discovered antenna-reduction effect helps make the unusually large cross-section of the Winwick phytotubes efficient at biomass production, without requiring high turbulence or high energy input.

The materials of the bioreactor body are mainly transparent, thermoplastic polymers. The fluting that encloses the PVs is typically made of PET as are the phytotubes. These are UV-stabilized with standard additives, such as benzophenones. The envelope is typically made from low-density polythene (LDPE), that is typically UV-stabilized with hindered amine light stabilizers (HALS, especially HALS-3) and UV absorbers (UVA-5). The piping and channels are of polyethylene/polythene (PE) and the groundsheet is of aluminised PE or PE/PET mix that can be recycled polymer from the transparent uses.

The gas in the envelope is chosen from CO_2, O_2/CO_2 or other gas, whichever represents the best site choice when the factors of: heat retention, fire risk, maintenance workers' safety, pests, lichen/mould growth and bubblemix contamination are considered together. The envelope encloses, and is fixed to, the phytotubes and to the internal piping, to keep them in place. Following deployment, the envelope also encloses the bubblemix, gases, algae and algal growth media.

The separation distance between the inflated phytotubes, within the inflated envelope, is important for two reasons. First, it allows sunlight to penetrate the algal media from several directions, thereby permitting the algal soup to be either denser in algae or the soup deeper. Second, as it allows sunlight (or the bed heating mechanism in cooler times) to warm one or other side of each phytotube, this results in slow, convective, circumferential flow in the soup. Combined with the low-energy, laminar flow lengthwise in the phytotubes that is provided by the energy-efficient, rotating impeller blades, the resulting slow, helical flow along the bioreactor results in all the algae being periodically exposed to suitable amounts of photosynthetically active radiation (PAR). The periodicity, when combined with the striping effect and possibly antennae-reduction, is designed to be sufficient for most algae in the soup to survive, grow and reproduce optimally, without the need for rapid, energy-intensive agitation, turbulent flow, costly artificial illumination, or the high, pipewall resistance involved in small-bore, tubular or thin-film bioreactors.

Commercial, anti-condensation (AC) coatings are provided to appropriate surfaces of the envelope,

phytotubes and fluting to reduce solar reflection, the coatings being selected from ones having little affect on PAR transmission and (for the internal surface of the phytotubes) do not encourage algal adhesion. A Teflon™–PFA or FEP coating may be used to reduce such adhesion where a given algal strain in use or prospect has that tendency. If such a coating reduces insolation, then it could just be applied to the film that would be at or under the surface of the soup.

The far end of the bioreactor is made of hollow, rotomoulded polythene or recycled PE/PET mix. Its form is roughly that of a sagging ellipse, freestanding on its long, flatter edge and supported on stability supports projecting from its lower, long edge. Its cross-section resembles a thin “witches hat” with five extra, roughly elliptical protrusions on one side, by which to attach the envelope and the four, phytotube ends. Subsequent to the rotomoulding operation, the centres of the phytotube formers on the rotomoulded item are cut out to allow lengthwise and transverse passage of the algal soup. The barcode of the impeller/harvestor unit, plus an endpiece code, are heat embossed in large characters on the exposed side of the bioreactor endpiece for identification and navigation purposes. The central database associates each barcode with the farm, access road, rectangle, layout, kytail (see Farm Layout section), sequence number, impeller/harvestor, bioreactor, GPS location, age, contents, history and status of the unit. This information is remotely available to maintenance workers, as are their team members’ GPS positions, schedules, timing, tech information, guidance and communications.

Inside, attached to each side of the envelope and sloping down towards the bottom half of the impeller/harvestor unit are narrow, open plastic channels to collect and conduct water that condenses on the internal, upper surface of the envelope to the storage area in the double hull of the I/H unit. Such water ballast would serve to stabilise the impeller/harvestor unit when otherwise empty. It would also be useful when new bioreactors were being set up, as water ballast might avoid undesirable movement of the impeller/harvestor unit when a bioreactor was being unrolled from it. When the I/H unit is half full, excess distilled water simply flows back into the bubble mix. The channels need only go partway along the envelope, perhaps 10m from the I/H unit on each side. Stored, distilled water may be pumped into the algal soup, or into the fresh/distilled water main at any time, or be tapped by maintenance workers for other purposes.

Water from this main pipe can be used to increase or replace phytotube liquid volume removed by harvesting and/or to reduce the salinity of the algal media, or to do the opposite for the bubblemix. The condensate channels therefore act as essentially passive, solar-powered salinity controllers and as economic producers of sterilised water for the algal soup and other purposes. The system can also be used for internal evaporative cooling, as the warm, condensing water vapour, once it has given up part of its heat to the air-cooled envelope, can be removed and replaced with cooler, dam or bore water.

Water for the original bubblemix mixture will usually be sourced from local, brackish bore water, seasonal stream flows or dams. This, like the water for the algal media itself, can, if desirable, be sterilised by one of the heat sources, such as geothermal or solar pond, to ensure that no unwanted, living organisms or spores remain viable. The bubblemix develops its wildlife-repellant, briny nature from the distillation process that concentrates the brine. Its long-lasting, bubble-forming properties are given it by the addition of bubblemix concentrate, which may be a form of detergent and/or gel. A biocide will normally be another component of the bubblemix, to keep it transparent and free of living organisms. A fluorophore (fluorescent material) may also be added to convert green light into frequencies usable by algae.

Any excess bubblemix brine from the distillation operation may be used in transparently-covered solar ponds to generate either process heat or electricity. The large amounts of heat that could be stored in an extensive system of solar ponds might act as backup process heat reserve, or as a ready energy resource for all-hours power generation, or to meet customers’ power demand surges.

Plants, including microalgae, look green because they are unable to utilise light in green wavelengths for photosynthesis. Now, there are many minerals, such as fluorite, and some organic, fluorescing dyes that transform light of one or more bands of wavelengths into one or more longer, less energetic wavelength bands. Thus, it is possible to transform unusable green light into yellow or red light that is usable by algae. Several transformational steps (hence several dyes or minerals concatenating the overall light wavelength change) may be required as each step may be too small to accomplish the green to yellow/red transformation in just one step. Presently, organic, fluorescing, designer dyes are both expensive and unstable under prolonged illumination. However, it may be that ground up fluorite of a certain kind and/or the invention of more stable and economic dyes will enable utilisation of

this additional source of energy by the algae in the bioreactors. As with the algae, a thixotropic gel may be a useful bubblemix additive to keep the fluorite in suspension and hence near the algae. It would also serve to retard leakage from any holes.

The design of the Winwick bioreactors allows the typically toxic (to algae) dyes to be incorporated safely into the bubblemix, which is separate from the algae, thereby potentially providing an additional, useful light source that is adjacent to the darker, lower part of the phytotubes at the precise time that this portion of the total insolation is transformed from a potentially harmful heat source into a beneficial, additional photosynthetic energy source for the algae.

The groundsheet, or inflatable 'mattress', is in transverse, fluted form that is deflated in transport. It is composed of a set of parallel, joined 'sausages' made of PE film bonded to a base of protective foam PE having raised edges to support the edge of the envelope. Sausages run the width of the bioreactor and are bonded together, typically by the application of an outer PE casing. The area of each sausage-edge sealed by the casing, and by being squashed together, gives it its rough shape of a plank on its side. Each sausage has two small orifices near the top of the sausage's sides, one near each end of the sausage on opposite sides of it. Matching orifices are aligned and glued together, typically with hotmelt polymer that also serves to strengthen the orifice. For redundancy purposes, twin, PE collapsible pipes are hotmelt-glued to each of the serried ends of the sausages to convey water to the far end of the groundsheet from the I/H unit. The orifices permit water to be pumped slowly into the flattened fluting so that, as the fluting fills and expands upwards, the envelope and phytotubes are raised sufficiently, starting from the far end of the bioreactor, to move their liquid contents by gravity into the I/H unit, from whence they may be pumped away. Once emptied, the groundsheet fluting may be pumped out and collapsed again.

Should the inflating part of the groundsheet become damaged or dysfunctional over time, then a remotely-controlled, battery-powered vehicle would be made to move just under the bioreactor endpiece and groundsheet from the far end, thereby pushing the algal soup ahead of it. It would look rather like a wide beetle, tortoise or gunless, battle tank with dimensions roughly 2.6x1.0x0.25m high. It would have four, wide, powered belts or tracks, two of them as caterpillar treads mounted on the base, the other two powering twin, parallel, triangular cross-section, rounded-lengthwise, turret-forming belts. The separate drives of the four belts propel and are used to steer the tortoise along, between ground and groundsheet.

For operation in cooler or more variable climates, several modifications may readily be applied to the construction of a Winwick bioreactor farm. These follow. First, more than one concentric envelope may be used with the bioreactors to insulate the phytotubes, the outer envelope of which may require an antifreeze bubblemix and/or be made from a polymer better suited to low-temperatures and possibly one with greater solar transparency than polythene. The PV shading might be made less in proportion to clear envelope. Conversely, at high altitudes where the insolation is overstrong, more PV may be useful. Cross-sectionally larger dimensions for the bioreactor would help to reduce heat loss in cool climates and even out algaculture temperatures where day to night ones vary greatly. Denser packing of bioreactors on the farm might have a similar effect. Algal strains active at lower temperatures or requiring greater salinity or sodicity might be selected, bred or created, as the algal soup of these would be less likely to freeze at the edges or in pipes overnight. In more extreme climates, the impeller/harvestor units, pipes and pipe bundles would require better insulation, which might be achieved with earth berming or burying and/or polymer foam coatings or blankets. Bed heating would be required for longer periods each year. And the sources of waste heat for bed heating might need to be widened to include geothermal heating from tapping ordinary geothermoclines or using heat from any biomass or industrial waste heat source that is locally available. On the credit side, less investment would be required for heat dissipation; there would be less chance of photo-inhibition occurring; and cooler, wetter climates would tend to provide better sources of waste nutrients for growing algae than do arid ones.

For very hot climates or seasons, adaptability takes more the form of using thermophilic algal species and using greater proportions of PV on the envelope. Insulation, or the burying of some pipes, may also be used against external heat and diurnal variation. Bed heating would probably not be required. This in turn might suggest a reduction in the cross-section of the phytotubes and envelope. Cold water from a deep lake or shallow aquifer could be used both to cool the algae and to induce circumferential motion in the phytotubes. Evaporative cooling of structure or contents could be considered, but might only be economical near a large body of water, such as a lake, the sea, or a major aquifer.

PHOTOVOLTAIC DESIGN

Using the bioreactors as a platform for the generation of photovoltaic power, whilst using the photovoltaic strips to optimise light to the algae provides an elegant solution to two problems.

Attached to the top of the envelope are bands or (broken) strips of semi-flexible photovoltaic film in wing form, mounted in the airspace between flutes (separators) inside two lengths of transparent polymer film. The slightly inclined, transverse fluting serves passively to air-cool the PV, thereby increasing its solar conversion efficiency. What energy is not converted into electricity, the air-cooled fluting convects as heat away from the PV and algae, thereby increasing the efficiency of the PV and helping to maintain the algae at their most productive temperature.

Should potential external conditions make it advisable, the open ends of the flutes may be covered with strips of transparent, thermoplastic flywire mesh, the better to secure the fluting to the adjacent fluting and to the envelope at the other open end, and also to hinder the ingress of detritus, birds and insects. Cleaning the fluting and PVs may be effected either by streams of high-pressure air or water, and/or by light rollers mounted on tubular supports that transmit backpack-powered ultrasonics. Distilled water for cleaning can be sourced from outlets on the impeller/harvestor units by maintenance personnel with backpack-mounted powerpacks and water containers.

The PV laminate is formed into centrally-vented (to permit the exit of cooling air), transverse bands or strips of PV running inside fluting, crosswise along the bioreactor. The strips have a lateral edge attached to springy, polymer extrusions, shaped in cross-section like an S on its side, with a curving vertical support running through the upper third of the S. When cold, the strips forming the top and bottom parts of the S are curled to expose more of the algal medium to insolation. When warmed by progressively more intense sunlight or temperature, they uncurl to shade more of the medium. The vertical support also uncurls, thereby increasing the thickness of the fluting and encouraging greater airflow. The uncurling is mediated by differential thermal expansion of the two sides of each PV strip, one side being composed of metal foil and/or dense, polymer foam with higher expansion coefficients than that of the nanopolymer PV film.

Each laminar PV strip is attached by one edge to the springy extrusion or strip. When cold, the PV is furled or curled up to a fraction of its width. However, in the ‘S’ formation, as its inside laminar surface is a material (a dense, foam polymer or metal foil) of high thermal expansion coefficient, when it is warmed by the sun, it uncurls proportionately to the heating, thereby causing the PV to shade more of the algal media from excessive insolation and heat, and to produce more PV electric power.

Alternatively, for economic reasons or if multiple flexing is deleterious to the selected PV material (a likelihood), two PV strips might sprout as wings from either side of the top of long, strut walls running inside the fluting and separating its two sheets. Struts are of hexagonal cross-section in elevation view and are typically made of clear, PET polymer. Each strut or spacer (made by plastic extrusion or joined sheet) runs approximately halfway across the top of each bioreactor, before it approaches the end of its paired strut on the other side. The two narrow sides of each collapsible strut hexagon are heat-sealed or ultrasonically welded to one or other sheet, joining them by the strut body. The PV wings are attached to the top of each strut, sandwiched between film and strut, by a curved, laminated strip that uncoils on heating. This action spreads the planar wings so that they intercept more sunlight and narrow the aperture slot by which sunlight reaches the algal soup. The ratio of light transmitted to that intercepted by the PVs can be determined at manufacture by changing either the spacing of the struts, the length of the wings, the length of laminate, or the degree of uncurling mediated by the thermal expansion coefficient differentials of materials comprising the laminate. Typical light to dark ratios will vary in the range from 1.5:1 to 0.25:1.

As sunlight will tend to fall more on left or right wings, depending on time of day and PV orientation, wings of each type are separately connected electrically. Typically, one type of wing will generate a higher voltage than the other at a given time. The orientation of one set of wings will tend to intercept more sunlight at low angles than would a near-horizontal, fixed PV receptor. And at low angles, more light will tend to enter the phytotubes from the side, thereby avoiding shading by the PVs above.

The hexagon shapes of the struts are transported in flattened form on reels, usually already attached to the fluting and thence to the envelope and other tubular bioreactor sub-assemblies and groundsheet. The top of the bioreactor envelope forms the lower sheet of the PV fluting. The reels are unrolled and the bioreactors are attached

to the impeller/harvestor unit and its opposite end-piece. After attachment and inflation of the envelope and phytotubes, gusting wind action over the curved bioreactor envelope expands the flattened-strut hexagons of the fluting vertically until each resembles a wall bulging on both sides of its midline. The expansion is effected by means of cable tie look-alikes having strut-mounted heads and ratcheting, sawtooth-lined strips that run through the strut wall at intervals along its horizontal middle line. Ratcheting ceases when a tube encasing the cable tie section that is located inside the hexagon butts up against both walls. The cable tie tail is left extending between the struts.

IMPELLER/HARVESTOR (I/H) DESIGN

Each impeller/harvestor unit, or central head, (see provisional patent diagram Figure 2) has a bioreactor body or arm attached to each side, rather like a spreadeagled, two-tentacled octopus. There are four, distinct, internal chambers in the I/H unit, two of which share the algal soup and gases with its own separate bioreactor body, a third for the drive box containing shared machinery, and a fourth as the internal conduit located over the external pipe bundle that transports external fluids and which is sealed by a plastic board embossed with the unit's barcode for easy aerial and ground-level identification. The unit also has a trapezium-shaped hollow or tunnel running under its middle. This straddles the pipe bundle. Pipe-bundle offtakes typically lead through holes in the tunnel roof then sideways to the relevant chamber and item of equipment. The tunnel is also used to connect services to the surveillance pole and computer post, the octopus's eyes and brain.

The impeller/harvestor body is made of rotomoulded, hollow or double-hulled, polythene. It is tank-like and has a rectangular base and a curved, openable top which is covered by the barcode plank and twin, separately removable, clear plastic film covers or semi-flexible sheeting, sealed at their edges by strapping, clips and seals. The impeller/harvestor's outer dimensions are approximately 2.5x2.2x0.9m.

Each I/H chamber that connects directly to a bioreactor body has two injection or rotomoulded polythene, drive shafts. Each of which mounts two multi-bladed axles made of polythene. The axles are of two kinds. One, the impeller, is designed to propel the newly-recarbonated, algal soup gently into the phytotube. It has curved blades designed to cause minimal splashing and rippling. The other, the agitator or thresher, is designed to break the structure of the thixotropic gel temporarily, so that for a short period it forms a non-viscous liquid that releases its contained microbubbles, allowing them to rise to the surface, combine and burst. The thresher axle has short, radially-aligned, possibly backwards-curving blades attached circumferentially to the wide-diameter shaft. These are designed less to propel the soup than to agitate it and so to dethixotropise or liquefy it. The blades cause moderate, local turbulence with minimal splashing and act partly to separate the microbubbles from any adhering algae. Thus, they are designed to rotate faster than the impeller type. They slice and disrupt the gelatinous bonds.

One axle type is slaved to the other type by polythene cogwheels built into their shafts. Each thresher is located non-adjacently at the inlet of two of the four phytotubes. Each impeller is located at the outlet to the adjacent two phytotubes. Thus, in the I/H unit, the threshed algal soup moves slowly from one phytotube to another (some of it via the harvesting zone), releasing its oxygen-rich gas on the way. This is pumped out of the I/H unit to the mains oxygen pipe.

Underneath almost the entire length of the impeller drive shaft or axle is a flat, small-bubble, sparge plate made of stainless steel (see Figure 3). This provides tiny, carbonating bubbles (microbubbles) to the outgoing algal soup. Baffles permit only soup from the lower half of the soup column to reach the impellers. This ensures that little of the froth produced by the large-bubble sparger, set further back, is destroyed before it can bubble over into the open Archimedes screw channel above, which does the harvesting. Two drive belts, powered by either or both of twin electric motors in the drive box power all drive shafts in the unit. Solenoids controlled by the unit's microcomputer, and over-ridable by central control, engage individual valves, pumps, drives and devices.

The small-bubble sparge plate type has dimensions approximately 2.3x0.6x0.018m. The large-bubble one has dimensions approximately 2.3x0.3x0.018mm. Both types are constructed of two sheets of approximately 0.5mm thick stainless steel sheet, welded together at the down-tapered edges and spot welded at points where the lower sheet is dimpled upwards to touch the upper sheet in order to maintain a separation of 15-20mm between the plates. For the small-bubble sparger, one or more reinforced plugholes admit a removable nozzle that is joined to a valve and an inlet pipe containing pressurised carbon dioxide gas. The large-bubble sparger has unscrewable pipe and fittings connecting it to the gas pump and thence to the airspace above the sparger. The small-bubble sparger is connected via a solenoid valve directly to the CO_2 main, so that both sparging operations may be carried out at

the same time. Prior to welding, the upper sheet of each sparge plate has many holes of controlled diameter and pattern made in its surface, preferably with raised and smoothed edges round the holes. This is done so as to minimise the chance of algae and grit clogging the holes and to facilitate early bubble release. The small-bubble sparge plate has perforations in it of approximately 0.05-0.2mm in diameter. The large-bubble sparge plate has perforations from 0.3-1mm in diameter, the chosen diameter depending on several factors, including gas pressure, algal strain, the viscosity of the gel, and the optimal froth-bubble size for harvesting. Each type of sparge plate is perforated only on its upper surface and only where its bubbles are required.

Electrically-driven ultrasonic (probably piezoelectric ones vibrating at 42kHz) generators or transducers are attached to the large-bubble sparge plates to perform regular, computer-controlled cleaning of plates, turbines and impeller box. The small-bubble sparge plates have less-damaging-to-algae sonic transducers attached. Used at low power, these transducers serve to facilitate the egress and detachment of smaller sparged bubbles (microbubbles), thereby helping to maximise gas exchange with the algal soup by increasing the total surface area of bubbles and by reducing their speed of ascent.

In the drive box are located motors, pumps, and valves. If feasible using commercially-available equipment, gases excepting that from the CO_2 main, are to be directed through a universal gas valve and pumped, if pumping is necessary to increase the pressure, by a single gas pump. Similarly, all liquids, except the algal slurry, are to be directed through a universal liquid valve and pumped, preferably through a single liquid pump. The flushing of pumps and valves to keep them clean and the materials they convey uncontaminated is controlled by the microcomputer.

Although sparging (generating bubbles of gas to travel up the soup column) happens at two places, at different rates, and for two different purposes in a Winwick impeller/ harvestor unit, they both affect the productivity of the algae, as well as the dispersion of algae, nutrients and waste products travelling in the soup in the phytotubes and in the impeller unit.

High gas entrance velocities from a sparger have been shown to cause algal cell death. The large number (hundreds) of perforations, their wide separation in large-area Winwick spargeplates, and low, overall gas requirement and velocity reduces this threat to negligible.

The use of sonics and ultrasonics to ensure microbubble detachment from the sparger, harvesting and periodic cleaning of surfaces in the impeller/harvestor unit is another matter. As high-energy ultrasonics can damage microalgal cell walls, algal gas vacuoles and photosynthetic antennae by decavitation and free radical formation, the frequency, energy level and timing of these processes are carefully selected to optimise the two, somewhat conflicting, requirements. In general, non-damaging sonics are used to facilitate microbubble detachment on a continuous basis, whereas ultrasonics for cleaning purposes are used only for periods of less than a minute every day and at less damaging power levels and frequencies that are still consistent with cleansing action. These cleaning periods will normally be arranged to fall within harvesting periods, so that any damaged algae will tend to be harvested at that time. Ultrasonic barriers and sound absorbants may also be employed to reduce the algal soup volume affected.

Small-bubble sparging is done in the impeller box under the impeller shaft to provide the algal stock with a sufficient amount of carbon dioxide nutrient to feed it during its passage through the length of two phytotubes (until another active spargeplate is reached). The sparging (assisted by the temporary, viscosity-lowering effect of the thresher's agitation on the thixotropic gel) also helps to remove the photosynthetic waste product of oxygen, which can otherwise retard algal growth.

A gel that slows upward bubble movement to almost any desired extent, also helps to ensure that there is high utilisation of the (initially nearly pure) carbon dioxide content of the sparged microbubbles by the algae, before the gas is largely lost to that above the soup, which is pumped off (typically, as a 90:10 oxygen:carbon dioxide mixture). Slow, small-bubble movement upwards in the weak gel also helps to ensure that, in the absence of turbulence, there are continuous micro-exchanges amongst small, transient groups of algae and with nutrient and waste material removal throughout the soup, thereby contributing to heightened productivity.

Large-bubble sparging may only occur at intervals when algal harvesting occurs, though continuous harvesting is also possible. Continuous harvesting may be indicated when algae, possibly under the influence of bubble attachment, rise to form a light-obscuring skin over the surface of the soup. Whilst small bubble sparging uses CO_2, large-bubble sparging will recycle the O_2/CO_2 mix above the algal soup for its gas supply. This serves

four purposes: it conserves CO_2; it ensures an adequate gas supply for harvesting for all bioreactors, even when many are harvesting at once; it maintains the relative purity of the gases; and it means that correct gas pressures are easier to maintain in the system. Large-bubble sparging only has a minor effect upon the microbubbles remaining in the soup after dethixotropisation. And as small-bubble (microbubble), carbonation sparging occurs just after the soup passes the harvesting chamber, so minimal CO_2 is lost due to harvesting. Thus, as a result of gel reformation immediately after carbonation and by slow and localised diffusion, the carbonating microbubbles continue to nutrify the algae throughout their passage along the phytotubes. Typically, by the time the microbubbles reach the surface and burst, the algae and aqueous soup solution will have extracted 90% of their total CO_2 content, replacing it with oxygen.

Large-bubble sparging is more violent than small-bubble sparging. This is so because, complementing the action of the thresher blades that liberate the microbubbles to ascend, it is designed to prolong the breakdown of the somewhat crystalline or ordered, thixotropic soup structure into a thin fluid. A thin harvesting fluid is desirable to allow bubbles to move upwards easily and so that the algae are thus exposed to frequent gas-liquid bubble interfaces, to which they may loosely adhere and thus be carried upwards with the bubbles to form a froth or algae-rich slurry that can readily be harvested. Another beneficial effect of this froth-flotation process is that the algae to liquid content of the froth, after the larger bubbles have preferentially burst, is many times greater than that in the original algal soup. Large-bubble sparging also has the effect of breaking up undesirable agglomerations of algae and of lipid, of providing macro-scale mixing, and even of partially cleaning the equipment.

In metallurgical froth-flotation, surfactants are usually needed to ensure that the valuable mineral particles are selectively captured by the bubble surfaces, leaving behind the dross. As algae tend to have a natural attraction to bubble surfaces, the addition of surfactant may not be required. However, if its use does deliver a net benefit for harvesting a given algal strain, then the surfactant(s) chosen may be able to be one that has a secondary use as an algal nutrient or catalyst.

Similar spargeplate designs in stainless steel are used to produce both small and large bubble sparging. The main differences being: the internal diameter and number of the sparge holes; the location of perforation zones; the pressure and composition of the gas; the sonic capabilities of the attached transducers; plate dimensions; and spargeplate location. Ultrasonic cleaning transducers are attached only to the large bubble spargeplate. Sonic, bubble-releasing transducers only are attached to the small bubble spargeplate.

The universal valve and pump system for liquids and the separate one for gases have the following design. Inlet pipes connect through one-way and solenoid-activated valves to one half of a length of pipe in the drive-box chamber of the I/H unit. A one-way valve and solenoid-activated pump are located at the centre of the pipe. The outlet pipes, each with its own one-way, solenoid-activated valve, are connected to the other half of the pipe. There is also attached a distilled water inlet valve at the end of the outlet side for flushing purposes. Pressure relief valves to the external environment, whose activation triggers an equipment fault signal concerning excessive pressure to the computer post and central command are located on each half of the pipe. Fluid flows when an instruction activates the selected valves and pumps. For the liquid system, a flushing action with fresh/distilled water occurs after each liquid transfer, first from the far end of the inlet end, then from far end of the 'outlet' end. This tends to clear all active ingredients from the universal liquid valve and pump system. Gas residues can be ignored in the gas universal valve and pump system. Apertures between chambers of the I/H unit, to the envelope, and to the external environment are formed by tubular attachments in the rotomould linking the twin hulls at I/H construction time.

Changing the salinity, sodicity, pH, temperature, level, pressure, algal strain or nutrient concentration of the algal media or bubblemix may be done by pumping the relevant material from or to a mains pipe - an action that is usually mediated by the local microcomputer and implemented by equipment in the impeller/harvestor unit. Initiation for this is directed by locally-stored program or is done remotely from the campus control centre, either by pre-set computer program or over-riding human intervention, possibly requested on location by the installation or maintenance staff.

Winwick Microalgal Growth (WMG) Method

The shading caused by the PV strips means that each alga in the algal soup, moving along the bioreactor, under the motivational force of the slowly rotating impeller blades, experiences rapid changes of dark and light. When the frequency of flashing light occurs for sub-second periods, with longer dark-recovery periods, the algae

use the incident light most efficiently for photosynthesis[1] and are less subject to photo-inhibition caused by excessive light. The flashing effect is reported to increase light-usage efficiency by nearly double, so less light is required for photosynthesis and more can be diverted to daytime solar power generation. The PV striping solution may be novel, as the Barbosa paper only refers to obtaining flashing light by other, far less convenient means.

The PV striping solution is also one that is adaptable to different conditions and algal strains. Given flexibility in PV dimensions, both the PV strips or wings and the spacings between them can easily be set differently at assembly, whilst the frequency of flashing to each alga can be varied for a given spacing simply by changing the variable impeller speed. The dark recovery period may be optimal when it is a few to several times that of the subsecond lighted period. This lighted period may be as short as 40μsec, but is probably here of the order of 0.2sec or 0.1sec if the strut plus thermo-active laminate area is made sufficiently transparent to PAR. The lighted period may again be reduced by the insertion of a narrow, double-sided PV supported by a curved, thermo-active laminate sited between adjacent sets of wings. These could act in a fashion similar to venetian blinds to moderate algal insolation under intense sunlight and to increase the flashing frequency. The optimal ratio of light to dark is probably algal strain and light intensity dependent, but may also be constrained by the minimum effective width of the PVs and the velocity of the algal soup under laminar flow conditions. As well, the extent of light dispersion and the average length of light path in the algal soup may affect the ratio giving maximum productivity.

There are other ways that Winwick technology makes more efficient use of solar energy than do other algaculture methods. Selected, thixotropic (becomes less viscous upon agitation) gels or gelators added to the soup mean that the algae are grown in a thin, tenuous thixotropic gel. This or these additions have several major benefits. First, suspension in even a weak gel means that a far wider range of algal strains can be used – not just the few that remain well-dispersed and suspended in aqueous media. Therefore, algal strains with superior growth and/or lipid-producing abilities can be used, without the need for the turbulent flow and costly agitation required by most other methods. Second, even a weak gel will tend to prevent dead or flocculating algae from either scumming at the surface, flocculating (clumping together), or precipitating (sinking), under which actions they may become less available for harvesting. It should be noted here that the mucilage, gels and lipids excreted by some algal strains are unlikely to interact with the applied thixotropic gel in any significantly adverse way. Third, it means that individual algae are less likely to be occluded (shielded) from nutrients or sunlight and the effective exchange of gases that is necessary for their optimal growth. Fourth, use of a gel means that the energy used for agitation and propulsion can be very significantly reduced, principally because agitation for the purposes of aeration, carbonation, mixing and dispersion is much less required. Fifth, because violent agitation is no longer required to ensure that algae do not plate or scum out on interfaces, the system avoids or minimises costly energy and material losses, downtime and/or cleaning operations. This suspensive action of the gel is even more important overnight, when agitation is minimal or non-existent in a Winwick system – unlike most others. Sixth, because the presence of even a weak gel substantially retards the diffusion of excessively acidifying CO_2 from the microbubbles into all parts of the solution and therefore into otherwise over-concentrated contact with the algae. Hence, most algae are enabled to metabolise the small amount of weak carbonic acid slowly diffusing into their immediate vicinity before it can reduce the pH to harmful levels. Thus, there is little or no need for the addition of neutralising, costly and complicating alkali to elevate the media's pH so it becomes more neutral and less harmful. And seventh, because using a gel and allowing additional, sunset-time oxidation of the soup, by means of reducing carbonation and/or aeration activity, means that the high energy cost of impulsion, agitation and sparging at night-time, required by some other methods, may be omitted entirely, or else very significantly reduced. This only-daytime power requirement also fits in nicely with the timing of solar electric power delivery from the local PVs.

Winwick bioreactors are designed for growing algae at low and most-areally-productive steady-state concentrations. There are consequentially low, light gradients that allow sufficient PAR to penetrate to the bottom of the phytotubes for algae there to maintain some photosynthetic activity. The low algal concentration also means that less of the light is diffused into the shaded zones and that therefore a more effective, light-dark regime can be maintained. It is shading of the moving algal soup by the PV strips, aided by short-lived shading of one alga by another just above it and between it and the sun, that provides the sub-second flashing light regime necessary: for

---

[1] Barbosa, M.J.G. V. (2003) *Microalgal photobioreactors: Scale-up and optimisation* Ph.D. Thesis, Wageningen University, Wageningen, The Netherlands. library.wur.nl/wda/dissertations/dis3423.pdf

efficient light usage; for minimal diversion of excess PAR by algal protective mechanisms into heat, a process known as non-photochemical quenching (NPQ); and hence makes for the high algal growth and high photosynthetic activity necessary for maximum overall productivity. Short-cycle flashing exposure is reported to be the only way that algae can efficiently utilise high intensities of solar insolation.

Due to the light-dispersive presence of microbubbles in the algal soup, the flashing light regime is most effective where insolation is strongest, near the upper or sunward surface of the soup – just where it is most needed to give protection from photo-inhibition. Deep in the soup, conditions nearer to continuous insolation occur. However, as the insolation is attenuated there, photoinhibition is not a problem.

Algae are able partly to adapt to new insolation conditions by a process termed photoacclimation. This takes between hours and days, though it may also be said to continue much longer via mutation, generation and natural selection. Under conditions of increased insolation, algae will adapt by reducing the size of their pigmented, photosynthetic antennae. This has the effect of making them more transparent, thereby increasing the light path. The same effects, but possibly faster and even more effectively, can be achieved via genetic modification or strain change.

Unacclimatised algae cannot produce optimally. Therefore, productivity will tend to be improved when growing conditions are maintained fairly stable, or at least do not change rapidly. An exception to this is a flashing light regime in the frequency range of preferably microseconds to under a second, or at least not more than a few seconds. The literature suggests a maximum of four seconds and says that maximal photo-synthetic efficiency is approached when the light/dark cycle time is close to the dark-reaction time of 1-15ms, with dark time exceeding that of light time by multiples. In Winwick bioreactors, the shorter times may be approached when one alga in the gel temporarily shades one just below it; whereas a flashing cycle in the order of a second is achieved by the velocity of the soup (100-250mm/sec) under a light-dark distance ranging from about 70-270mm, but commonly perhaps around 215mm. This cycle time may be reduced to half or even a quarter by the methods mentioned above, but at the expense of less dark, dark recovery time.

Winwick bioreactors are designed to maintain reasonably even insolation conditions. Insolation variation throughout the day and over weather and seasonal change is smoothed by the adaptive, curling/uncurling action of the PV supports and the structural arrangement of bioreactor components. Insolation excess over timeframes in excess of a second is controlled by fast-cycle flashing externally and by virtue of an alga's location in the phytotube relative to the surface. Internally deep in the soup, insolation is reduced to productive and non-harmful levels by light dispersion, conversion and attenuation. These external and internal effects, together with operational changes made to algal concentration and soup velocity, make it easier for algae in a given Winwick bioreactor to maintain an acclimatised state with antennae of stable size.

The above factors, amongst others, cause the maximum of insolation to be converted into biomass – which translates into maximal light-usage efficiency. For Winwick bioreactors, it is the efficient areal utilisation of PAR that is important, not the volume utilisation. Moreover, employing a low-concentration soup minimises problems associated with adequacies of insolation, nutrition and waste removal. It also minimises potential problems with congestion, clumping and chemo-suppression, where the proximity to many other algae and the chemical concentrations that they together release, reduces algal growth generally.

Stressing microalgae with nutrient deficiency (typically of nitrogenous nutrients) is known in the literature to cause them to reproduce less rapidly and to modify their metabolic pathways to favour the production of lipids rather than carbohydrates – even to convert some of their carbohydrate into lipid. As Winwick bioreactors use software to vary growing conditions and algal strains, it is a simple matter for individual bioreactors to be programmed or remotely re-set at will to cause nitrogen or other nutrient deficiency or stressful conditions. Thus, algal soup from nutrient-sufficient bioreactors may be pumped to nutrient-deficient ones to produce harvestable algae of higher lipid content, after allowing the necessary extra photosynthetic time (typically 0.3-3 days, depending on the algal strain) for the metabolic change to occur. Thus, unlike most batch production or hybrid (open and closed bioreactor combinations) systems, Winwick bioreactors can maintain optimally-productive algal concentrations in both nutrient-sufficient and nutritionally-stressed ones. The pairing of Winwick bioreactor tubes off a single impeller/harvestor unit provides a ready bioreactor location for algal stressing. It could also provide backup in the event of one harvesting unit becoming temporarily less-effective or inoperable, as algal soup would be simply pumped from the nutrient-sufficient one to the other, rather than being harvested in the first one.

Winwick Solar Power (WSP) Method

The WSP method provides standardised, economical and accessible platforms for the installation of baseload PV power generators. It utilises a simple system, based upon thermally-activated laminated strips, to adjust the coverage of the PV progressively to optimise insolation between the algae and the PVs.

The PV fluting system serves a fourfold purpose: shielding the algae from excessive or damaging heat and insolation (sunlight); producing solar electric power to run the machinery and to generate substantial excess power for sale; strengthening the envelope around its area of prime, near-horizontal exposure to degradative, solar radiation and weathering; and to provide the alternation of light and dark to the moving algal soup that is necessary to gain optimal PAR usage, without photo-inhibition. The width of the strips and the intervals between them is so calculated as to provide the required, sub-second light and usually longer dark-recovery intervals between light exposures that result from the modest velocity of the soup along the bioreactor that is, in turn, provided by the relatively slow-spinning impeller blades.

Any of several existing commercial or near-commercial brands of flexible, preferably thermoplastic nanopolymer, PVs may be employed. The one from Nanosolar Corporation is the one currently preferred. The width and spacing of PV strips along the envelope would be selected at assembly time in order to suit the climatic conditions of the site and the algal strains for which the bioreactor is being built.

PROCESSING PLANT

Traditional processing plant at Winwick facilities includes various, relatively standard, chemical engineering units, such as liquid, slurry and gas pipes, heat exchangers, filtration plant, centrifuges, pumps, valves, sensors, actuators, fractional distillation towers, anaerobic digestors, storage reservoirs and tanks.

Novel processing plant includes: profiled drillhole reactors for WCR, WMS, WFTAS, WSS, WAS and WLE purposes, together with WOF units to separate the biofuel products. The novel WMG and WSP plant is located in the bioreactor farm areas, the others at campus processing facilities.

Process breakthroughs come from three, newly perceived opportunities:

- to use the clean, heat energy and power obtainable from geothermal resources and bioreactor-mounted PVs to power a biorefinery and to use the waste heat therefrom to warm the bioreactors;
- to use the pressures available from pumping fluids down deep (often existing) drillholes to drive a wide range of physical and chemical engineering processes most economically and sustainably, including those of:
    - algal cell rupture
    - lipid transesterification
    - supercritical water partial-oxidation of hydrocarbons and organic waste (including gassy, dilute aqueous suspensions of algal cell walls left over after lipid extraction, or similar organics ranging from agribusiness wastes, weed species, organic rubbish, mixed plastic waste and/or sewage) to produce syngas or subsequently methanol
    - Fischer-Tropsch reactions to produce fuels and chemicals from inputs such as syngas, utilising catalysts and promoters disseminated throughout heavy oil or other carriers, into which have been introduced bubbles of reactant gases that are adiabatically compressed or otherwise heated and cooled so that they react together as they are pumped down and up the parallel, drillhole reactor pipes
    - Other similar, pressure/temperature-driven reactions, such as ammonia synthesis
- to use the cultivation of algae to biosequester CO_2 and to produce a 90:10 O_2:CO_2 gas mix that can be transported by pipe and used by industry in biorefineries, combustion, refining and chemical production operations.

The particular advantages of Winwick technology, beyond its simple economy, its minimal ecological footprint, its production of baseload solar electricity, and its productivity, is that it frees algal strain selection, breeding and modification from concentrating solely on those few species that give high proportions of lipids. It is to be noted that robust strains having the highest biomass productivity, often several times that of lipid-rich strains, tend to be those with low lipid content. Prolific, fast-growing and robust species that tend to produce carbohydrate

rather than lipids may now be seriously considered, as their carbohydrates may now be converted efficiently into oils. The only minor downside of carbohydrate conversion appears to be that more of the nitrogenous content could be lost than would be the case when the biomass is anaerobically digested to release the nutrients. However, any loss can be replaced by using a higher proportion of Winwick bioreactors to grow nitrogen-fixing blue-green algae/bacteria or by employing the WAS process.

DRILLHOLE REACTOR CONSTRUCTION

As already discussed, the outer part of Winwick drillhole reactors is formed typically from disused, in-situ drillhole casings – though in some instances the drillholes may be drilled specifically for reactor purposes. Whilst most useful when drilled into a geothermal resource, they can still serve their reactor purpose drilled elsewhere. Their small footprint and emissions would allow them to be drilled in locations most suited to obtaining access to reactant materials or markets, such as beside factories or agribusinesses, in forests or on transportation corridors. The laser drilling and material expulsion technologies of the Archimedes Project of Geoternity Corporation are claimed to reduce deep, earth-well construction costs by as much as75%. If/when achieved, they could make purpose-built, Winwick drillholes economic at virtually all sites.

In the simplest case, a profiled inner pipe, having wide and narrow sections, is lowered into the drillhole. As it is secured above the bottom of the sealed drillhole, it forms a link between the profiled pipe internal and surrounding drillhole pipe annular cross-section, through both of which the carrier fluid reactants (often in the form of mixed-gas bubbles), catalysts and promoters are pumped. Pumping may be in either direction. Constrictions in one pathway cause additional compression of the fluid, whereas widenings cause local decompression. Both generate turbulent mixing. Compression may also result in decavitation (bubble implosion) and its energetic concomitants. Chemical reactions will tend to take place either in solution, adsorbed on catalyst surfaces, or where gaseous reactants interface with catalysts and possibly other reactants at bubble surfaces. Their total surface area is larger when the introduced bubbles are smaller. Products may be partially shielded from further reaction or the equilibrium reaction going in the other direction by phase separation or product dissolution in the carrier. Reactions and physical of phase changes can occur in both down and up conduits.

When a fluid fills the conduits, gravity ensures that the pressure increases with depth. Depending on the density of the fluid, in a 4km deep drillhole, the pressure may easily reach 1,000atm or more. The density of the fluid may need to be increased by the addition of heavy, often powdered materials in order to offset the pressure of the surrounding rock and fluids. This can be an advantage as solid catalysts often take the form of transition metals or their oxides that tend to be heavy. In a liquid carrier they can be highly concentrated yet dispersed for easy access, provided that the presence of carrier fluid at active catalytic sites does not hinder access or reaction overmuch. As the pressure at a given level in both pipes is approximately equal, it takes little energy to pump material through them both. Thus, hyperbaric pressures that assist chemical reactions or desirable physical changes to occur can be achieved at little energy cost.

Whereas suitable, gross reaction temperatures may be achieved by the use of heat exchangers on the surface (typically making use of low-cost, geothermal heat) or by the adiabatic heating effect of gas bubbles in the fluid being compressed, fine control of fluid temperature may be achieved by the use of superheated steam or chilled water introduced to the fluid by means of a long, hollow metal pipe or lance. Typically, this will run from the surface someway down the centre of the inner, profiled pipe, perhaps 30-300m. The lance may be inserted to adjustable depths, should different reactions benefit from it. The selected depth of the lance's nozzle opening could be used: to minimise the chance of blowout; to ensure that reactant bubbles in the fluid had been suitably compressed to facilitate transport downwards; to minimise coalescence with the steam; and to help determine at what depth reaction conditions would be reached.

Alternatively, or when a central lance would overmuch constrict the flow of fluid, the steam may be introduced by means of one or more hollow, split collars around the drillhole casing at selected depths. Typically, these would be welded onto the casing after accessing it via a second drillhole, drilled parallel to the first. The sideways excavation, drilling through the casing, collar placement and welding might be done with remotely operated tools able to be lowered down the new, possibly relatively shallow drillhole. An insulated pipe would carry the superheated steam to the correct depth, where electrically-operated valves would open each nozzle to the required amount to heat the drillhole contents at the location to the required temperature. Potential downsides to

this alternative may be that it would be somewhat more difficult to arrange for heat exchanges amongst different, concurrent processes occurring in concentric pipes, and the direction of flow might need to be reversed.

The main factors determining the heating effect of steam on the carrier and its reactants are its temperature, pressure, and the degree to which its valves are opened. Maximum bulk temperatures in drillhole reactors may be constrained by the temperature at which the carrier (usually a heavy oil or water) degrades, vaporises or turns into a supercritical fluid at a particular pressure. However, much higher, highly-localised temperatures can occur at the instant of bubble decavitation that may promote some reactions. When cooling of an exothermic reaction is required, possibly on the upward leg, additional pipes containing cool fluid may be used to form a heat exchange or cooling system.

Drillhole Reactor Technology Prospects

There are potentially many uses for Winwick Drillhole Reactor (WDR) technology. For instance, it would find profitable use wherever industrial chemical reactions use catalysts, high pressures (10-1,000+atm) and temperatures up to the degradation point of heavy oil, circa 1,000^{0}C, or where large-scale, supercritical fluid reactions are beneficial, such as in the generation from wastes of valuable chemicals and energy. Such reactions comprise a large number, possibly the majority of industrial, chemical engineering processes. Hence the technology may benefit very many current industrial processes. In particular, supercritical fluid reactions and reactions utilising many different reactant gas mixtures and carrier combinations might be investigated.

WDR technology could end up unifying, by means of a multifactorial matrix, many disparate chemical engineering processes. It could do this by providing both a common and an economical high-pressure reaction vessel, together with a means of economically experimenting with many reaction factors. As pressure-dependent reactions usually depend on a certain minimum pressure being reached before reasonably fast reaction occurs, a drillhole having a zone of much higher pressure usually would not deleteriously affect reactant conversion into product, whilst its results would cover the range. This means that different-depth and width drillhole reactors could all contribute to filling in the matrix of possible valuable reactions, rather than being just isolated experiments.

This document relates how such different processes as: algal rupture; transesterification; biomass gasification to syngas; various FT reactions, including the synthesis of methanol and alkanes; together with ammonia synthesis and similar high-pressure reactions might be placed in a multifactorial matrix using WDR. However, there are potentially many more as yet unknown reactions that might be unified, selected and made more economical under WDR technology.

Some of the many factors affecting reactions that might readily be explored under WDR standardisation could include: reactant concentrations; phases; carriers and their effect on catalysis and product removal; catalyst mixes, forms, sizes, shapes and concentrations; promoters; surfactants; solvents; temperature gradients and intensities; pressures; durations; decavitation; compression/decompression regimes; turbulence; supercritical fluids; bubble size; fluid velocity; adsorption; diffusion; desorption; conversion; reaction rate; and separation.

Why WDR could become an efficient means of finding better reaction conditions, quicker, is not only due to the ease and relatively low cost of testing new combinations, but because with WDR it is relatively easy in most cases to use a research technique called acceleration-stat (A-stat). This is an experimental method that can be used as a fast and accurate tool to determine kinetic parameters to optimise conditions – in our case reaction conditions. It was used to good effect in the Barbosa study. Basically, what it does is to change experimental conditions slowly enough so that new equilibria are closely approached, but rarely reached, whilst the results are periodically measured on-line, but without the need for separate or batch-type experiments. This allows optima to be plotted and determined far more quickly than otherwise, and with negligible error. It therefore allows far wider experimentation for a given cost. Using WDR may therefore become a useful tool for Winwick technology developers and extenders.

Similarly, WDR might be used to re-optimise reasonably well-known chemical reactions falling within the WDR zone, as well as for discovering new, useful reactions. Such new reactions might even be suggested by observing the developing multifactorial matrix population of viable and optimised reactions. For instance, it might be a profitable way to search for new catalysts and catalytic forms and to trial them. Additional catalyst and promoter candidates might progressively be added to the carrier with jumps in product concentration reflecting a good, new catalyst or interaction amongst catalysts. Similarly, might other reaction conditions be gradually changed and the

effects measured at any desired intervals, without interruption.

Drillhole Reactor Uses In Winwick Biorefineries

Drillhole reactors may be used to produce syngas or methanol via partial oxidation using hydrothermal or supercritical water processes from algal biomass (in our case from the algal materials left over after lipid and selective protein extraction). From the syngas may be produced various FT-fuels, also using Winwick processes. Processing steps using WDR for pressurisation and temperature control are likely to be far more economical and friendly to the environment than are traditional methods that rely on fossil fuel and high-pressure pumps to achieve elevated temperatures and/or pressures. Moreover, as WDR can utilise 'dry wells', depleted ones, or non-functional HFR ones, much of the expensive drilling cost may often be avoided.

Processing microalgal cells to produce biofuels involves overcoming several physical and economic problems. These include the high costs involved in: rupturing the tough, slippery algal cell walls; heating; dewatering; chemically transforming the viscous, algal lipids into methyl esters; and separating and recombining them into valuable transport fuels, products and recyclable waste. Brute force methods have traditionally been used to address these problems. However, these are increasingly costly, unsustainable and typically involve damaging greenhouse gas and other emissions. The novel method proposed, bypasses the step of removing water from the algae by processing the algae in aqueous phase, thereby facilitating oil, water, and solid phase separation. It also rationalises the number of separate processing steps, making use of carbon-neutral and economical drillhole resources.

For some algal species, particularly those low in lipids, it may actually be more profitable to bypass one or more of the nutrient-stressing, froth-flotation harvesting and lipid/protein extraction stages and to pump the extracted algal soup directly (though possibly after heating and material additions) into a WSS drillhole reactor.

An HFR drillhole resource has two components in addition to the drillhole casing of thick steel that often has an external concrete cladding: pressure and heat. These components can separately be replicated away from a drilled, HFR resource, but at typically greater financial and environmental cost. In the Winwick process, pressure and heat are used successively: to produce the desired transformations in the algal slurry (rupture the algae); to transesterify the lipids; to separate (fractionate) the individual oil fractions; and to produce syngas, methanol, ammonia, and various other FT fuels and chemicals.

An HFR drillhole typically has three diameters, narrowing from the surface. When this occurs, the different diameters may be exploited to allow a number of different WDR processes to take place, concurrently or separately, in a single drillhole. Otherwise, separate drillholes or pressure vessels may be used. For a three-diameter drillhole, concentric pipes may be inserted inside the drillhole casing. The widest inserted pipe might separate the up and down flows of the transesterification process, as this requires least pressure. The next two inserted pipes might separate the up and down flows of the algal cell rupture process at the same time as cooling deeper exothermic reactions. The profiled member might be either the inner or outer one, depending on cost and profiling preferences for the other two processes. As the supercritical water and FT processes require the greatest pressure, these are the pipes to go deepest. Although it/they may similarly be constructed of two concentric pipes, to reduce wall-frictional losses it may be more profitable instead for the narrowest pipe to have inserted or welded an internal, crosswise divider inside a single pipe. This divider may be offset from the full diameter to form two segments, sufficient to allow for the reduction in volume caused by gas compression and dissolution. The segment divider may also be constructed to provide profiling, and hence discontinuous pressures and temperatures, should that be so desired.

Winwick Cell Rupture (WCR)

For the first process, Winwick Cell Rupture, the gas-rich, aqueous slurry from the Winwick impeller/harvestor units is pumped down a blank-ended drill-hole, typically via a profiled pipe, set inside the thick, metal casing of the drill-hole. The profiled pipe ends anywhere short of the blank or sealed end, to link the pipes. Now, HFR resources are usually located a few kilometres below the surface, however a much lesser depth (and hence lesser pressure) should still be adequate for the rupturing process. Nor must this drillhole be necessarily associated with a geothermal resource. It can be located anywhere, preferably having been drilled for some other, now obsolete, purpose. The increasing pressure on the downward journey progressively provides an effect of dissolving most of

the gas bubble contents into the algal media water and, by osmosis, into the algal cells and their inner vesicles.

A second effect of the increasing pressure is decavitation. As the small bubbles of gas implode as their last vestiges dissolve in the water under ever increasing pressure, tiny and highly-localised, but highly energetic, shock waves and microjets occur, and very high, very localised, instantaneous temperatures result. The energy of these effects is often sufficient to rupture nearby algal cell walls and/or to progress chemical reactions.

The profiling of the inner pipe is such that at points within it, and on the upward return slurry journey outside it, there are created regions of relative local compression (chokes or choke points) and decompression, as well as different fluid velocities and degrees of turbulent mixing. When gases are involved, compression and decompression also result in significant local, adiabatic (internally-generated due to gas compression) heating and cooling. To ensure rapid overall decompression on the upward journey, the downward inner pipe will normally have a significantly greater cross-section (and hence a slower flow rate) than does the lesser cross-section of the upward, outer annulus pipe. However the difference is not made so large as to involve excessive wall-frictional losses in the narrower cross-section pipe. At the local decompression regions generated by the widening of the profile of the pipe and due to the overall upwards decompression due to gravity, gas tends to come out of solution. When it comes out of solution suddenly within a vesicle or alga, the sudden increase in relative gas pressure inside tends to rupture the container (the vesicle or algal cell wall) with great efficiency and completeness, releasing its contents into the main, aqueous solution. Thus, the algal lipids and other cell contents are freed to take part in further transformational processes. Happily, as the rupturing force comes from expanding the entire contents of each alga or vesicle with gas, minimal damage is caused to its more fragile contents, such as the intricately-folded proteins. As heating is not required for rupture, and is indeed contra-indicated for high gas solubility, high temperatures are preferably to be avoided during the rupture process. Should these be likely, then a separate, shallow drillhole may be used.

The four main phases of rupturant (the product of the rupturing process) comprise: the solid components (chiefly the ruptured cell walls comprised of glycoproteins and polysaccharides); the aqueous phase; the immiscible (non-mixing), oily lipid phase; and the gaseous phase. These can be coarsely separated by means of centrifuging, using an inline, vortex centrifuge and near ambient pressure. The centrifuging also serves to expel residual cell contents from the cell sacs. It should be noted that it is far easier to separate, relatively heavy ruptured cell walls from water than it is to separate complete algae from water – particularly when the deflated cell sacs can remain wet.

As the algal lipids (triglycerides) are somewhat viscous at ambient temperature, if sufficient temperature has not been reached by the rupturant, it may first be passed through a heat exchanger, using waste HFR or other heat, to bring its temperature up to a modest 60^0C. This is sufficient to reduce the viscosity of the lipids significantly, making physical separation easier, less costly, and more complete, whilst not usually being high enough to damage fragile co-products.

The released lipids are hydrophobic and thus tend naturally to aggregate and to separate from the aqueous phase with only minimal subsequent de-watering effort being necessary. The solids, being denser than water and lipids will also tend to separate from them, the process being aided by the vortex centrifuging. The oxygen-rich gas is easily removed and used elsewhere.

As Winwick's rupturing, drying, transesterification, fractionating and bed-heating processes require heat, the heat produced by the FT processes, along with any extra that would be available from the HFR resource, may beneficially be used for these.

Winwick Lipid Esterification (WLE)

As the presence of water deleteriously affects transesterification (it can cause undesirable saponification – soap sudsing), the lipid-rich component of the rupturant liquid is heated and any residual water is allowed to boil off as steam at atmospheric pressure when the lipid-rich mixture is heated to over 100^0C. The resulting steam itself is condensed and returned to the system. After the steam has been removed from the lipids, they are pumped through a heat exchanger (maybe the same one) to bring them to 107^0C and thence transferred into a sealed reaction vessel or drillhole reactor where relatively shallow depths can produce 5atm pressure. Where HFR or FT exothermic heat is not available, this heat may be produced by any other economical means. In warm to hot climates, this may best be done using solar ponds. Otherwise, ordinary geothermal heat may be used or waste heat

from industry. Because the triglycerides that make up the algal lipids have boiling points well above these temperatures, they are not lost earlier on.

The triglycerides in the lipid-rich liquid are then transesterified in the reaction vessel or drillhole reactor to make them even less viscous and thus usable as transport fuels. This is done by mixing one or more of the many recognised catalysts, together with six moles of methanol for every mole of triglyceride in the lipids to be transesterified and adding the mixture to the lipids. Although only three moles of methanol are required to react stoichiometrically with one of triglyceride, the excess methanol is added so as to drive the equilibrium reaction to transform methanol and triglyceride into methyl esters and glycerine. Due to the pressure applied, the methanol at this temperature remains liquid so that it reacts in close contact with the lipids to produce fatty acid methyl esters (FAMES, which combined in different proportions constitute several different types of biofuel) and glycerine. With the possible use of ultrasonics to hasten the reaction, and the right selection of vessels, pumping and catalysts, the whole process can be made a continuous one, rather than a batch one. Alternatively, and probably more cost-effectively for this purpose, the mixing, cavitation and decavitation produced when the reactants are pumped hot through a modestly deep, pressurised, profiled pipe as above, may be used to replace the function and cost of ultrasonic irradiation in transesterification, or else the reaction can just be left to take its time (several hours).

Winwick Oil Fractionation (WOF)

When the transesterification reaction has occurred, the heavier glycerine may be drawn off from the bottom of the containing vessel or centrifuged off. The lighter lipid fractions may then be fractionally distilled (fractionation) using additional HFR heat to produce the various fuel products: methanol (the excess), petrol, jet turbine fuel, biodiesel and residual fuel oil (RFO). Now, HFR temperatures of 250^0C are not unknown. However, as only the C8:0 and C10:0 FAMES have lower boiling points than this at atmospheric pressure, the C12, 14 and 16 FAMES will require either partial-vacuum distillation, or else the application of higher temperatures from a different, hotter heat source.

The partial vacuum distillation route is probably the most economical here, as it can use cheap Winwick solar electricity to power it. The bulk of the methanol and FAMES can be separated using atmospheric pressure distillation at less than maximum HFR temperatures. As most of the remaining FAMES can be separated using vacuum distillation at these temperatures, no extra high temperature heat source should be required. The smallest, least valuable, fraction is the RFO that is left behind undistilled, together with possibly some of the catalysts and other impurities. Unless catalyst recovery is economical, this RFO/catalyst mixture may be used as the carrier in other Winwick processes, sold as fuel oil, or become raw material to other conversion processes. It might also be treated with supercritical water in a Winwick variant reaction to form more valuable products or be pyrolysed to form syngas and thence more valuable, lighter oils and saleable biochar.

The catalysts from the transesterification process may be recovered from the residue after fractionation. These may or may not be reusable or recyclable, depending on their nature and whether or not they have been neutralised, poisoned or otherwise affected. The methanol is recycled, transformed or sold.

Should high temperature distillation be desirable, the availability of gas/oil well methane and oxygen, or the development of solar concentrators for this and other purposes at some facilities, makes these obvious and reasonably economical sources of such incremental heat energy.

Any heat recovered from these processes might be: fully utilised in the lower temperature processes of Winwick technology; used to generate power; or used in nearby agribusiness, factories, heat stores, campuses and towns. Waste heat from the higher temperature processes is re-used in the lower temperature ones in cascade. The heat waste from the lowest temperature process may be employed to warm the bioreactors during cold or dark periods or for growing thermophilic strains of algae. Otherwise, it might be returned to the fluid that extracts the geothermal heat to produce electric power or to a cooling pond.

Due to the availability of economical heat sources at the facility, the crude glycerine will usually be: distilled to pharmaceutical grade; used as raw material to produce more fuel; or used elsewhere in the biorefinery or in associated agribusinesses.

At cool times, the waste heat resulting from the cascading of heat reuse and production in these processing steps, and/or other HFR heat, is used to improve algal insolation (exposure to sunlight) by convection and to warm the algae sufficiently to keep them at high activation and productivity. Cool times may also be a signal to introduce

cool-climate algal inoculant into the bioreactors, and vice versa in warm or hot times.

By-product Recovery

When the lipids have been extracted from the rupturant, valuable by-products, such as nutraceuticals, proteins and vitamins, that would be deleteriously affected by the higher temperatures occurring later, may, if desired, be extracted from the aqueous phase. More might be recovered from the solids using washing and re-centrifuging processes.

The aqueous phase, which contains a large portion of the nutrients, may then be treated to extract its more valuable components by electrophoresis, adsorption or other standard methods. If the residual nutrients are already in a form able to be ingested by algae, then they may be sent directly back to the bioreactors to make up most of the nutrients that had been removed from the soup during harvesting. Alternatively, after removal of the more valuable proteins, carbohydrates and vitamins, the aqueous residuum and the wet slurry of remaining solids can be piped to the anaerobic digestor, where the action of anaerobic bacteria converts them mainly to methane, CO_2 and free nutrients. These are all recycled to the bioreactors.

Alternatively again, if more economical sources of nutrients can be made available (e.g. treated sewage, agribusiness, on-site ammonia production or industrial waste), the cell wall solids can readily be turned into high-protein, human food or stockfeed. Note also, that for algae and diatoms having cell walls of calcium carbonate or silicic acid/silica, the digestor's action will produce less methane and may require special treatment to free these essentially inorganic materials for recycling.

Substantial portions of algal nutrients are held in the amino acid (glycoprotein)- and carbohydrate (polysaccharide)-rich, algal cell walls and other structural elements.

Thus, an even better alternative to the release of the nutrients by anaerobic digestion, which degrades their energy value significantly, is to use partial-oxidation under hydrothermal or supercritical water conditions. In a Winwick facility, the oxygen can be provided economically by algal photosynthesis, whereas economical pressure and heat are available from the drillholes and HFR resource. Cooling can be provided from the other heat-consuming Winwick processes. With appropriate catalysts, this supercritical water gasification (SCWG) (also known as supercritical water oxidation (SCWO) or hydrothermal oxidation (HTO)) reaction can produce syngas (comprising mainly CO + H_2) from the biomass. This is termed the Winwick Syngas Synthesis.

Winwick Syngas Synthesis (WSS)

This WSS, or biomass SCWG, reaction is different from the other Winwick drillhole chemical reactions in that it does not use a heavy oil to carry the bubbles of mixed, gaseous reactants down with it to regions of high pressure and temperature. Instead, the carrier is the water in which the slurry of empty algal cell walls or other organic material is carried. The slurry (or alternatively thin, algal soup) may have water content ranging from 70-99+%, depending on the degree of concentration it has undergone and what additions have been made to it. To it is added small bubbles of a gaseous mixture of oxygen and carbon dioxide (excess CO_2 matters little) deriving mainly from the bioreactors to the desired stoichiometric proportions for the intended product and to provide sufficient gas to ensure that sufficient, compressive adiabatic heating occurs to start the SCWG reaction after surface-level heating has been provided by heat exchangers, possibly supplemented by subterranean lance/collar steam heating.

Catalysts are not required at the low biomass concentrations used in WSS, but water may be added to the slurry for pumpability or to ensure more complete, desired reactions. The reactants are then pumped down the drillhole reactor, to return to the surface via a separate route, typically the outer drillhole pipe. Super-heated steam may be injected into the reaction mixture a suitable way down the drillhole to ensure that the correct reaction temperature is reached even further down the drillhole, after the compressing gases have adiabatically heated the slurry up even more to fast reaction temperature. Cooling may be accomplished by injecting coolants (typically chilled water) on the upward journey or via heat exchange processes. Pumping, drillhole length, oxidant concentration, and the increasing pressure of the liquid on the downward journey are factors that ensure that the supercritical conditions and the duration of them are achieved sufficient just to partially oxidise the algal cell walls into principally CO + H_2 (that together comprise syngas) and possibly some, somewhat less-desirable CO_2 and CH_4. Methane formation is favoured at sub-critical temperatures, whereas syngas is favoured at high temperatures and high dilution. Steam will also participate in the reaction, to a controllable degree, by means of the water-gas shift

reaction to produce hydrogen:

$$CO + H_2O \rightarrow CO_2 + H_2$$

Undesirable destruction of nutrient nitrates and ammonia is minimised by the choice and concentration of oxidising and reducing agents and by the time and conditions provided for the various reactions to occur. After separation, the freed nutrients are returned to the bioreactors, together with make-up nitrogenous nutrients processed from the cyanobacteria bioreactors, digestor or ammonia plant.

As supercritical water reactions can eventually be harmful even to a thick, steel drillhole casing or profiled pipe, it may be profitable to coat, sheath, plasma spray or electrolytically deposit on the inside of the drillhole a protective layer or layers. Such layers might include oxides, chromates, ceramics, titanium, or other non-reactive chemicals. Of course, the selected coating or sheath might also function as a catalyst. Coatings such as Teflon and silicones and composites containing glass or carbon fibre would only be considered if they are inert and retain sufficient strength and adhesion under such supercritical conditions and drillhole stresses.

Winwick Fischer-Tropsch Alkane Synthesis (WFTAS)

The syngas resulting from WSS can then be converted into controllably-long alkanes that go to make petrol, diesel and jet fuel via a Fischer-Tropsch (FT) process variant that utilises a Winwick drillhole reactor. This process is termed the Winwick Fischer-Tropsch Alkane Synthesis (WFTAS).

Many other chemical engineering processes may be facilitated using WDR technology. Predominant amongst these is the Fischer-Tropsch synthesis reaction that can use the products of the partial combustion of wellhead methane and algal-produced oxygen to form synthesis gas, which is comprised of hydrogen and carbon dioxide:

$$2CH_4 + O_2 \rightarrow 4H_2 + 2CO$$

Of the competing reactions in the Fischer-Tropsch process, important ones comprise the general set:

$$(2n+1)H_2 + nCO \rightarrow C_nH_{(2n+2)} + nH_2O$$

Such reactions are highly exothermic.

The low temperature Fischer-Tropsch (LTFT) reactions that produce the most valuable, long-chain alkanes occur from 200-280^{0}C in the presence of catalysts made typically from iron and/or cobalt and which often are deposited in thin films upon a non-reactive, high surface area base, such as some ceramics or treated minerals may form. The high temperature (HTFT) process occurs from 300-350^{0}C and uses an iron catalyst. Both can be performed by Winwick FT variants.

In these Winwick variants, the catalyst is typically incorporated in a gas-bubble-carrier liquid, rather than being loose or localised in a catalyst or slurry bed. Thus, the catalysed reactions take place on catalytic surfaces typically located within a few molecular distances of the bubble surface as the bubble is carried down and up the drillhole, the heavier, higher boiling point products dissolving into the typically hydrocarbon carrier for later release by fractionation. This dissolving action partially shields them from further carbon-chain addition reactions. Thus, the absorption of desirable, middle boiling point alkane fractions into the carrier, before they become too long and heavy, provides an additional means for ensuring that production of the more valuable fractions is favoured. By typically remaining as gases at these temperatures and pressures, the lighter fractions tend to remain inside the bubbles until they add sufficient CH_2 segments to become desirable-length alkanes.

Typically, LTFT reactions are carried out at pressures from 20 – 60atm. Even higher pressures would be even more favourable, but are usually not cost effective. However, using Winwick technology these more favourable conditions are available economically from existing geothermal or other drillholes. However, as the FT reactions are highly exothermic, it will be convenient for the drillhole used to also be the site for Winwick processes that require heat. Balancing the volumes used in each process can, possibly with some additional surface-based or near-surface cooling processes, be used to obtain the right temperature band for each process to occur in. Using Winwick variants of FT processes, pressures of up to and exceeding 1000atm may well be cheaper to achieve than ones twenty times less (~50atm) on the surface, thereby delivering superior economics of production.

Use of somewhat higher pressures also speeds up the reaction time of the synthesis gas from hours to minutes and may improve the yield considerably. Furthermore, combinations of higher pressure and reduced reaction time can be so chosen as to produce alkanes of the most valuable lengths, which are C12 to C20 – those comprising diesel and jet fuel. Evidence for these claims may be derived from Latin American applied research

conducted at the Universidade Federal do Ceara in Brazil[2].

In Winwick's FT process variation, the finely-divided iron, or iron on ceramic, catalyst is distributed in the carrier oil that is pumped down the central, profiled pipe and up inside the enclosing drillhole casing. The carrier oil may vary in weight from relatively light diesel to heavy, residual fuel oil. This carrier oil carries the small, injected bubbles of stoichiometrically-mixed synthesis gas ($CO + H_2$) for reaction. These bubbles are carried down and up the drillhole by the velocity of the circulating, pumped, carrier oil. The only pumping costs are those to offset pipe wall friction, turbulence and fluid density differentials. Energy is not required to compress gas. The reaction gases come into contact with the catalyst, typically at the bubble-oil interface, their concentration possibly being increased at the interface by the addition of an appropriate promoter or surfactant, as in froth flotation for mineral separation. As froth flotation is known to work particularly well in aqueous solutions, an emulsion of oil and a high-boiling point polar solvent, or a chemically-shielded hydrocarbon may be used instead for some purposes as the carrier.

In the production of diesel by this means, the carrier oil may itself be diesel, thereby possibly simplifying the subsequent separation process. For the production of other products such as methanol, a heavier oil, such as residual fuel oil, is a more appropriate carrier. Although the carrier may be a long-chain alkane, it reacts less readily with CO and H_2 to lengthen its chain than do shorter alkanes, as it is both less mobile and attaches less readily to the catalytic surface. Nonetheless, the carrier will needs be replaced periodically, though it may be regenerated or transformed into more valuable hydrocarbons via cracking.

By the above means, transport-fuel hydrocarbons produced by Winwick versions of FT synthesis can be made considerably more profitable than those undertaken at traditionally lower pressures on the surface. In many circumstances, the improvement in economics will be sufficiently strong as to overcome the otherwise superior economics of piping directly to city consumers, the natural gas that when partially oxidised produces the synthesis gas (syngas), even where such pipelines have available capacity and are nearby to remote, "stranded gas" sites.

The synthesis of methanol, diesel and other biofuels or chemicals under Winwick conditions is akin to various supercritical fluid chemical reactions. Indeed, methanol can also be synthesised from syngas under supercritical conditions. One such synthesis uses *n*-hexane as an additional solvent, temperatures from 200-210^{0}C, and pressure in excess of 80atm. Supercritical conditions are also used to oxidise, or (with limited oxidant) to partially oxidise, both hydrocarbons and carbohydrates in aqueous solution, as well as many other compounds, such as cellulose, plastics, sewage and hazardous organic waste.

Thus, Winwick technology can be extended to the direct partial oxidation of algal cell walls, which are composed mainly of carbohydrate, using oxygen derived from algal photosynthesis to produce syngas. Using the Winwick drillhole method, this in turn is converted by supercritical or FT processes into various biofuels or chemicals.

Winwick Methanol Synthesis (WMS)

The methane and CO_2 from the digestor or WSS process are used with other impure methane from other sources (typically from gas/oil wells and coal mines) to be combined with the O_2/CO_2 mix from the bioreactors and steam to form methanol in a simple, drillhole reactor methanol plant.

It should be noted that methanol powers high-performance racing cars and is likely to become an increasingly popular fuel to power fuel cells powering electric vehicles and portable devices. The particular advantages of methanol, ethanol and DME (dimethyl ether) derived from methanol is that they can use the existing supply chain and service station outlets with little or no modification. DME can also be sold in re-usable pressure packs and the alcohols in bottles or cans. Methanol can also be converted to petrol, plastics and important industrial chemicals – possibly again via Winwick drillhole reactions.

As methanol is typically produced by employing pressures of up to 1,000 atm and modest to high temperatures (80-800^{0}C), depending on the intermediates and catalysts used, it may also be produced, with very substantial economies, using geothermal or other drillholes, where the pressures can exceed 1000atm and the temperatures can exceed 250^{0}C (or much more using superheated steam supplementation and adiabatic heating) at 4,200 metres depth.

---

[2] Farias, Silva, Cartaxo, Fernandes and Sales (2007). Effect of operating conditions on Fischer-Tropsch liquid products. *Latin American Applied Research, 37* (4), www.scielo.org.ar/pdf/laar/v37n4/v37n4a09.pdf

There may be additional benefits from thermally linking the various drillhole processes. The methanol-producing and FT reactions are exothermic and will thus benefit from cooling via other Winwick processes.

Winwick Ammonia Synthesis (WAS)

Using a Winwick variant of the Haber-Bosch process, it may also be possible to utilise the high pressures available in a drillhole reactor to produce ammonia (NH_3) and thence to produce replacement nitrogenous nutrients for the algae and for sale as fertiliser. The Haber process reacts nitrogen and hydrogen in the presence of a catalyst derived from the partial reduction of magnetite (Fe_3O_4) with hot hydrogen. A substantial proportion of heavy, magnetite catalyst in the carrier would serve the dual purpose of increasing the carrier density – a useful function in deep drillholes. Before reaction, small quantities of calcium-, potassium- and aluminium oxides are added to the magnetite to improve catalyst performance. The catalyst is highly porous and adsorbs onto its surface individual atoms from the molecular reactant gases that then can react to form ammonia after diffusion apart and radical formation of reactant molecules' atoms on or near the catalyst surface.

In the standard, exothermic Haber process:

$$N_2(g)+3H_2(g)\Leftrightarrow 2NH_3(g)$$

reaction occurs from 300-550^{0}C and at 150-250atm. Under these conditions, a yield of 15% ammonia is achievable at each pass. However, as four molecules of gas react to produce two of ammonia in the equilibrium reaction, it will be seen that the reaction is favoured more strongly, the higher the pressure. As the reaction does occur, but is slow at room temperature, fast reaction at much higher pressure may be feasible at temperatures from 20-280^{0}C, thereby removing the need for one or more of the expensive, between-pass cooling stages and multiple re-passages of the standard Haber process. Furthermore, with Winwick drillhole pressures of up to 1,000atm being easily and economically achievable, it may be that much higher, single-pass conversion rates are possible. The feasibility of the desired catalytic reaction still occurring when the catalyst is carried in heavy oil or other liquid carrier and is exposed principally to the reactant gases at bubble surfaces will only be proven by experimentation. If it becomes proven, then the Winwick variant might well replace the standard Haber process. Of course, at high enough pressures, the reaction may take place sufficiently fast even without catalyst or promoter, or with a gas or liquid phase catalyst.

At Winwick sites, the hydrogen is readily generated from methane or algal cell walls reacted with water and oxygen. It can also be retrieved from syngas using membrane filtration techniques to separate the hydrogen from the carbon monoxide (CO). And the CO may then be reacted with water to produce even more hydrogen in the water-gas shift reaction. The nitrogen may best be separated from air using membrane techniques, powered by Winwick solar electricity. It may also be retrieved from the flues of power stations that burn air, once the CO_2 has been cooled and then removed by, say, the new adsorptive, zeolite imidazolate framework (ZIF) technology and the NO_x/SO_x contaminants have been removed by other standard processes. Therefore, WAS drillholes may also be advantageously located beside traditional, fossil-fuel powered power plants.

CLAIMS

1. A method of cultivating phototropic microorganisms, particularly microalgae or diatoms, in a bioreactor comprising the steps of:

entraining a culture of the microorganisms in a tenuous, gelated, thixotropic carrier medium having nutrients therefor and moving the medium along a passage which in cross section is closed and which has transparent walls through which the culture is irradiated to enable photosynthesis;

providing process parameter control means associated with the passage; and

selectively varying the process parameter control means to thereby selectively control parameters or conditions of the cultivation and photosynthetic activity of the microorganisms moving within the passage.

2. A method as claimed in Claim 1 and further including the steps of:

moving the carrier medium at a sufficiently slow speed to enable laminar flow thereof along the passage; and

effecting convective turnover of the culture and medium as they flow along the passage by differentially heating the medium laterally relative to the flow direction so as to produce a generally helical flow of the culture and medium.

3. A method as claimed in Claim 2 and wherein the carrier medium has a viscosity or tenuous structure sufficient to impede gravitational settling, surface scumming, or deposition onto solid surfaces by the microorganisms, at the same time as prolonging the residence time in the medium of the gaseous phase nutrient and impeding clumping of the microorganisms into less productive clusters.

4. A method as claimed in Claim 2 or 3 and wherein the viscosity, structure and composition of the medium and culture are monitored and are controlled to promote an optimal concentration of active microorganisms.

5. A method as claimed in Claim 2, 3 or 4 and wherein the viscosity and thixotropicity are increased by addition of a gel substance (e.g. a water swellable, or hygroscopic, organic polymer gel with high water absorptivity) to increase the impedance to gravitational settling and to the passage of gaseous phase nutrient up through the medium (except at locations of designated medium agitation, where the viscosity is deliberately reduced to enable gas liberation, algal harvesting and sparging with nutrient gas to proceed) but without preventing access by the microorganisms to nutrients in the medium nor preventing removal of excreta of the microorganisms in a gas liberation process.

6. A method as claimed in any one of Claims 2 to 5 and wherein the convective turnover is promoted by exposing one lateral side of the passage to greater radiant, conductive or convective heat than the opposite lateral side.

7. A method as claimed in Claim 6 and wherein the radiant heat comprises angled incident solar radiation or wherein the heat differential from heating or cooling is applied via a thermal element running longitudinally and next to the passage.

8. A method as claimed in any one of Claims 2 to 7 and wherein a heating or cooling mechanism extends along one lateral side of the passage so that heat transfers promote convective turnover in the medium to expose otherwise shaded microorganisms to radiation.

9. A method as claimed in Claim 8 and wherein the heating (or cooling) mechanism comprises a pipe in which is circulated fluid at a temperature greater or less than the culture and medium.

10. A method as claimed in any one of the preceding claims wherein the process parameter control means includes at least one envelope located around part or all of the closed passage (or, where multiple co-extending adjacent passages are provided, the envelope(s) surround part or all of the grouped, multiple, closed passages).

11. A method as claimed in Claim 10 and wherein the closed passage is enclosed within the envelope (and preferably multiple further passages also being enclosed side by side within the same envelope) and the process parameter control means includes a control space defined between the outside of the wall of the passage and the inside of the wall of the envelope, the control space being provided with an insulating material, the method including the step of selectively controlling radiation conduction and convection passing heat between envelope and passage, either way by selectively varying a property (such as the quantity, dispersion or quality) of the insulating material.

12. A method as claimed in Claim 10 or 11 wherein both the microorganism bearing medium within the passage and the control space are pressurised separately at greater than atmospheric pressure.

13. A method as claimed in Claim 12 wherein the pressure differential of gas and/or liquid between the passage and the control space is selectively varied so as to control the cross sectional shapes of the passage and the control space, and optimise the shape and depth of the medium in the passage to suit changing external parameters or cultivation requirements.

14. A method as claimed in Claim 13 wherein the control liquid within the control space provides hydraulic support to the side walls of the passage which are flexible and thereby promotes adoption by the walls of the passage of a more optimal cross-sectional shape for the microorganism bearing medium.

15. A method as claimed in any one of Claims 10 to 14 wherein the envelope has a control liquid therein operative in providing insulating properties of the space in the envelope, the envelope being provided with condensate collection channels extending longitudinally partway along the inside of the envelope walls, the channels being arranged gently sloping to collect water evaporating from the control liquid and condensing inside the envelope, the evaporating of water from the control liquid increasing its salinity and impeding its attractiveness or usefulness to organisms including animal life, the collected water being capable of providing sterile distilled water for use in the cultivation, harvesting and processing of the microorganisms, such as by enabling the replacement of water removed during harvesting with a safe, local equivalent.

16. A method as claimed in any one of the preceding claims wherein the process parameter control means (preferably the envelope) has provided externally thereof a base sheet or groundsheet assembly providing an upper light reflecting surface located under and on both lateral sides of the passage and in proximity thereto so as to

reflect incident photosynthetically active radiation (PAR) into the medium through the transparent walls and base of the passage, and to provide physical protective properties beneath the envelope when being located on, moved on, or removed from a supporting ground surface.

17. A method as claimed in any one Claims 10 to 16 wherein the passage is defined by a flexible polymeric material composed of the material of the transparent wall and wherein the envelope also comprises a tube composed of a flexible polymeric material of greater dimensions than the passage so as to enclose the same, the passage and envelope being initially flattened and provided in a form of a roll, being deployed by unwinding the roll, and thereafter being expanded to their operative configurations by supplying them with fluids.

18. A method as claimed in Claim 17 and further including servicing ducting or pipes through which fluids flow to support processes occurring in the bioreactor, the flexible polymeric tube constituting the envelope also encloses the servicing ducting or pipes, and wherein the servicing ducting or pipes are composed of flexible materials and being in the roll and being deployed by unwinding the roll along with the passage, envelope, and any attachments.

19. A method as claimed in Claim 17 or 18 wherein the passage when deployed from the roll and expanded adopts a shape when the medium is moving therein of rounded cross sectional shape having a greater width than depth.

20. A method as claimed in any one of the preceding claims wherein the microorganism bearing medium is moved through alternating zones of relatively higher and relatively lower insolation so that microorganisms are exposed to PAR in a pulsed manner, preferably with the duration of each complete cycle of higher and lower PAR exposure being less than one second and preferably with somewhat greater recovery time of relative darkness than the PAR exposure time of each cycle whereby radiation can most efficiently be photosynthesised by microorganisms and reducing the likelihood or effect of photoinhibition in the microorganisms.

21. A method as claimed in Claim 20 whereby the transparent outer envelope top surface is provided with bands or stripes having PAR attenuating or excluding properties relative to the transparent parts of the envelope between successive bands, the bands extending generally transverse to the direction of flow of the medium, whereby the bands, their adaptive width and their relative placement define the width and separation of the alternating zones of relatively higher and relatively lower insolation within the passage.

22. A method as claimed in Claim 21 wherein the bands are composed of photovoltaic (PV) material electrically connected whereby incident solar radiation can be utilised by the PV bands to generate electricity for use in performing the method or for use in associated operations (or for sale) and, in the zones intermediate between successive bands or beyond them, the incident radiation can be used in photosynthesis by the microorganisms.

23. A method as claimed in Claim 22 wherein the bands are inserted within fluting made largely of transparent polymer film enabling airflow therethrough so as to promote passive PV air-cooling to improve PV conversion efficiency and to help maintain the microorganisms within their most productive temperature range, the PV material comprising ribbons of transverse-curved material, attached to and/or acting as part or all of the support members

within the fluting and projecting into the airflow passages of the fluting, the fluting being affixed to the top surface of the envelope of the bioreactor.

24. A method as claimed in Claim 23 wherein the fluting comprised of the envelope, the outer film of the fluting, and the support members of PV ribbon and other material, is able to be compressed in thickness, along with the bioreactor tubes, to improve transportability.

25. A method as claimed in any one of Claims 21 to 24 wherein the ribbons, bands, strips or stripes are provided by bodies having shapes or configurations that are thermally responsive so as to provide relatively greater areas to intercept incident radiation upon being heated above a certain threshold.

26. A method as claimed in Claim 25 wherein the bodies comprise transverse-curled or rolled material having the property of progressively uncurling or unrolling upon exposure to a threshold and higher temperatures by incident radiant energy or increasing ambient temperature.

27. A method as claimed in Claim 26 wherein exposure of the transverse-curled ribbons, bands or stripes to a threshold temperature commences uncurling by utilising differential coefficients of expansion of different materials forming part of the ribbon material, thereby reducing excessive insolation that would otherwise enter the medium and increasing the amount of electric power produced, and conversely, when lower insolation or ambient temperatures cool the strips, they curl up transversely, allowing more light to the medium and producing less power.

28. A method as claimed in claim 27 wherein the transverse-curled ribbons, bands or stripes are generally S-shaped in transverse section when in the curled condition and wherein the different materials include a material with different (higher or lower) thermal coefficient of expansion to the PV or to another layer in the ribbon on one surface section of the S-shaped ribbon so as partly or wholly to uncurl that section upon being heated to or beyond the threshold temperature by incident radiation.

29. A method as claimed in Claim 25 wherein the bodies are movable from retracted positions towards extended positions in which they present greater surface area to incident radiation and hence greater interception of incident radiation upon exposure to a threshold and higher temperatures by incident radiant energy or increasing ambient temperature.

30. A method as claimed in Claim 29 wherein the bodies comprise wings and wherein exposure of the bodies to the threshold temperature commences raising of the wings from retracted positions towards their extended positions by utilising differential coefficients of expansion of different materials forming mountings of the wings, thereby reducing excessive insolation that would otherwise enter the medium and increasing the amount of electric power produced, and conversely, when lower insolation or ambient temperatures cool the mountings, they lower the wings towards their retracted positions, allowing more light to the medium and producing less power.

31. A method as claimed in claim 30 wherein the mountings of the wings form hinges to which the respective wings are mounted and wherein the hinges are each composed of different materials in laminar form with different (higher or lower) thermal coefficients of expansion so as to progressively open out and raise the wings mounted

thereto upon being heated to or beyond the threshold temperature by incident radiation or ambient temperature increase, and wherein the mountings of the wings are located on supports within an air space between transparent polymer films, the supports being initially in a collapsed condition for storage and, upon being installed, adopt an erected condition and ratchet arrangements prevent return to the collapsed condition.

32. A method as claimed in any one of the preceding claims wherein the nutrients in the carrier medium are introduced, at least in part, to the medium by introducing gas by way of sparged microbubbles to the medium.

33. A method as claimed in Claim 32 wherein the step of introducing gas includes introducing carbon dioxide gas into the medium before the medium enters and moves in the tubular passage.

34. A method as claimed in Claim 32 or 33 wherein the step of introducing gas to the medium is performed at a processing station through which the microorganism bearing medium is circulated and from which medium flows into the passage and into which the medium after having passed through the passage and its return passage is returned, the step of introducing gas being performed in a treatment zone of the processing station by bubbling carbon dioxide in fine bubbles into the medium within the treatment zone.

35. A method as claimed in Claim 34 wherein the step of bubbling carbon dioxide in fine bubbles into the medium within the treatment zone is performed by a sparging member having raised-edge perforations through which carbon dioxide gas bubbles are introduced into the medium, the sparging member or plate being vibrated (e.g. by a piezoelectric or magnetostrictive transducer mechanism associated with the sparger) at a frequency to promote the ready release of carbon dioxide bubbles from the perforations enabling smaller or microbubbles to be generated.

36. A method as claimed in Claim 35 wherein the sparging member or plate is vibrated at a sonic frequency to promote release of carbon dioxide bubbles.

37. A method as claimed in any one of Claims 33 to 35 and further including the step of releasing waste gas from the medium performed at a waste release zone of the processing station, wherein the waste release zone is located where the medium and microorganisms therein return from the passage and enter the processing station and is both upstream of the treatment zone where carbon dioxide gas is introduced into the medium and upstream of the zone where harvesting of the microorganisms occurs.

38. A method as claimed in Claim 37 wherein at the waste release zone there is performed a fluidising step in which the medium and microorganisms therein are agitated by an agitator which reduces viscosity of the medium or dethixotropises the medium and thereby promotes the release of gaseous waste (oxygen) from the medium into the gas body above it.

39. A method as claimed in Claim 38 wherein the step of moving the medium along the passage comprises impelling the medium by an impeller at the processing station which propels the medium into which nutrient gas has been introduced at the processing station in a manner to promote laminar flow of the medium along the passage, and wherein the impeller and the agitator are coupled together so as to operate synchronously, and wherein the

agitator has a vigorous action upon the medium and the impeller has a gentler impelling action.

40. A method as claimed in any one of Claims 32 to 38 wherein a gas phase exists within the closed passage above the level of the carrier medium, the gas phase within the passage accepting oxygen from the photosynthetic process in the medium below which oxygen is progressively collected in the treatment zone along with microorganisms for recovery and processing.

41. A method as claimed in any one of Claims 33 to 40 wherein the processing station includes a harvesting zone in which microorganism bearing medium is sparged with a flow of harvesting gas through a harvest sparger, the flow of harvesting gas promoting froth flotation and concentration in the froth of microorganisms, the sparging gas being taken renewably from that immediately above the medium in the processing station and typically comprising an oxygen and carbon dioxide mixture of around a 90:10 ratio, together with lesser component gases such as water vapour and nitrogen.

42. A method as claimed in Claim 41 wherein the harvest sparger is vibrated at a suitable power level and/or frequency by a transducer for short time periods, preferably less than 60 seconds per day in total, so as to limit adverse effects on the microorganisms so that the vibration serves to clean the harvest sparging member and immersed surfaces within the processing station.

43. A method of cultivating phototropic microorganisms, particularly microalgae or diatoms, in a bioreactor comprising the steps of:

entraining a culture of the microorganisms in a carrier medium having nutrients therefor and moving the medium along a closed passage at a sufficiently slow speed to enable laminar flow thereof along the passage, the passage having transparent walls through which the culture is irradiated to enable photosynthesis;

effecting convective turnover of the culture and medium as they flow along the passage by differentially heating the medium laterally relative to the flow direction so as to produce a generally helical flow of the culture and medium;

providing process parameter control means associated with the passage; and

selectively varying the process parameter control means to thereby selectively control parameters or conditions of the cultivation and photosynthetic activity of the microorganisms moving within the passage and the processing centre.

44. A method of cultivating phototropic microorganisms, particularly microalgae or diatoms, in a bioreactor comprising the steps of:

entraining a culture of the microorganisms in a carrier medium having nutrients therefor and moving the medium along a closed passage having transparent walls through which the culture is irradiated to enable photosynthesis, the transparent walls having multiple bands or strips or ribbons of material having PAR attenuating properties relative to the transparent walls between successive bands, the bands, strips or ribbons extending generally transverse to the direction of flow of the medium, whereby the bands, strips or ribbons, their effective width

and their relative placement define the width and separation of the alternating zones of relatively higher and relatively lower insolation within the passage;

providing process parameter control means associated with the passage; and

selectively varying the process parameter control means to thereby selectively control parameters or conditions of the cultivation and photosynthetic activity of the microorganisms moving within the passage.

45. A method as claimed in Claim 44 wherein the microorganism bearing medium is moved through the alternating zones of relatively higher and relatively lower insolation so that microorganisms are exposed to PAR in a pulsed manner, preferably with the duration of each complete cycle of higher and lower PAR exposure being less than one second and preferably with somewhat greater recovery time of relative darkness than the PAR exposure time of each cycle whereby radiation can most efficiently be photosynthesised by microorganisms and reducing the likelihood or effect of photoinhibition.

46. A method as claimed in Claim 44 or 45 wherein the bands, strips or ribbons are composed mainly of photovoltaic (PV) material electrically connected whereby incident solar radiation can be utilised by the PV material to generate electricity for use in performing the method or for use in associated operations (or for sale) and, in the zones intermediate between successive bands, strips or ribbons, the incident radiation can be used in photosynthesis by the microorganisms.

47. A method of cultivating phototropic microorganisms, particularly microalgae or diatoms, in a bioreactor comprising the steps of:

entraining a culture of the microorganisms in a carrier medium having nutrients therefor and

moving the medium along a closed passage having transparent walls through which the culture is irradiated to enable photosynthesis, the transparent top surfaces having externally thereof multiple bands or strips or ribbons having PAR shielding properties relative to the transparent areas between successive bands or ribbons, the bands or ribbons extending generally transverse to the direction of flow of the medium, whereby the bands or ribbons, their effective width and their relative placement define the width and separation of the alternating zones of relatively higher and relatively lower insolation within the passage, and wherein the bands or strips or ribbons are provided by bodies having shapes or configurations that are thermally responsive so as to provide relatively greater area to intercept incident radiation upon being heated significantly.

48. A method as claimed in Claim 47 wherein the bodies comprise curled or rolled bands, strips or ribbons of material having the property of progressively uncurling or unrolling upon exposure to a threshold temperature and higher temperatures by incident radiant energy.

49. A method as claimed in Claim 48 wherein exposure of the curled or rolled bands, strips or ribbons to a threshold heating effect of insolation commences uncurling by utilising differential thermal coefficients of expansion of different materials forming part of the material, thereby reducing excessive insolation that would otherwise enter the medium.

50. A method as claimed in Claim 47 wherein the bodies are movable from retracted positions towards extended positions in which they present greater horizontal surface area to incident radiation and hence greater interception of incident radiation upon exposure to a threshold and higher temperatures by incident radiant energy or increasing ambient temperature.

51. A method as claimed in Claim 50 wherein the bodies comprise wings and wherein exposure of the bodies to the threshold temperature commences raising of the wings from retracted positions towards their extended positions by utilising differential coefficients of expansion of different materials forming mountings of the wings, thereby reducing excessive insolation and heat that would otherwise enter the medium, and conversely, when lower insolation or ambient temperatures cool the mountings, they lower the wings towards their retracted positions, allowing more light and heat to the medium.

52. A method of performing processing operations on a flowable feed material, the method comprising the steps of:

flowing the feed material from an initial level down a confined path or drill hole which descends underground by a substantial vertical distance to a working depth so that the pressure experienced by the feed material at that working depth is substantially greater than the initial level;

providing working conditions for the flowing feed material at the working depth to utilise the relatively high pressure in performing the processing operations on the feed material; and

returning the flowable feed material by a return passage having undergone the processing operations at the working depth from the working depth at least a substantial vertical distance away from the working depth so as to conduct further processing operations on the reaction products within the flowable media.

53. A method as claimed in Claim 52 wherein the processing operations carried out on the flowable feed material include at least one physical change of the flowable medium and reactants therein, said physical change being brought about by the effects of the pressurisation of the feed material descending from the initial level to the working depth as well as the working conditions provided at the working depth which include conditions to effect mixing, decavitation, and depressurisation.

54. A method as claimed in Claim 53 wherein the reactants comprise microalgae or diatoms from which valuable substances are to be recovered, the method comprising the steps of:

flowing a slurry of the microorganisms, flowable medium and gases from a ground surface level down the path to the working depth so that the pressure at that depth is substantially greater than at the ground surface level whereby the microorganisms are exposed to substantially increased pressure and osmotic gas transfer into their cells but without incurring the cost of active pressurisation and subsequent depressurisation;

providing conditions at the working depth to utilise highly-localised decavitation energy and rapidly changing pressures by means of choking and decompression as a result of ascent in the fluid column to induce lysis of the microorganisms; and

returning to the ground surface level the slurry of lysed microorganisms and substances released by the lysis for processing and separation of released valuable substances.

55. A method as claimed in claim 54 wherein the step of providing conditions to induce lysis comprises flowing the slurry in a closed and profiled passage or loop, typically formed by a profiled pipe within an outer pipe, with a series of expansion and compression zones where the partly gas-bubble-filled microorganism slurry undergoes abrupt pressure changes thereby inducing lysis of the microorganisms via ruptures of cells and vesicles caused by explosive decompression and the microimplosions and microjets resulting from decavitation.

56. A method as claimed in claim 55 wherein the passage has multiple restrictions arranged in series so that the slurry passes through the restrictions sequentially, each of the restrictions being followed in the flow path in the passage by an abrupt increase in cross-sectional area of the passage to thereby define the respective expansion zone of relatively lower pressure.

57. A method as claimed in claim 56 wherein the passage or bore descends underground by at least 100 metres for pressurisation sufficient for a microorganism lysis process.

58. A method as claimed in any one of Claims 52 to 57 wherein the processing operations include chemical reactions induced to occur within the flowable feed material, the chemical reactions being initiated, caused, accelerated, or enhanced as a result of the increase in pressure to which the feed material is subjected in descending from the initial level to the working level or experienced at the working level.

59. A method as claimed in Claim 58 wherein the path comprises a passage or bore which descends underground by at least 100 metres, and preferably by some thousands of metres, so that the pressure in the fluid at that depth is of the order of 1,000 atmospheres, and wherein the feed material comprises a heated mixture of reactant fluids (typically heated via heat exchangers located on the ground surface level) which are entrained typically as bubbles in a fast moving, catalyst bearing high boiling point liquid such as residual fuel oil as carrier, and at the working depth in the passage or bore there is generated methanol from stoichiometric volumes of methane, steam, oxygen and carbon dioxide.

60. A method as claimed in claim 59 wherein the methane is sourced from anaerobic digestion of algal cell walls from the processing of microorganisms, or from waste material, or from hydrocarbon deposits, and wherein the oxygen is sourced from photosynthesis by microorganisms.

61. A method as claimed in Claim 58 wherein the chemical reaction comprises synthesis of a syngas comprising a mixture of carbon monoxide (CO) and hydrogen (H_2), the feed material comprising bubbles of a mix of oxygen and carbon dioxide and steam in an aqueous slurry if carbon based substances including carbon based substances, and wherein the slurry at least upon reaching the working level achieves supercritical water conditions.

62. A method as claimed in Claim 61 wherein the slurry being flowed down the path from the initial level includes a proportion of gaseous material wherein pressurisation of the slurry as it flows downwardly to the working level is compressed and the slurry thereby experiences adiabatic heating.

63. A method as claimed in Claim 61 or 62 wherein the carbon based reactants include micro-organisms or diatoms which have undergone lysis so as to release lipids which have been recovered and removed therefrom.

64. A method as claimed in Claim 58 wherein the chemical reaction comprises a Haber ammonia synthesis and wherein feed material include suitable catalyst substances added to the reactants to promote the Haber process.

65. A method as claimed in Claim 58 wherein the chemical reaction comprises a Fischer-Tropsch alkane synthesis and wherein feed material include suitable catalyst substances added to the reactants to promote the Fischer-Tropsch process.

66. A method as claimed in Claim 65 wherein the reactants comprise syngas derived from the method as claimed in any one of claims 61 to 63 and wherein the production of syngas is carried out at a first working depth, and wherein the Fischer-Tropsch synthesis is carried out at a substantially deeper second working depth to which the products from the syngas synthesis are flowed downwardly to increase the working pressure in the flowable medium suitable for the Fischer-Tropsch process.

67. A method as claimed in any one of Claims 64 to 66 wherein the reactants and catalysts are entrained in an oil carrier medium and small bubbles therein provide surface conditions for the chemical processes to progress.

68. A method as claimed in Claim 66 wherein the heat from the exothermic reactions is transferred to raise the temperature of feed material flowing downwardly to undergo the chemical reaction at the working level, the feed material being heated comprising at least one of:

- the feed material in the method as claimed in Claim 54 to undergo lysis of the micro-organisms,
- the feed material in the method as claimed in Claim 59 flowing down in the path to undergo the chemical reaction producing methanol,
- the feed material in the method as claimed in Claim 61 flowing down the path to undergo the syngas synthesis process,
- the feed material in the method according to Claim 64 flowing down in the path to undergo the Haber reaction,
- the feed material in the method according to Claim 65 flowing down in the path to undergo the Fischer-Tropsch reaction.

69. A method as claimed in any one of Claims 54 to 57 wherein the slurry comprising the aqueous carrier medium and the lysed micro-organisms resulting from the reaction at the working level includes lipids released upon lysis of the micro-organisms, the method including the further steps of separating or at least concentrating the lipids by gravitational or centrifugal separation, and reacting the lipids in a transesterification reaction conducted under controlled temperature and pressure conditions at a predetermined level in the underground facility where moderately elevated pressures are experienced sufficient for the transesterification reaction.

70. A method as claimed in any one of Claims 52 to 69 wherein the steps of the method are at least partially

performed underground in a deep drill hole so that the elevated pressures experienced by the flowable feed material comprising flowable medium and reactants result from the ambient pressure experienced at substantial depths below ground surface level, the depth of the drill hole preferably being at least 100 metres and most preferably being in the range of from 1,000 to several thousand metres.

71. A method as claimed in Claim 70 wherein heat for promoting the processing operations carried out at depth is in part derived from elevated temperatures of the ground in which the deep drill hole is provided.

72. A method as claimed in Claim 71 wherein the deep drill hole is provided at a hot fractured rock geologic formation utilising at least one deep drill hole created to access the hot rock formations deep below ground surface level, the processing operations being carried out within processing apparatus lowered from ground level into the deep drill hole to the required depth for achieving the desired temperature and/or pressure conditions for the respective processing operations.

ABSTRACT

Described are methods of cultivating phototropic microorganisms, particularly microalgae or diatoms, in a bioreactor by entraining a culture of the microorganisms in a tenuous, gelated, thixotropic carrier medium having nutrients therefor and moving the medium along a passage at a sufficiently slow speed to enable laminar flow which in cross section is closed and which has transparent walls through which the culture is irradiated to enable photosynthesis. The method includes effecting convective turnover of the culture and medium as they flow along the passage by differentially heating the medium laterally relative to the flow direction so as to produce a generally helical flow of the culture and medium. Also described are processing methods, both physical and chemical, performed underground e.g. in drill holes, to utilise ambient elevated pressures, including processes to implement lysis of the micro-organisms, producing methanol, syngas synthesis, Haber ammonia synthesis, and Fischer-Tropsch reactions.