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Control Laws of Photosynthetic Compartment. Biomass Light Studies

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I. INTRODUCTION

Development of the most appropriate control system for the IV compartment of the MELISSA loop requires a thorough knowledge of the behaviour of the compartment under different culture conditions. This knowledge is expressed in the form of a mathematical model that allows foreseeing the biomass behaviour under certain culture conditions. During the previous studies for this compartment, a model has been developed and validated under different conditions.

One of the important parameters of the model developed is the one describing the volume of the bioreactor that is under illumination. This volume, usually known as the working illuminated volume (WIV), is expressed as a percentage of the total bioreactor volume (TV). During previous high dilution rate tests a value of the WIV corresponding to 52% was used. During the simulation of the previously performed tests a discrepancy among the simulated biomass steady state values and the measured ones appeared. One possible explanation suggested the possibility that the WIV might be different under different light intensities. The reason was due to the fact that for high light intensities, part of the light flux might enter the non illuminated volume, while under low illumination levels, light would only penetrate the culture on the area located directly in front of the lamps. This is a variation, difficult to quantify 'a priory', that may have an important influence on the observed performance. It was decided that to be able to properly assess the values of other parameters in the model, some tests were needed were the WIV was equal to the TV and therefore the value of the WIV would not change in different illumination conditions. By this way the proper validation of the model, under conditions were the total volume is the illuminated volume can be done by Clermont Ferrand laboratories.

Therefore the purpose of the first part of this tests is to evaluate the biomass performance in the bioreactor currently used when the WIV is equal to the TV.

The first version of the mathematical model already developed was incorporated as a part of the control software being developed by ADERSA. It is necessary therefore to test the performance of this control software and evaluate the possible modifications required. This is the purpose of the second part of this technical note were three different productivity values are tested allowing to evaluate the performance of the control system.

II. PART I

WORKING ILLUMINATED VOLUME EQUAL TO TOTAL VOLUME TEST.

As explained previously, the culture behaviour in the airlift bioreactor had to be tested in conditions were the working illuminated volume was the same as the total volume. To achieve this purpose, the liquid level of the bioreactor was lowered to the cylindrical glass part of the bioreactor, so that TV=WIV. The bioreactor volume thus reached was 4.25 litters, instead of the 7 litters used in previous tests. It must be mentioned that the illuminated part of the volume in normal conditions is not 4.25 but 3.69 litres due to the fact that, to allow proper agitation, the internal draft tube had to be removed. Being the internal draft tube higher than the illuminated part of the bioreactor filled, its presence impaired agitation.

The decrease in volume forced to operate the bioreactor without using the probes that are located on the top part of the bioreactor. Therefore the pH, biomass sensor (Monitek), oxygen and liquid sampling (TechSep) probes had to be removed. Lack of the pH probe forced to maintain the pH by using a constant current of CO_2 gas, that was regulated manually daily, using the pH value measured off line, from the daily obtained samples. Bioreactor liquid level volume was maintained by means of the level of the output tube.

In these conditions different tests were done for two different flow rates and two different light intensities for each of the flows.

II.1 Test 1

In this test the dilution rate of the bioreactor was set at 0.035 h^{-1} (residence time 28.6 h). Light intensity was set at 75 % of the controller action which corresponded to a calculated value of the light intensity (Appendix 1) at the bioreactor surface (Fr) of 133 W/m^2. After setting up these conditions the total biomass concentration level was followed by measuring the dry weight. The biomass concentration reached a steady state at a level of 1.3 kg/m^3 (figure 1). At this point, light intensity was increased by means of setting the light controller action at 85%. This corresponded to a calculated Fr value of 305 W/m^2.

After 3 residence times biomass stabilised around an average concentration value of 1.85 kg/m^3 of dry weight. Short after having modified the light intensity set point, a power cut resulted in the failure of a light power supply (1/5 of the lamps off). The power cut was restored immediately but replacement of the power supply couldn't take place until a spare one was found one day later. This fact resulted in a slowest acceleration of growth than usual, and delayed the onset of the steady state. However this accident had no effect on the final steady state of biomass concentration reached. The results of these tests are depicted in figure 1.

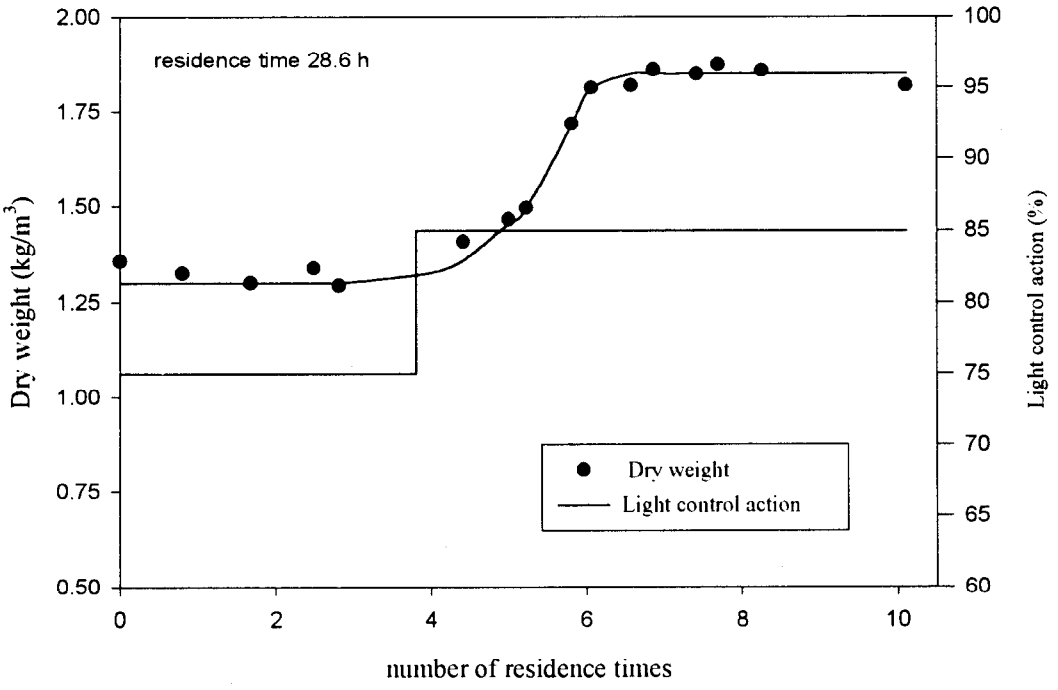

Figure 1: Evolution of the biomass concentration during test 1.

II.2 Test 2

In this test the dilution rate of the bioreactor was set at 0.05 h^{-1} (residence time 20. h). Light intensity was set at 65.69 % of the controller action, which corresponds to a value of the light intensity at the bioreactor surface (Fr) of 50 W/m^2. After setting up these conditions the total biomass concentration level was followed, as in the previous case, by measuring the dry weight concentration of the taken samples. Biomass concentration reached a steady state at a biomass concentration of 0.49 kg/m^3 (figure 2). At this point light intensity was increased by setting the light controller action at 85%. This level corresponds to a calculated Fr value of 305 W/m^2.

After 4 residence times biomass concentration stabilised around a value of 0.98 kg/m^3 of dry weight. The results of these tests are depicted in figure 2.

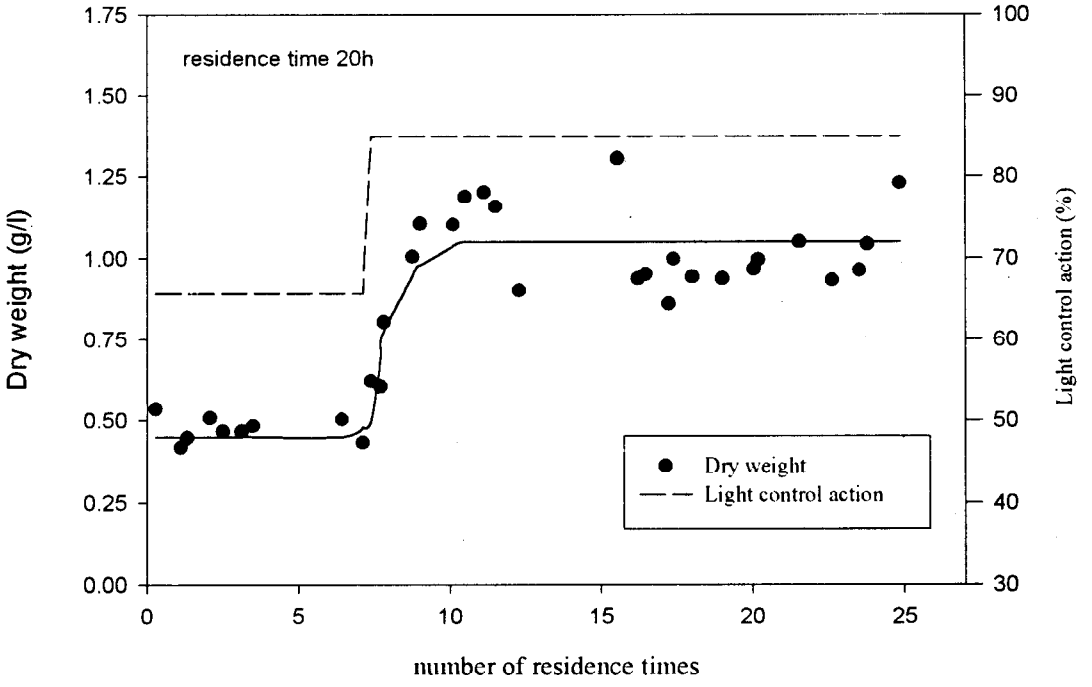

Figure 2: Evolution of the biomass concentration along test 2.

II.3 Discussion of the WIV=TV tests

As explained in the introduction the purpose of these tests is to evaluate the biomass behaviour in conditions were the working illuminated volume is equal to the total volume. These tests should allow to evaluate if the correction applied in the mathematical model (a factor of 0.52) accounting for the effect of the non illuminated volume on the biomass produced is applicable in all conditions, or if alternatively, this factor should be a variable due to the fact that in conditions of low biomass concentration and high illumination conditions the illuminated volume could be higher as some light might enter the non illuminated volume. This fact implies that the biomass concentrations obtained could be higher than expected.

In the first part of the test, the flow rate and light intensity used were the same as the ones used for the second part of the high dilution rate tests previously done (Vernerey 1996, TN 25.110). It must be mentioned that due to the re-calibration of the bioreactor light availability levels with a commercial light sensor, the values stated in this technical note differ from the ones stated on TN 25.110. However the light supplied to the bioreactor is the same as the voltage applied to the lamps is the same. Therefore the two experiments are comparable.

One simplified way to explain the behaviour of the cells in the bioreactor might be as follows. In a light limited continuous culture, cell concentration increases up to a level were the light energy consumed by the cells allows to sustain a biomass growth equal to the amount of biomass leaving the bioreactor in the output flow per unit time. Once this point is reached the biomass concentration in the bioreactor remains constant, and therefore growth rate equals the dilution rate. It can be also assumed that, for the same organism, the amount of light energy consumed by the cells to produce a certain amount of biomass per unit time is fairly constant at the same culture conditions (dilution rate, pH, temperature,..). At a higher growth rate the energy consumption per unit time is higher. Therefore given a certain photosynthetic organism and culture conditions, the cell concentration that will be obtained will depend on the efficiency of our culture device to supply the necessary light energy.

Given certain illumination geometry and light intensity, the amount of energy supplied to a certain illuminated volume per unit time is constant. Also the energy collected by one cell depends either on the time it remains in that volume and the concentration of other cells in that volume that shield part of the energy available to that cell. Simplifying, one can imagine the amount of energy a cell has to collect per unit of time as a certain amount of photons. Therefore, if we assume that for a certain growth rate a cell has to collect a certain amount of photons per unit time, it follows that, in a steady state continuous culture, the cell concentration will equilibrate at a level that allow to collect that energy in the time the cells remain inside the illuminated volume. Addition of a dark volume to the bioreactor will decrease the average time a cell remains in the light flux due to the average time it spends in the dark area. The average time a cell spends in the illuminated area will decrease in the same proportion as the illuminated volume decreases with respect to the total volume. As in the steady state the amount of cells grown are equal to the cells leaving the bioreactor, being the growth rate equal to the dilution rate, and the energy required per unit time for the same growth rate is the same, it follows that if the non illuminated volume increases, the cell concentration has to decrease in the same proportion so as to allow the collection of that energy per cell in less time.

In the first experiment in this series an average concentration of 1.3 grams per litre of biomass have been obtained for the low light intensity and 1.85 grams per litre have been obtained at high light intensity. These concentrations have been obtained using an illuminated volume of 4.25 litres, which is also the total volume. In the equivalent experiment done in TN 25.110 the illuminated volume is only of 3.69 litres, due to the volume taken up by the internal glass tube and its support, and the total volume of the bioreactor is 7 litres. Light flux crossing this decreased volume is however the same because the light intensity and illuminated surface areas are the same (The decrease in volume is due to the addition of the glass tube). Therefore the quantity of energy available to the cells per unit time and unit volume is the same than in the previous case.

If this decreased volume were the total volume, the concentration of biomass reached in this smaller volume would be, however, the same because the available energy in one unit of volume is the same. However the 3.69 litres of volume are only 52.7 % of the total volume (3.69/7) and therefore one can assume (in a well agitated bioreactor) that this biomass will remain only 52% of the time in the illuminated volume.

Consequently in a first approximation one can assume that the biomass concentration will be only about the 52% than the one that should be found if the total volume were the illuminated volume. In this case the concentrations that would be obtained in the bioreactor if filled up to its 7 litres would be 0.685 and 0.974 grams per litre of biomass respectively for the low and high light intensities. The values obtained in TN 25.110 were respectively of 0.66 and 0.9 grams per litre of total biomass.

Therefore if we accept this first calculations, the previously applied correction of 52 % for the effect of the non-illuminated volume to the biomass calculation appears to be correct. The data obtained in that first test as well as the one obtained in the second test and the previous technical note 25.110 can be used to verify the model predictions in those conditions used. Being the best candidate to do this verification the group developing the model at Clermont ferrand.

With respect to the use of the model for control purposes, it would be desirable to fit it so as to give the concentration values found in the bioreactor that is actually used, and the precise culture conditions were it is going to be used, or to provide a way to adapt the predicted values, accordingly to the actual results found. This way any difference found using different bioreactors or culture conditions, and not completely explained by the model, can be taken into account.

III. PART II

TESTS OF GPS CONTROL LAW.

As explained in the introduction the successful operation of the MELISSA loop depends on the proper control of each one of its compartments. The mathematical model previously developed for compartment IV was incorporated in the general purpose station (GPS) control algorithms in order to evaluate, and modify it to adapt its operation to the loop requirements.

Some modifications have been done lately either on the software or the hardware that call for a revision of the accuracy and precision of the GPS operation. The different software modifications done lately were mainly done at the change from version 2.0 to 2.1 (FULGET 1995, TN 24.2) were the changes introduced affected the change in the calculation of the pump action, the decrease in the maximum Fr allowed in the GPS (from 8000 it was decreased to 400), the change in the units (Volume in the bioreactor 7000 ml to 7.0 l, illuminated volume 3900ml to 3.9 l (but note that in Binois 1994 illuminated volume is 3.69 l). Also Ea: 871 and Es :167 in the GPS, however in Cornet 1982 those values were Ea: 813 and Es: 175 ; afterwards those values were modified in TN 19.2 to be Ea: 872 and Es: 200).

After those first modifications the software structure was modified so as to allow operating different compartments at the same time, perform screen graphics, store data, and include a numerical filter for the data read. This software version is the one used in the present tests (Pons 1996, TN 25.5).

With respect to the modifications in the hardware, it has to be mentioned that in first place the lamp in the biomass sensor failed and therefore it had to be re-calibrated to give the appropriate biomass concentration. At this point it appeared a doubt about to which value of biomass (total biomass, vegetative biomass or active biomass) was the most appropriate to calibrate the sensor. The model used in the GPS is an older version than the one used in Photosim. The main difference resides in that in Photosim there is a clear distinction between those different biomass component values, and all of them are calculated, even under nitrate limiting conditions were vegetative biomass increases due to glycogen accumulation. In the GPS however, the vegetative biomass is always calculated to be equal to the active biomass and therefore under nitrate limitation conditions, the vegetative biomass does not increase. Furthermore the amount of exopolyssaccharide concentration is not assumed to change according to the illumination conditions and is taken to be always 20% of the total biomass. The biomass value read from the sensor by the GPS is taken, in that model, to be the total biomass. This implies that model predictions were going to be accurate only in the cases were no glycogen in produced and the EPS content is 20 %. In nitrate limitation conditions and high light intensities were Glycogen and EPS are produced in higher amounts, the model in the GPS will predict lower values than the real ones.

It is clear then that with the model currently used by the GPS is difficult to obtain accurate values of the Fr because the model is only valid in conditions were a total biomass having a 20% of polyssaccharide and no glycogen is the one being measured by the sensor.

Due to these facts, and for the previous tests were the GPS was not used, the biomass sensor was calibrated so as to give active biomass. The reason being that it is the

value that appeared to be more directly related with absorbance values in different cultural conditions, as the EPS content, was supposed not to be measured by the sensor. The EPS content should change in different culture conditions and if it is not measured the relationship among absorbance and total biomass has to be different for different culture conditions. In that case the calibration of the biomass sensor can not be done using a constant value. It must be mentioned however that after the high dilution rate experiments and nitrate limitation test, either the values of the biomass sensor follow more accurately the total biomass readings, that is including EPS, or alternatively it has to be assumed that on those tests the EPS content did not change.

Additionally, the light intensity values available at the bioreactor surface were recently determined using a commercial spherical sensor supplied by Clermont-Ferrand lab (appendix 1). The results of that determination allow to ascertain the values of Fr more accurately and to have a correlation among the voltage applied to the lamps and the Fr. This way it is possible to know the Fr knowing only the value of the light control action. This fact is used later to check for the real values of the Fr calculated by the GPS.

Furthermore some comments have to be done about the GPS calculations such as that the GPS corrects for the temperature variations, using a gauss function (Binois 1994). To our knowledge this model has not been previously verified and therefore it would be advisable to verify first the growth model and in a subsequent step to verify the temperature corrections. For this reason this correction was suppressed during the second part of the GPS tests.

In the following tests, the operation of this control software is tested by means of setting different desired productivity levels on the system station, and allowing the control station to set the light intensity and the flow rate to the required values to reach the desired levels.

III.1 GPS Test A

In this test the biomass production levels were set to a 50mg/h of biomass production using a flow rate level of 0.07 l/h. As explained before the model used in the GPS assumes a constant biomass composition having a 20% of EPS content and no glycogen, probably because this were the conditions of the biomass used when the model was first fitted to experimental data. However the EPS and glycogen content are known to change depending on the culture conditions, and corrections to the model accounting for this fact were already proposed in TN 19.2, which have not been incorporated to the GPS. It follows that for any culture conditions in that the biomass composition is different than the one used to fit that model, the GPS calculations will not be accurate. If a biomass with a higher content of EPS or glycogen evolves during the tests, the biomass and Eb values calculated by the model will probably not be the correct ones. This has been observed to happen.

In a first attempt to converge GPS prediction and reality, the calibration coefficient of biomass was set so as to give 'active biomass' (assuming an EPS content of [redacted]. With this value the Fr values predicted by the GPS from the values of EB and [redacted] biomass were found to be approximately correct (Figure 5 initial 60 hours). In this case it has to be remembered that the values of productivity calculated are of active biomass.

At this point biomass productivity set point was increased to 70 mg/h. The GPS set the Fr value to its maximum allowed level of 400 W/m^2 (figure 5) at the next control period (which takes place every half an hour) and the biomass started to increase. It can

be easily seen that as biomass concentration increases, and while the set point of Fr is maintained at 400 W/m^2, the light control action is slowly decreased and consequently the calculated value of Fr decreases (Figure 5 time 60-110 hours). This response reflects the fact that the Fr calculation fails because as biomass increases and the Fr is calculated to be constant it is in fact decreasing, because light is being decreased by the GPS (figure 5).

After that, a period of about 15h happened were the biomass values collected by the program were not updated until the problem was detected. The problem was solved after re-initialisation of the computer and biomass-measuring device. After a short period of instability, the productivity value was maintained at a slightly lower value than the set point and it was maintained at that level by successive variations of the light intensity levels. As can be seen in figure 4 the strong variations on the light intensity caused an important instability on the temperature values. Temperature changes are known to affect the biomass growth rate and this is taken into account in the program by a gauss function (1994). The flow rate was maintained constant during the entire test (figure 3) as expected.

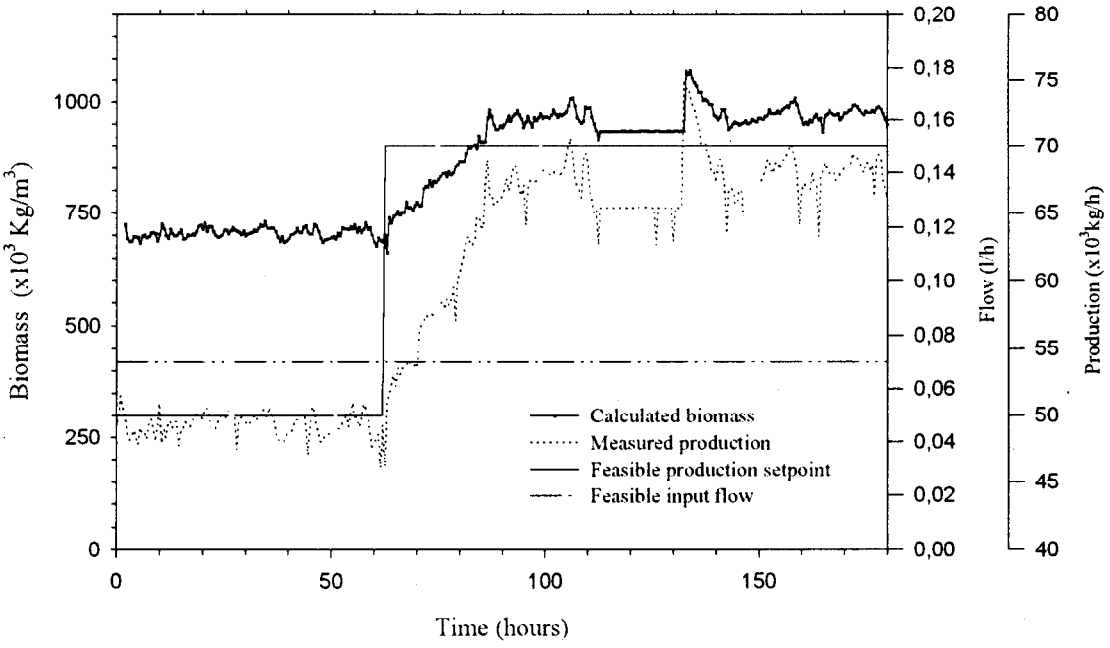

Figure 3: Evolution of biomass concentration, productivity and flow during GPS test A.

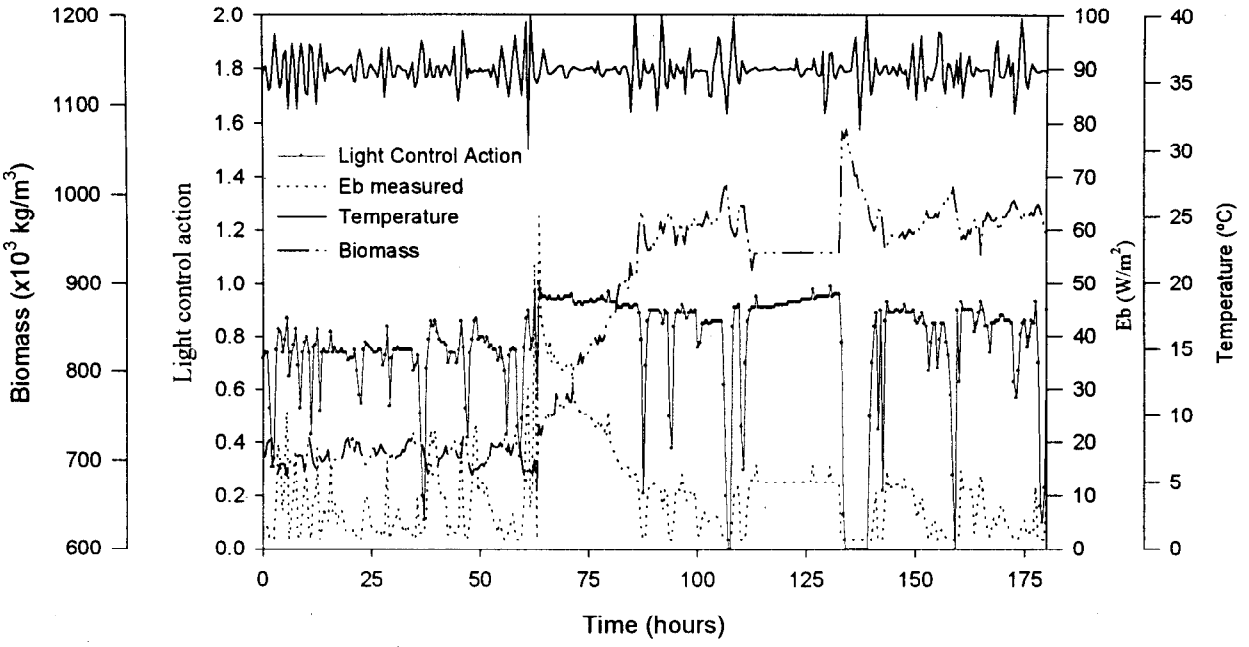

Figure 4: Values of light control action and levels of light measure inside the bioreactor (Eb) during the GPS test A.

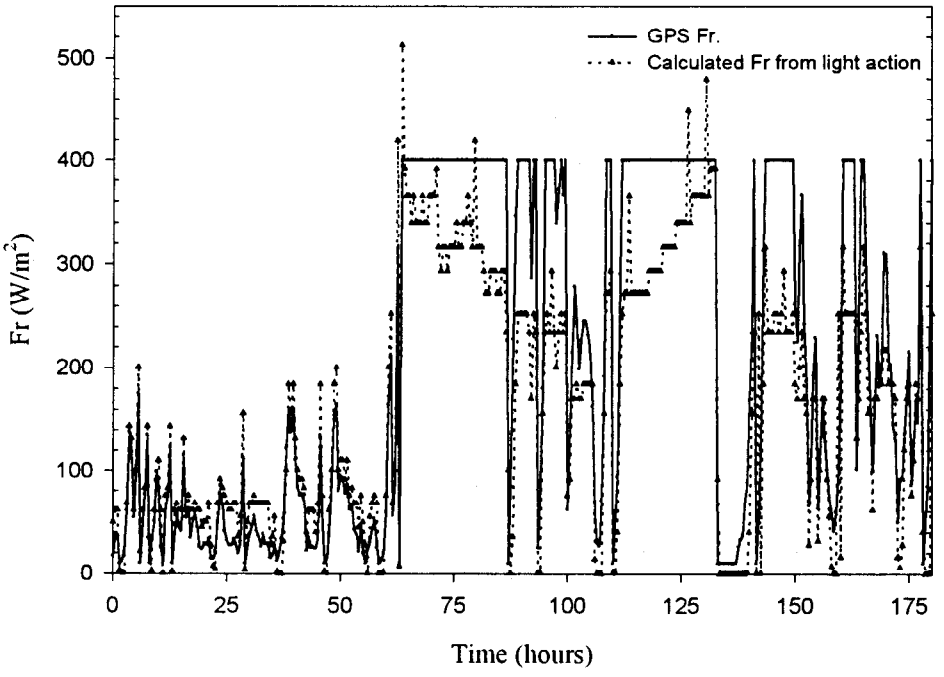

Figure 5: Values of Fr calculated by the GPS and the corresponding values calculated from the light control action according to appendix 1.

III.2 GPS Test B

To continue with the tests, the biomass productivity set point had to be set at a value of 120 mg/h of biomass. The GPS should calculate that this level of productivity could not be attained at the currently used flow (0.07 l/h) and consequently should modify it so as to allow attaining the desired productivity.

In a first attempt, the GPS successfully calculated the new set point of flow (0.78 l/h) and a productivity of 115 mg/h of biomass as the attainable values. Accordingly it proceeded to increase the light intensity to its limit of 400 W/m^2. The biomass increased but, unfortunately, and in parallel to the biomass increase, there was a decrease in the light controller action sent to the controllers, due to the fact that as the biomass increased the calculated Fr was more and more deviated. Therefore although the GPS calculated 400 W/m^2 the real Fr was decreasing and the set point could not be reached.

In order to overcome this problem and to allow the controller to operate, the limit of the maximum of Fr (400 W/m^2) was increased near to the maximum value the variable could contain (32000 W/m^2). This way, although the calculated Fr was mistakenly calculated as being higher that it really was, the controller could drive the biomass to the set point.

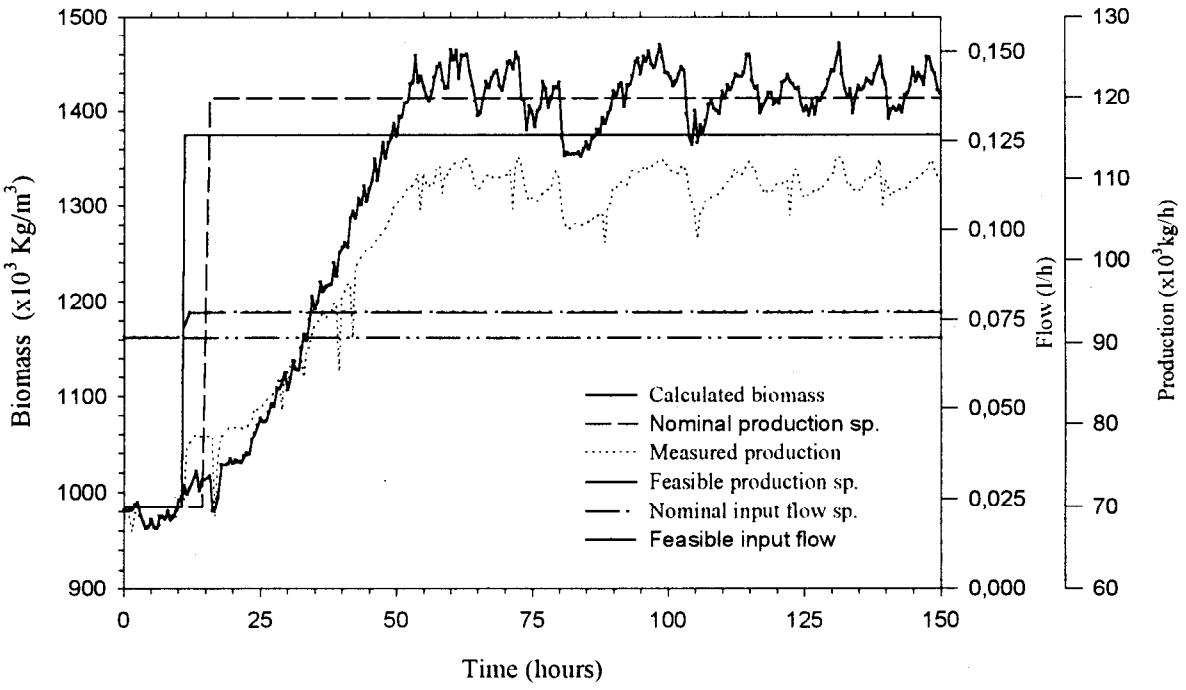

Figure 6: Evolution of biomass productivity, concentration, flow and productivity set points during GPS test B.

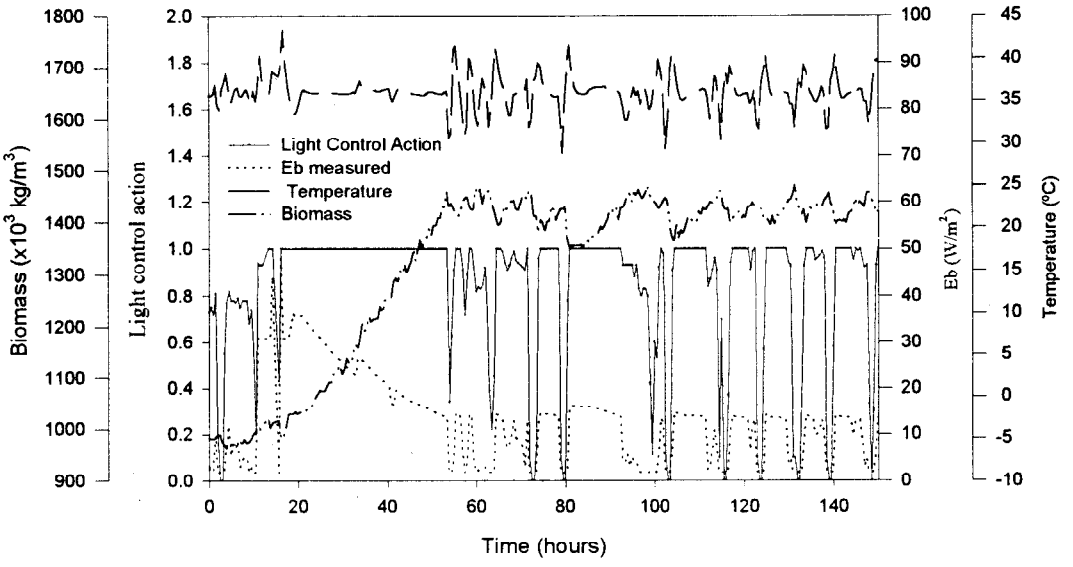

Figure 7: Evolution of light control action and light intensity measured inside the bioreactor during GPS test B.

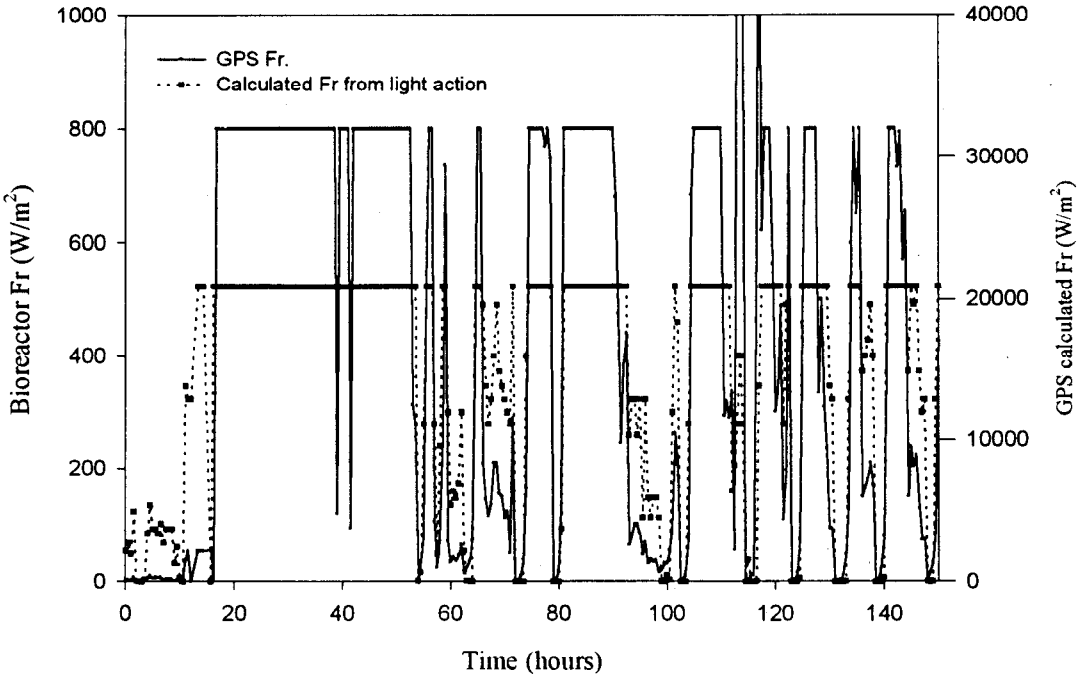

Figure 8: Evolution of GPS calculated Fr and the Fr calculated from the light control action according to appendix 1.

To begin the test, biomass was washed out down to the level corresponding to the productivity reached in the previous test and the set point of productivity reset to the value of 70 mg/h of biomass in order to repeat the test. Once this productivity was sustained the new productivity value of 120 mg/h of biomass was set. Again the GPS correctly calculated the maximum productivity value obtainable of 115 mg/h of biomass at a flow of 0.078 l/h, and set this conditions as the feasible ones (figure 6).

As in the previous case the light measured at the inside of the bioreactor (Eb) decreased in accordance with the increase of the biomass (figure 7). The Fr values calculated by the biomass reached the maximum level, being it much higher than the real values calculated from the value of the light control action (figure 8). This time however the light control action was maintained at its maximum value, allowing the biomass concentration to adequately increase. The biomass productivity set point was reached in about 48 hours. After that point the biomass productivity was maintained at a level slightly under the feasible productivity set point. As can be seen in figure 10 the continuous illumination changes, had a strong effect on the temperature value stability.

III.3 GPS Test C

In the final part of this series of tests the productivity level had to be decreased to a value of 100 mg/h of biomass, and the biomass evolution recorded.

Once the new set point of biomass productivity was set, the GPS calculated that this level of productivity could be attained with the flow rate set point of 0.07 l/h. Therefore it set the feasible flow, set in the previous test at 0.078 l/h to the nominal set point of 0.07 l/h (figure 9).

Light intensity was decreased temporarily (figure 10) so as to allow the biomass concentration to decrease and the new productivity set point was attained in about 24 h. The productivity level was maintained, as in the previous cases at a slightly lower value than the set point, by alternating periods of high light intensity and low light intensity.

As in the previous cases the Fr values calculated by the GPS were higher that the ones calculated from the controller light action. The changes on the illumination conditions affected the temperature values and resulted in continuous oscillations as in the previous tests.

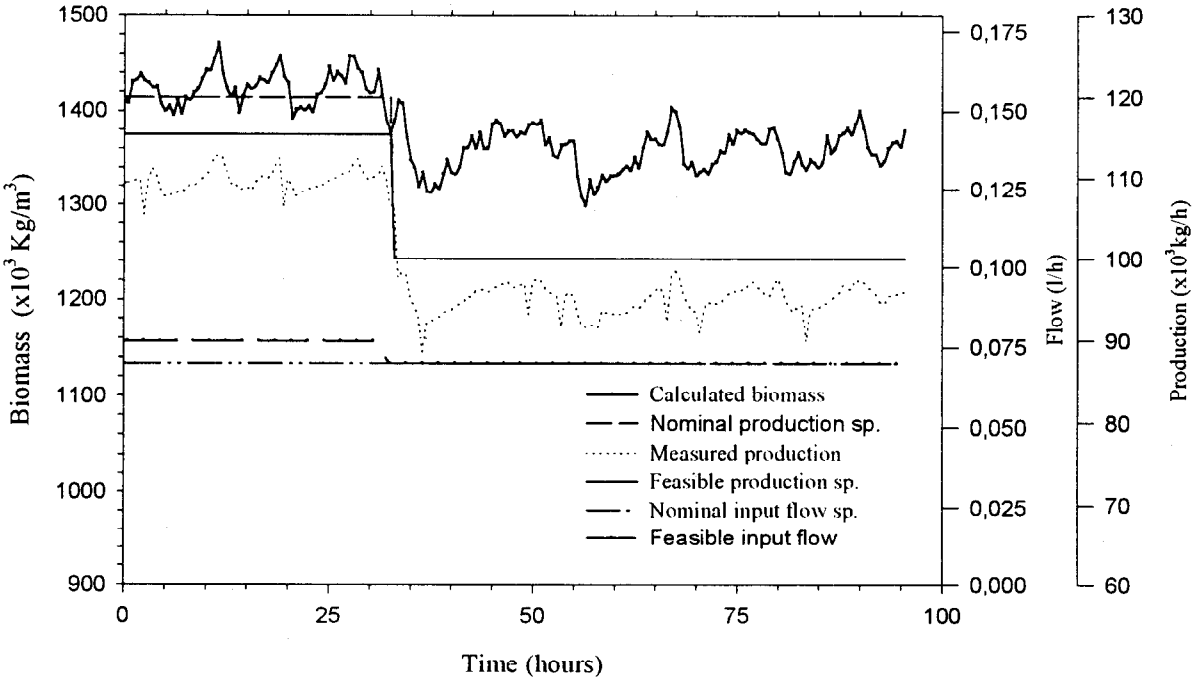

Figure 9: Evolution of biomass productivity, concentration, flow and the corresponding set points during the GPS test C.

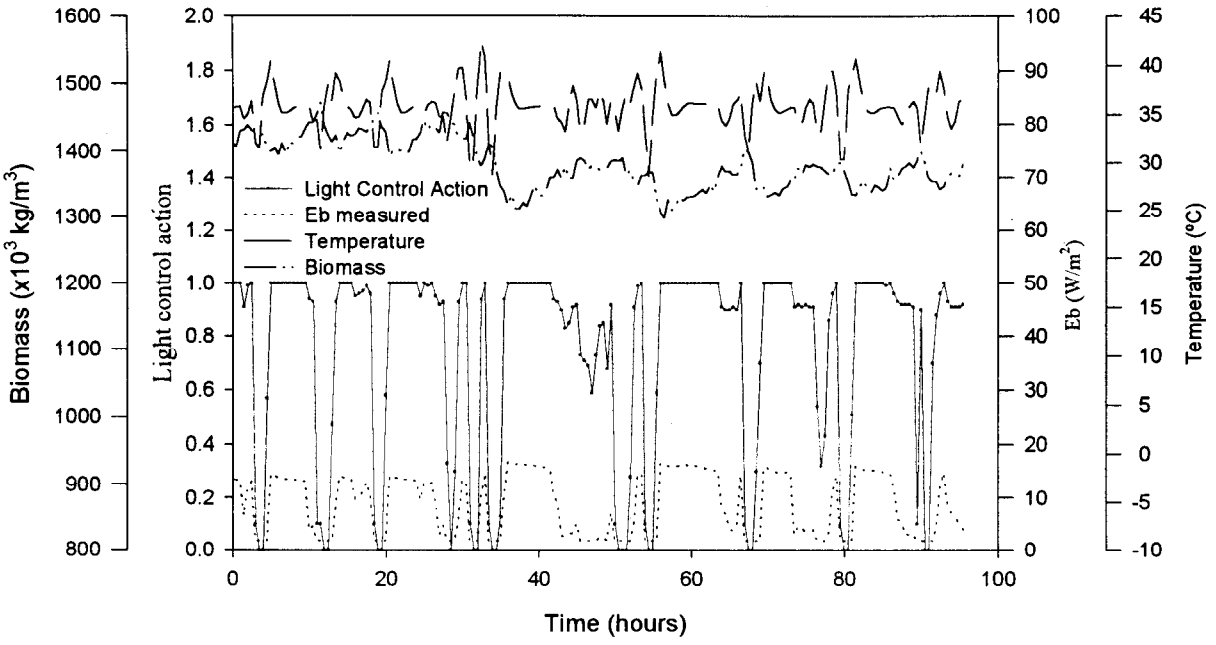

Figure 10: Evolution of light intensity measured inside the bioreactor and of light control action during GPS test C.

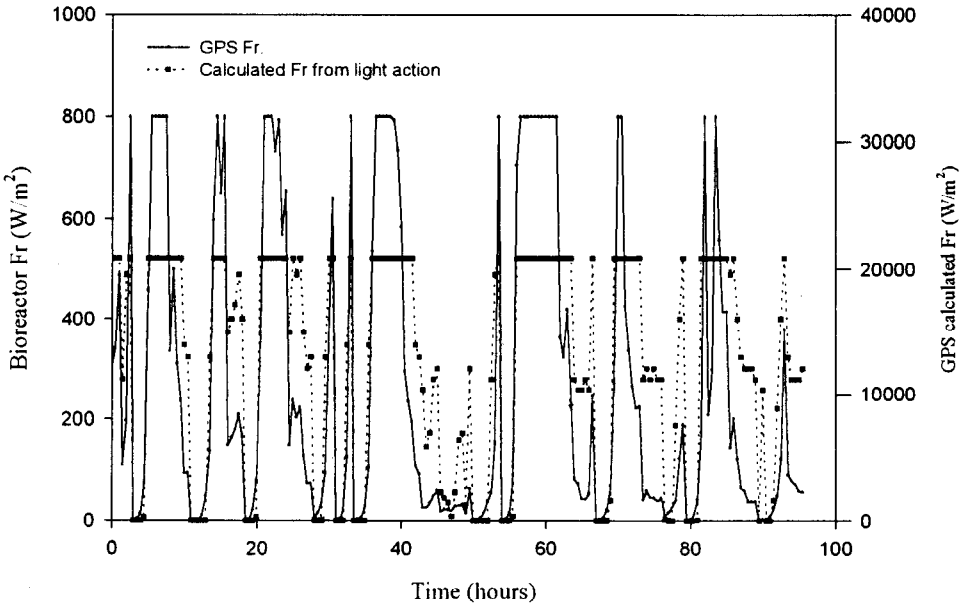

Figure 11: Evolution of GPS calculated Fr and Fr calculated from the light control action, according to appendix 1, during GPS test C.

IV COMPLEMENTARY TESTS

IV.1 GPS Test D

As explained previously and in appendix 1 it was possible to calibrate the Fr available in the bioreactor by using a commercial spherical sensor supplied by the Clermont Ferrand laboratory. The availability of the bioreactor Fr values as a function of the different voltages applied to the lamps allow the calculation of that Fr knowing the action of the light controller and the effect of this action on the voltage given by the power supply. This relationship can be easily incorporated into a mathematical function. The use of this function by the GPS allows to simplify the Fr determination for control purposes and certainly eliminate the Fr determination problems found in previous tests. In order to proceed with this simplification, a new control function, using this simplified method of Fr calculation, was developed by ADERSA, and incorporated in the GPS program. Details and source code of this GPS modification will be given in technical note 37.9.

To proceed with the first of these tests, culture conditions were set as in the previous GPS test A. That is a biomass production set point of 50 mg/h and a flow rate of 0.07 l/h. Once the steady state was obtained, the new set-point was given as in the GPS test A. That is 70 mg/h and the same flow rate. Evolution of the biomass concentration obtained can be seen in figure 12. Evolution of the light control action and the now calculated Fr can be seen in figures 13 and 14.

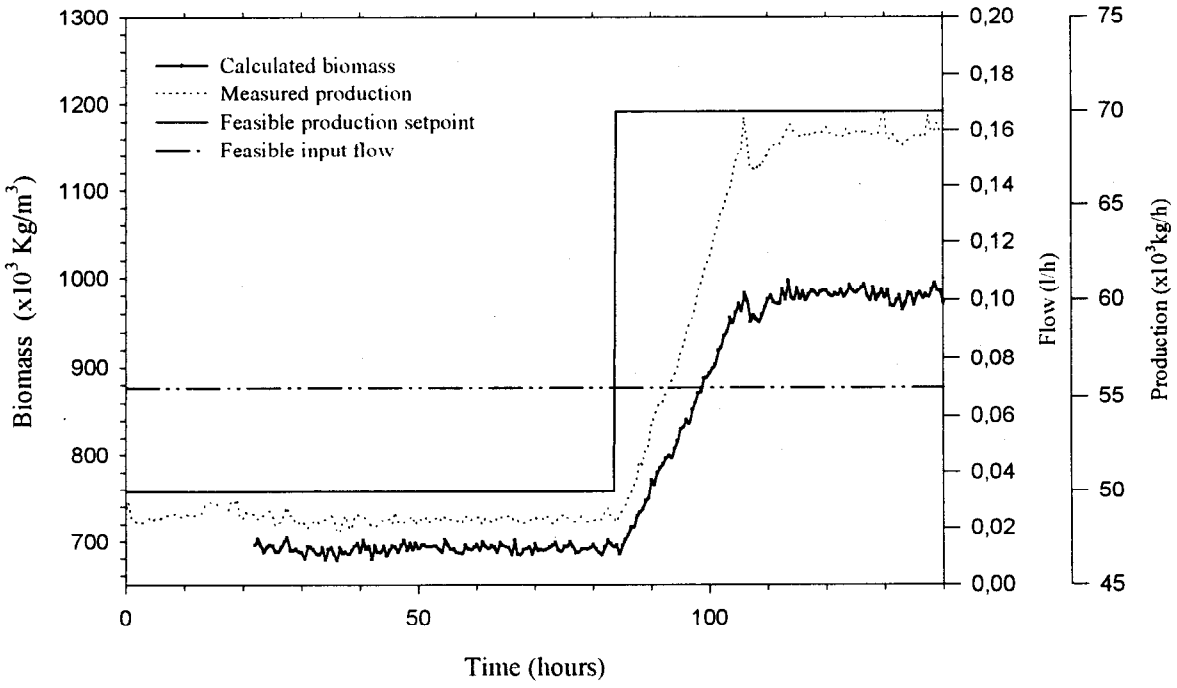

Figure 12: Evolution of biomass productivity, concentration, flow and the corresponding set points during the GPS test D.

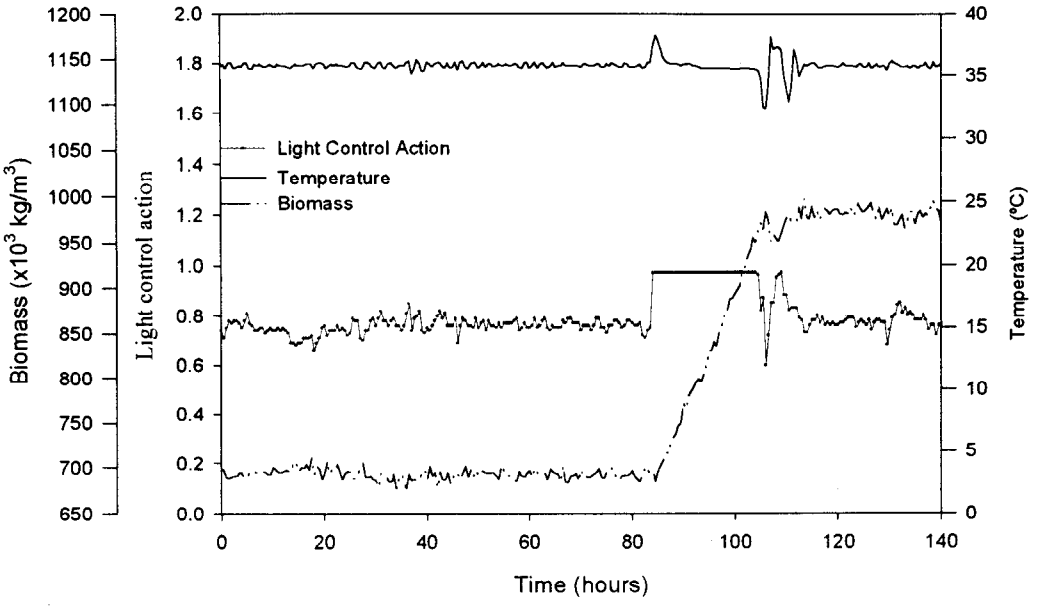

Figure 13: Evolution of temperature. biomass and light control action during GPS test D.

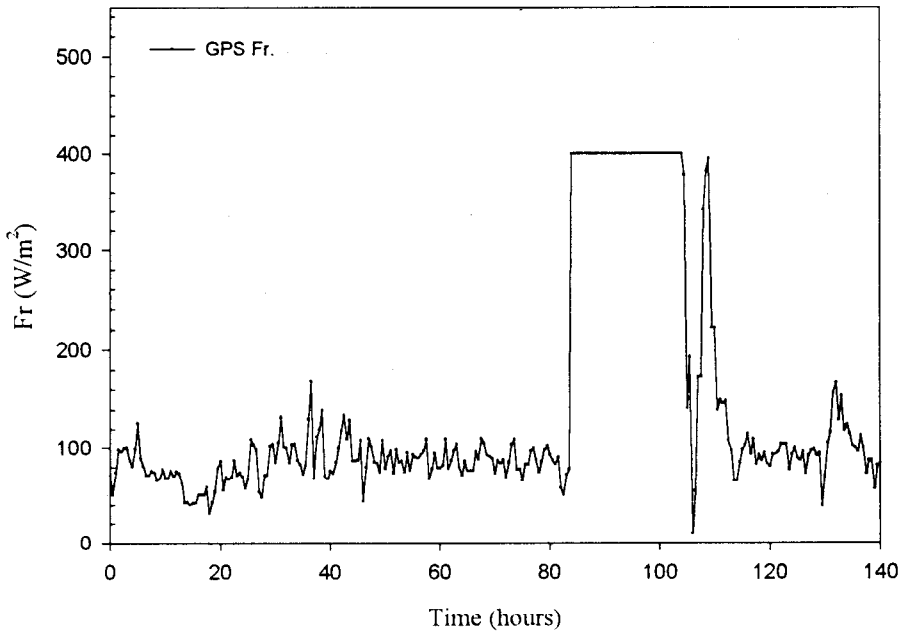

Figure 14: Evolution of GPS calculated Fr. which is calculated from the light control action, according to appendix 1, during GPS test D

IV.2 GPS Test E

In previous tests it has been observed that the obtained steady state productivity, is maintained at a value that is always slightly under the set point. To correct this behaviour a modification in the operation of the control subroutine has been done by ADERSA.

Once installed the new subroutine, the productivity set point was set at a value of 90 mg/h. and the GPS started. As it can be seen in figure 15 after about 24 hours the steady state has been reached and the bioreactor was ready to test the increase in productivity. The new productivity set point value was set at 120 mg/h. The GPS correctly calculated that the new productivity value could be only 110 mg/h and increased the flow rate to 0.78 l/h to be able to obtain it.

After about 20 hours the set point had been reached. However at that point the GPS was accidentally switched on-off a couple of times. During the time it was off the light intensity was too low to maintain the productivity value and the biomass concentration started to decrease. After a short time the GPS was started again and soon it regained the control of the bioreactor driving the biomass again to the required set point. The obtained steady state value appeared to accurately follow the required set point, and therefore that the previous situation had been corrected. At this point the productivity set point was decreased again in order to obtain a lower productivity value (80 mg/h) required for the next test. In this case the GPS also performed correctly its task of driving the biomass to the set point without showing any anomalous behaviour and its operation was considered successful. Evolution of related variables can be seen in figures 16 and 17.

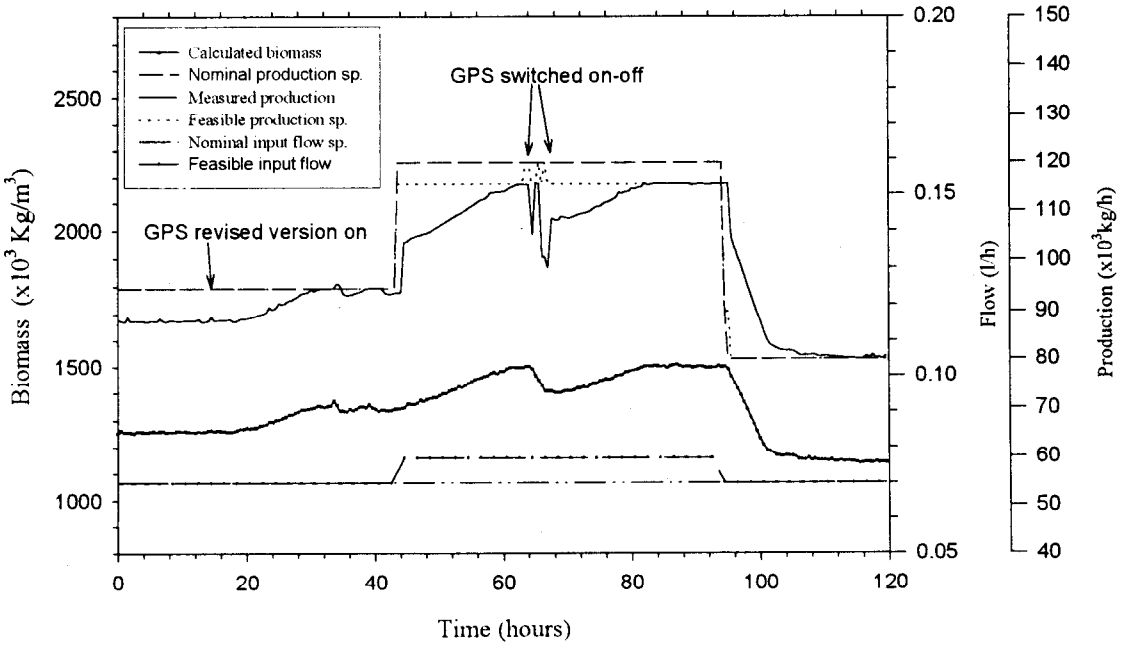

Figure 15: Evolution of biomass productivity, concentration, flow and the corresponding set points during the GPS test E

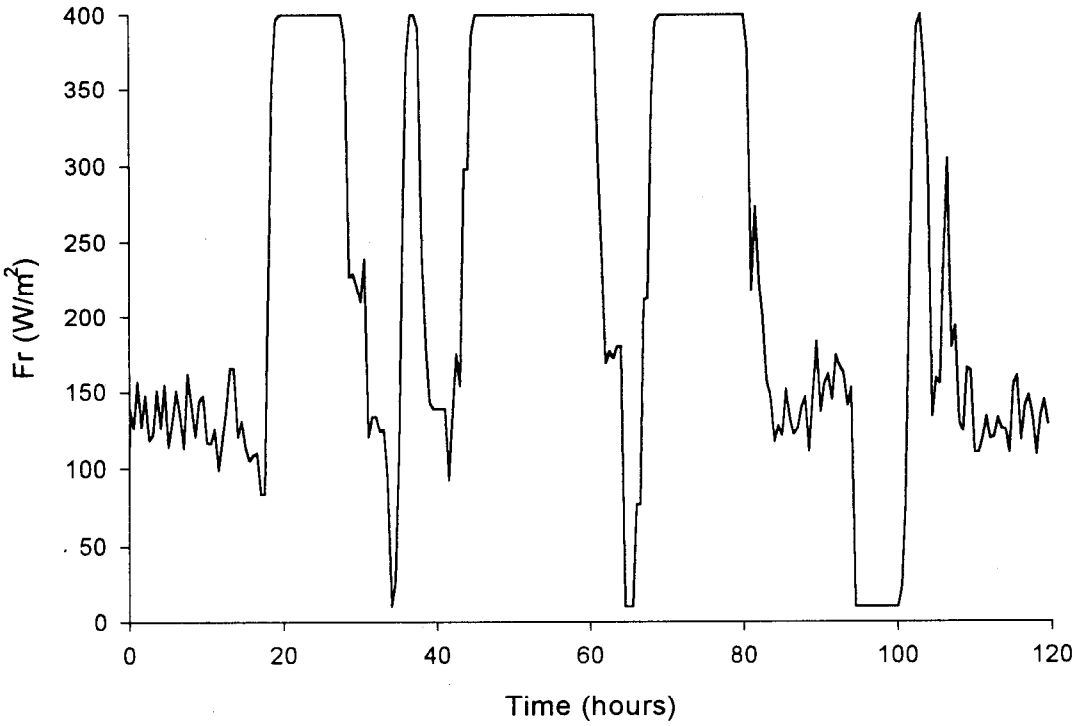

Figure 16: Evolution of GPS calculated Fr, which is calculated from the light control action, according to appendix 1, during GPS test E.

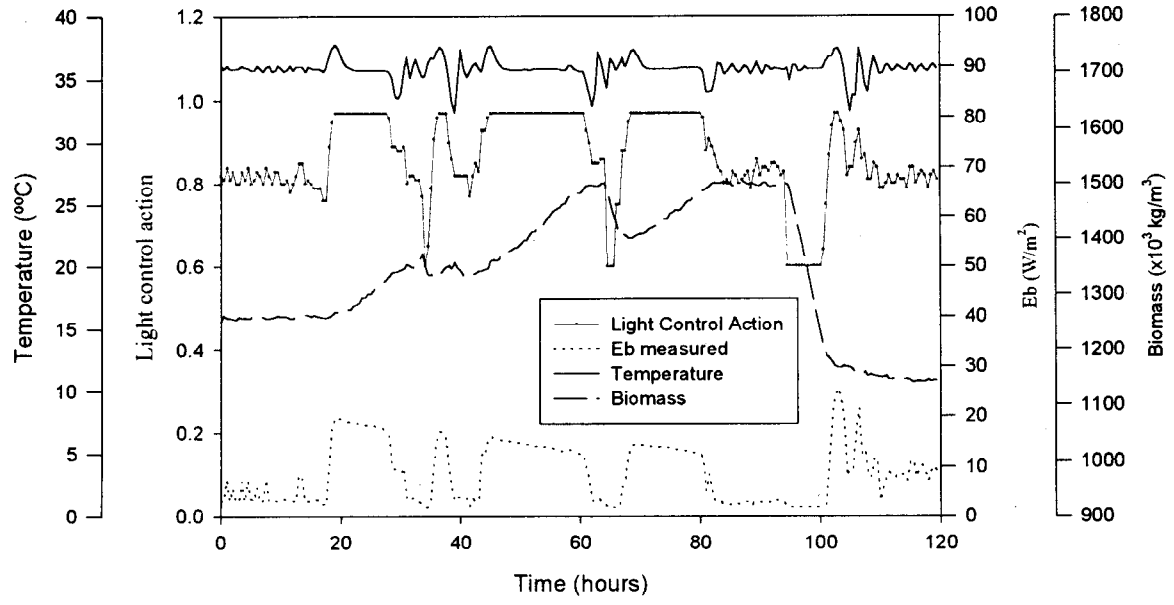

Figure 17: Evolution of temperature, biomass, Eb and light control action during GPS test E.

IV.3 GPS Test F

During the previous tests the value of the biomass concentration has been averaged every 10 minutes before its value was taken for the control action evaluation. It appeared the possibility that the control action could be more stable if averages were taken using a time span for 30 minutes instead of 10 minutes.

To test this possibility the GPS control subroutine was modified again by ADERSA and the resulting code was incorporated to the GPS. For this test productivity set point was set at 80 mg/h and once the steady state was ascertained, a new productivity set point of 120 mg/h was fixed. Evolution of variables followed in this test

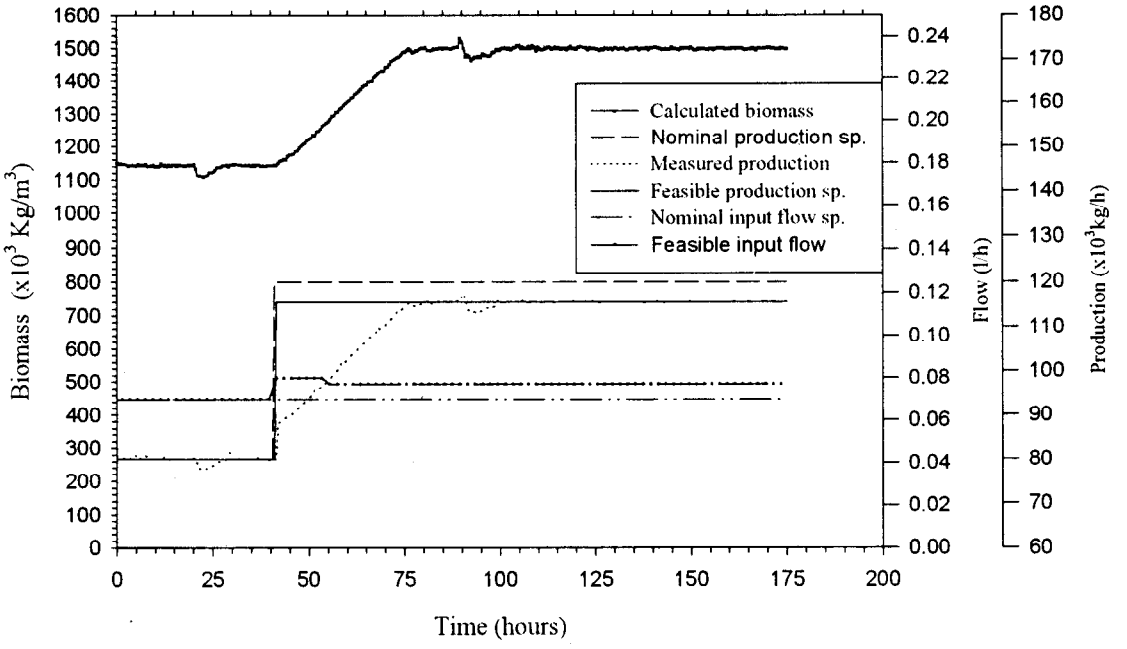

Figure 18: Evolution of biomass productivity, concentration, flow and the corresponding set points during the GPS test F

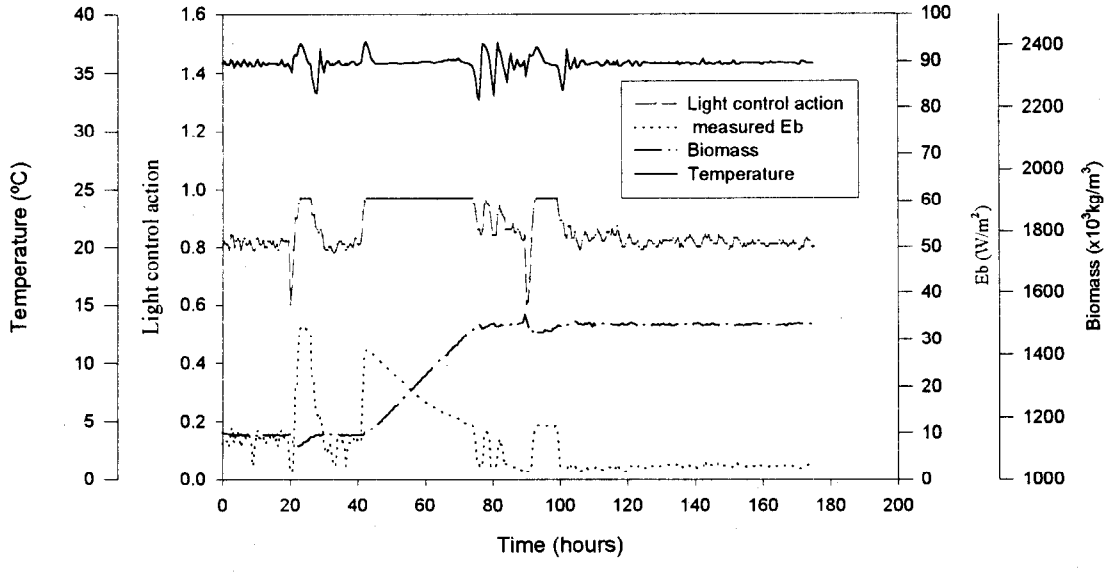

Figure 19: Evolution of temperature, biomass and light control action during GPS test F.

Evaluation of the stability improvements done with this change can be seen in the corresponding ADERSA technical note. However the operation of the controller appeared correct. The controller is able to drive the biomass to the set point and there is no gap between the set point and the productivity value. Therefore its operation is considered successful.

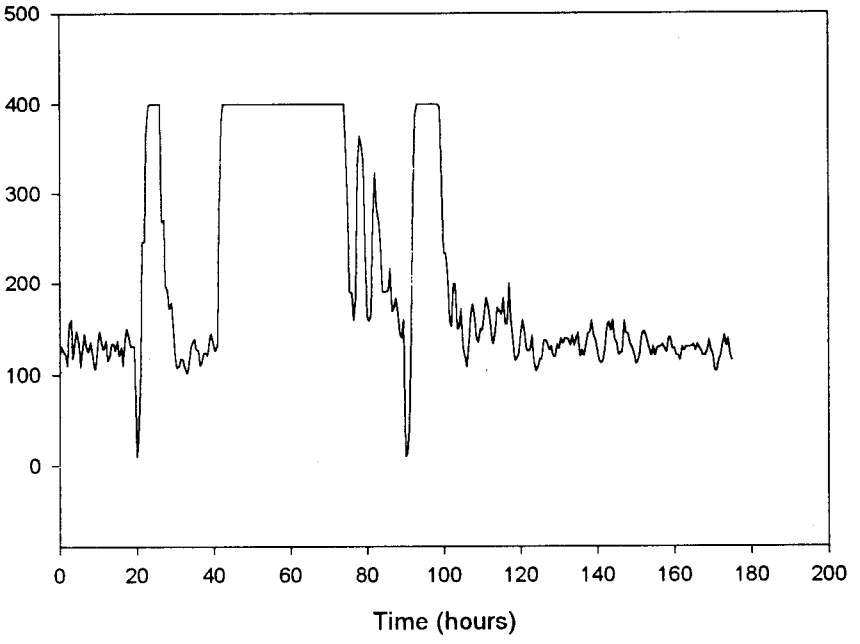

Figure 20: Evolution of GPS calculated Fr. which is calculated from the light control action, according to appendix 1, during GPS test F.

IV. 4 GPS TESTS CONCLUSIONS

The first GPS tests, showed that the control supplied by the GPS allow to maintain the biomass at productivity levels quite close to the set point. The values reached however were always slightly under the set point. Besides this point its operation as a controller appeared to be correct.

The values of Fr calculated by the GPS model differed from the ones calculated from the light control action and which correspond to the real ones, as explained in appendix 1. This fact implied that the part of the model, which predicts the Fr, should be improved so as to allow an accurate prediction under a wider range of conditions that it did before. As an alternative to be used for the control aspects the calculation of the Fr from the light control action appeared very interesting. The availability of the Fr values as a function of the action of the controller allowed implementing such an approximation. In the first of the complementary tests this approximation was used. The evolution of the biomass productivity was similar to the one observed during the GPS test A. However, this time the Fr supplied was more stable. This is probably due to the fact that the range of the scale of the Fr is much smaller than the one used in the first test, being this range between the usual 10 and 400 W/m^2.

The stability on the light supplied, improved the stability of the temperature control, which was able to recover its average value during the first couple of hours after a strong disturbance. The disturbance caused by the change in the illumination conditions was attempted to be minimised by using different controller set points or a decrease in the temperature of the cooling liquid down to -10 °C degrees. During the light intensity changes it was not possible to maintain that low temperature which increased up to 0 °C degrees in the cool water tank supply. This fact suggested that an improvement in the cooling fluid supply should be pursued. As in the short term a powerful cooling loop is going to be installed for the new 77 litres airlift bioreactor, this bioreactor will be connected to the mentioned cooling loop, and therefore the constant temperature of the cooling fluid supplied will be assured.

Besides the improvement of setting the light intensity using the output of the controller, two new improvements were incorporated in the GPS. One of them allowed eliminating the gap appearing between the productivity set point and the other one allowed to average the biomass measurements over a period of 30 minutes instead of 10. As a result of all those changes the GPS operated successfully under the frame of the tests performed.

V. REFERENCES

BINOIS C. (1994a) Automatisation d'un écosystème artificiel utilisé comme systèmme de support de vie. Premiere interaction modèle/ systeme de contrôle.CCN5-Final Report. Contract 8125/NL/FG.

BINOIS C. (1994b) Technical Note 18.2. Contract 8125/NL/FG.

CORNET J.F. ; DUSSAP C.G. ; GROSS J.B. (1993a) Modelling of Physical Limitations in Photobioreactors. Adaptation of the Light Energy Transfer Model to Cylindrical Geometries. MELISSA Contract PRF 130820. Technical Note 19.1.

CORNET J.F. ; DUSSAP C.G. ; GROSS J.B. (1993b) Modelling of Physical Limitations in Photobioreactors. Modelling of Exopolysaccharide Synthesis in Cultures of *Spirulina platensis*. MELISSA Contract PRF 130820. Technical Note 19.2.

FULGET N. (1995) Study for the non-Linear Model Based Predictive Control of Spirulina Compartment Using Knowledge (PO142356) Model. Technical Note 24.2.

PONS P. ; ALBIOL J. ; GODIA F. ; General Purpose Station. Main program update. ESTEC/CONTRACT11549/95/NL/FG Technical Note 25.5.

VERNEREY A. ; ALBIOL J. ; GODIA F. (1996) IV Compartment high dilution rate tests. ESTEC/CONTRACT11549/95/NL/FG Technical Note 25.110.

APPENDIX 1 :LIGHT CALIBRATION OF AIRLIFT BIOREACTOR

For the operation of the photobioreactors determination of the light availability is of key importance. Determination of light availability at any point of a bioreactor with radial illumination is possible provided the light intensity at the bioreactor surface is known.

Determination of the light intensity at the surface of the bioreactor can be done by measuring the light intensity at the axis of the bioreactor, using a spherical light sensor that integrates the light reaching its radially illuminated surface. Conversion of the light intensity measured by the spherical sensor to the light intensity at the surface of the bioreactor can be done using the following equation :

$$Fr = Eb\frac{rb}{\pi \cdot Rb}$$

Were Fr is the light flux at the bioreactor surface ; Eb is the light intensity measured by the sensor ; rb is the radius of the sensor (30 mm); Rb is the radius of the bioreactor(48 mm).

As the available light sensor is calibrated in $\mu mols/m^2\ s^2$, and the mathematical models used in this work use W/m^2, it is necessary to convert the units of the sensor to the units used in the model. In this case the conversion coefficient to used has been 0.291, which has been calculated by J.F. Cornet by integration of the used lamps spectrum in the range 350-750 nm used by the *Spirulina* cells.

In order to measure the Eb values, the airlift bioreactor was emptied and its internal draft tube dismounted in order to allow the introduction of the spherical light sensor.

Light intensity measurements were done at different vertical positions and for different voltages applied to the lamps. The results of this measurements are plotted in figure 12 .

The measurements obtained for each voltage at different vertical positions were averaged so as to obtain a light intensity value for each voltage applied to the lamps. The light intensity values measured by the sensor in $\mu mols/m^2\ s^2$, were converted to Fr values using the above-mentioned formula and conversion coefficient factor. As a result of this measurements a relationship between the voltage applied to the lamps and the Fr of the airlift bioreactor was obtained (figure 13).

The voltage applied to the lamps is modified by the controllers by an electric signal (0-5 V) sent to the lamp power supplies. In order to know the voltage applied to the lamps from the action of the controllers is necessary to obtain a relationship among the mentioned controller action and the lamp voltage. The power supplies allow for an adjustment of the action by setting the maximum voltage applied to the lamps when a maximum input signal (5V) is sent to the lamps. The conversion among between the action and voltage is done linearly. To obtain this relationship, different % of controller action was set and the voltage received by the lamps on its support was measured. On the first measurements it was realised that at percentages of the controller action higher

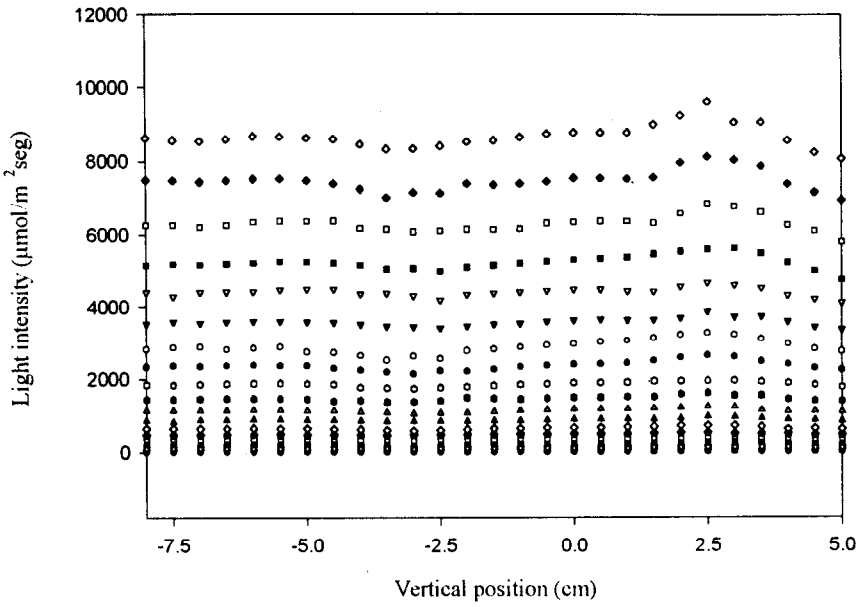

Figure 21: Light intensity values measured by the spherical sensor for different light intensities and different vertical positions. Position 0 corresponds to the second lamp in a vertical row. Superior and inferior lamps are positioned at 2.5 and -2.5 cm respectively.

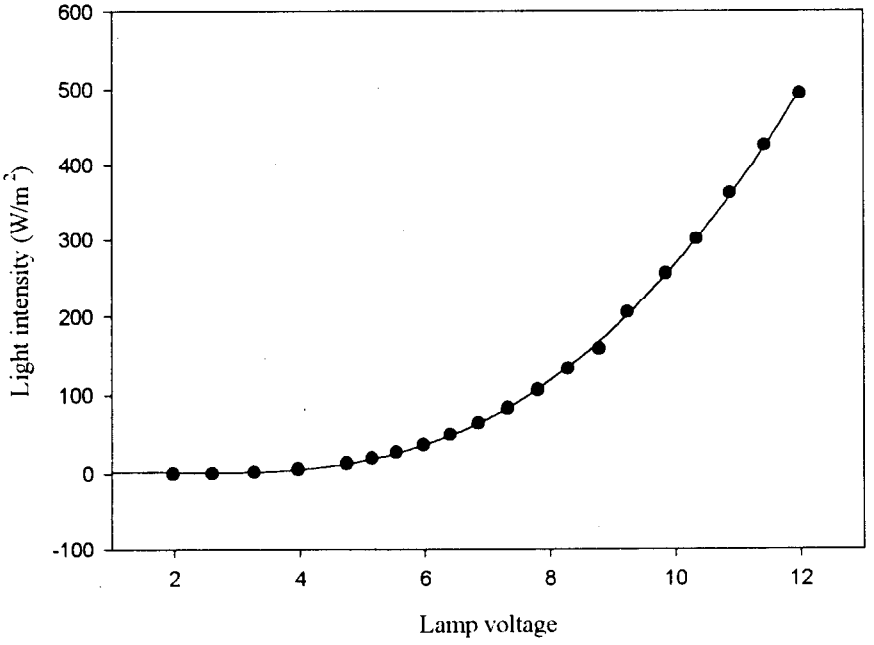

Figure 22: Values of Fr. calculated at the surface of the bioreactor for different lamp voltages.

than 90% the voltage applied to the lamps never increased from the value of 11V. In order to be able to apply the full 12V to the lamps the power supplies were re-scaled so as to reach 12V at 100 % of the controller action. However in order to allow correlating previous experiments done with the previous scale, the relationship among the controller action and the lamp voltage previous to the re-escalation is also given. The results of those measurements are depicted in figures 14 and 15.

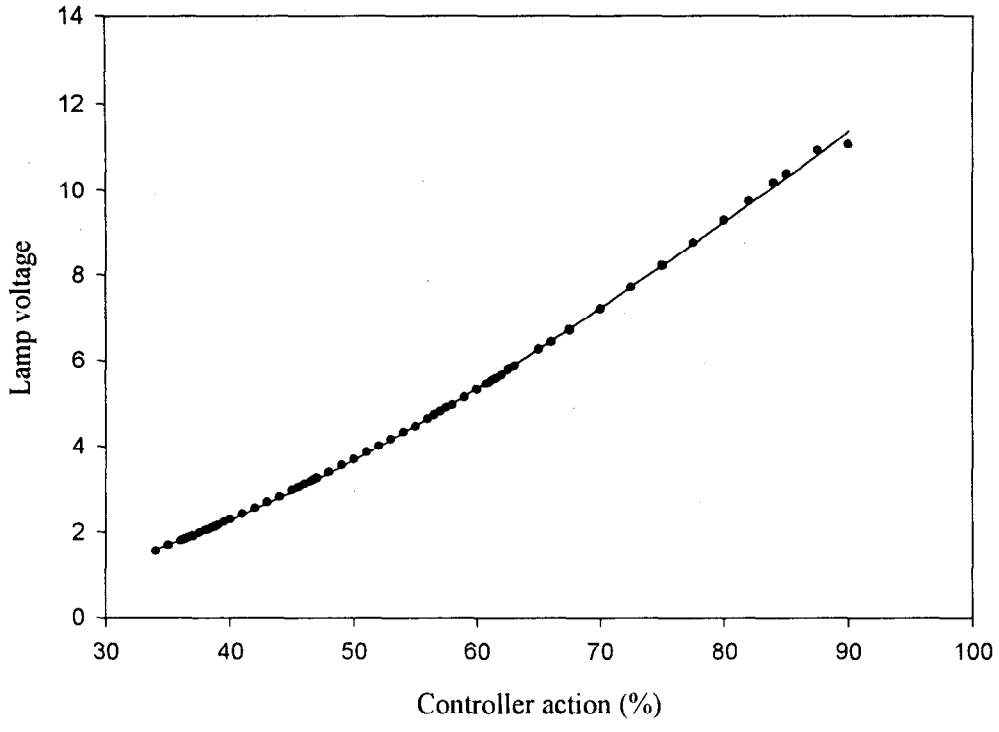

Figure 23: Relationship between the controller action and the voltage applied to the lamps before the re-scale.

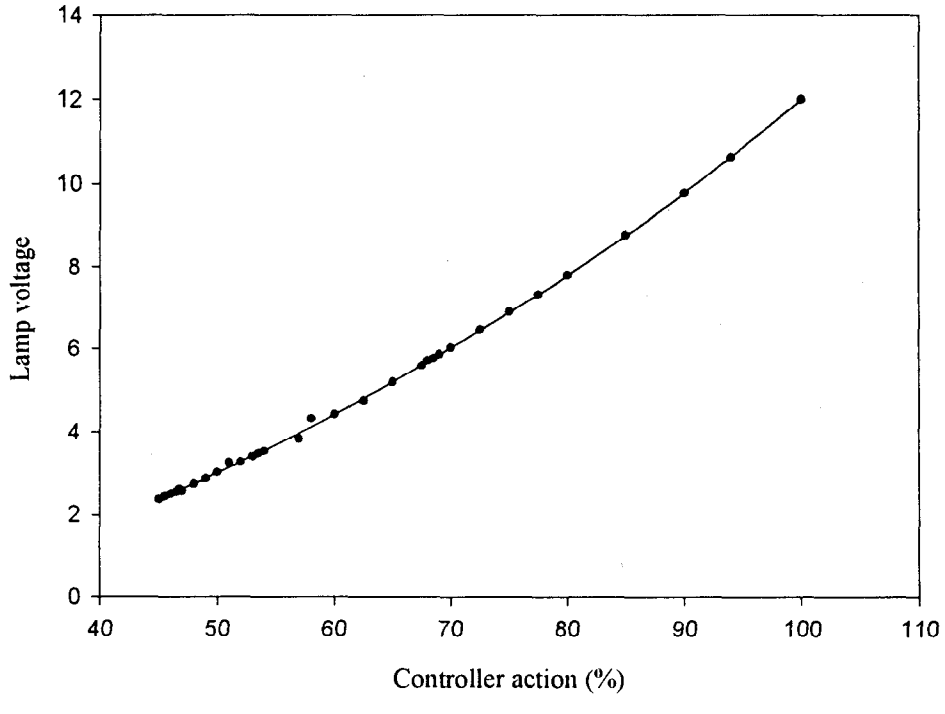

Figure 24: Relationship between the light controller action and the voltage applied to the lamps after re-escalation.

The obtained relationships will allow calculating the Fr values from the known value of the controller action. From the above given data it is possible to deduce a function to be used on the GPS. This has already been done by ADERSA. The function implemented on the GPS for this calculation is the following:

$$Fr) = e^{(6.27*ctact)} - 33.03$$

Where ctact is the value of the controller action in the range 0-1.