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APPENDIX 4

ABSTRACT

The objective of this paper is to present an estimate of the second law thermodynamic efficiency of the various units comprising an Environmental Control and Life Support Systems(ECLSS). The technique adopted here is based on an evaluation of the 'lost work' within each functional unit of the subsystem. Pertinent information for our analysis is obtained from a user interactive integrated model of an ECLSS.The model was developed using ASPEN. A potential benefit of this analysis is the identification of subsystems with high entropy generation as the most likely candidates for engineering improvements.

THIS WORK HAS been motivated by the fact that the design objective for a long term mission should be the evaluation of existing ECLSS technologies not only the basis of the quantity of work needed for or obtained from each subsystem but also on the quality of work.

In a previous study Brandhorst [1] showed that the power consumption for a partially closed and a completely closed regenerable life support systems were estimated as 3.5 kw/individual and 10-12 kw/individual respectively. With the increasing cost and scarcity of energy resources, our attention is drawn to evaluate the existing ECLSS technologies on the basis of their energy efficiency. In general the first law efficiency of a system is usually greater than 50%, [2]. From literature, the second law efficiency is usually about 10%, [3]. The estimation of second law efficiency of the system indicates the percentage of energy degraded as irreversibilities within the proces. This estimate offers more room for improvement in the design of equipment.

From another perspective, our objective is to keep the total entropy production of a life support system as low as possible and still ensure a positive entropy gradient between the system and the surroundings.The reason for doing so is as the entropy production of the system increases, the entropy gradient between the system and the surrounding decreases, and the system will gradually approach equillibrium with the surroundings until it reaches the point where the entropy gradient is zero. At this point no work can be extracted from the system. This is called as the ' dead state ' of the system, [4].

METHODS OF SECOND LAW ANALYSES :

The irreversibilities or entropy generation within a process is evaluated on the basis of the second law of thermodynamics using two widely used techniques. These are:

- Availibility Analysis/Exergy Analysis
- Lost Work Analysis

Availibility analysis or exergy analysis is a widely used technique. This was first proposed by Guoy and Stodola [5,6]. Availibility is a measure of the useful work potential of a stream which is at a different state other than the environment. This concept has been extensively used in determining the efficiency in areas ranging from space heating to cryogenic processes, [7,8].

The method of Lost Work Analysis was first proposed by Seader [9].

For our study we chose the lost work approach as it provides a more intuitive feeling for the irreversibilities within a functional unit.

CONCEPT OF LOST WORK ANALYSIS :

The basic requirement of the second law is :

The total entropy change of an isolated system,

$$\Delta S_{sys} \geq 0.0 \tag{1}$$

For a control volume with a steady state process where the surroundings are at a temperature of T_0, the rate of change of the total entropy of the system is given by, [10] The rate of change of total entropy of the system = Net rate of entropy transfer by flowing streams + Rate of entropy exchange with the surroundings from heat transfer

Thus

$$\Delta(Sm)_{fs} - \frac{Q}{T_0} > 0.0 \qquad (2)$$

where $\Delta(Sm)_{fs}$ is the difference in entropy between the feed and the product
Q is the net heat transfer from the system to the surroundings

For a steady state flow process there is no internal energy accumulation within the system. The law of conservation of energy can be expressed as ,

$$\Delta[(H + \frac{1}{2}u^2 + zg)]_{fs} = Q - W_s \qquad (3)$$

where $\Delta[(H + \frac{1}{2}u^2 + zg)]_{fs}$ is the difference in energy between the inflow and the outflow streams.
Q is the heat flow into the system
W_s is the work done by the system

For any system which requires work the amount of work required will be a minimum if the system undergoes a reversible change. This minimum work required is called the " ideal work ", (W_{ideal}). Since there is no degradation of work the entropy generation for a reversible process is equal to zero and equation (2) becomes

$$Q = T_0 \Delta(Sm)_{fs}$$

Substituting the above value in equation (3) and rearranging gives

$$W_{ideal} = T_0 \Delta(Sm)_{fs} - \Delta[(H + \frac{1}{2}u^2 + zg)]_{fs} \qquad (4)$$

In most processes the kinetic and potential energy terms are negligible, and equation (4) can be written as

$$W_{ideal} = T_0 \Delta(Sm)_{fs} - (\Delta H)_{fs} \qquad (5)$$

It is justified to mention here that from an availibility viewpoint, according to the defination of W_{ideal} as given in (5), the minimum work required is equivalent to the difference in availibility between the input and the output streams.

For a work producing process the "lost work" is the work which is lost due to irreversibilities within the process. It is expressed as the difference between the ideal work which could be produced by the process (W_{ideal}) and the actual work produced by the proces (W_s). Thus from equations (3) and (5), W_{lost} can be written as

$$W_{lost} = T_0 \Delta(Sm)_{fs} - Q \qquad (6)$$

Conventionally, there are two kinds of processes. A spontaneous process is one which produces work, i.e W_{ideal} is positive. Then

$$W_s = W_{ideal} - W_{lost} \qquad (7)$$

A nonspontaneous process is one which requires some form of external work to be supplied, i.e Wideal is negative. Hence

$$|W_s| = |W_{ideal}| + W_{lost} \qquad (8)$$

Thereby the second law efficiency for each type of process can be defined as

$$\eta_2 \text{ (spontaneous process)} = \frac{W_s}{W_{ideal}} \qquad (9)$$

$$\eta_2 \text{ (nonspontaneous process)} = \frac{W_{ideal}}{W_s} \qquad (10)$$

METHODOLOGY ADOPTED :

The following steps were performed to evaluate the lost work and second law efficiency of each subsystem of an ECLSS based on the above developed concepts :

- Defining the subsystem boundary of the ECLSS subsystem chosen, i.e identifying the input and output streams from the subsystem chosen.
- Choosing the reference temperature. For our study we chose the space craft cabin temperature of 70°F.
- Evaluating the W_{lost} within each functional unit of the ECLSS subsystem.
- Depending on the subsystem information provided, we calculated the W_{ideal} for each subsystem.
- Knowing W_{lost} and W_{ideal}, the second law efficiency is thus evaluated.

It is to be noted that in order to calculate W_{lost} and W_{ideal}, detailed information about the input and output streams is required, i.e enthalpy, entropy and mass flow rate. To obtain the necessary data we developed a psuedo steady state model of the ECLSS using a state of the art chemical process simulator called ASPEN (Advanced System for Process Engineering). The underlying feature of our model is that the inputs to the ECLSS subsystems are regulated by auser interactive model of the crew in the space craft. The crew model is appended to the main ASPEN code.The capability of the crew model is that given crew specifications of age, weight, gender and activity level, the model can be used to compute the flow rates of the different waste streams from the crew, which then serve as inputs to the ECLSS.

RESULTS :

A conventional ECLSS consists of the following subunits [11] :

- Solid waste management
- Humidity condensate removal
- Trace removal subsystem
- CO2 reduction subsystem
- CO2 removal subsystem
- O2 generation subsystem
- Water recovery subsystem

Presented herein are the results obtained for a few sample technologies which are commonly in use in an ECLSS design.

WET OXIDATION OF SOLID WASTE :

The solid waste is oxidized in an autoclave at a pressure of 1067 psia in the presence of water,[12]. The reaction temperature depends on the carbon content of the feed and is usually between 100 and 374 °C. For our modeling purposes we assume that only the carbon content of the feed is oxidized.

For the ASPEN model the reactor is modeled using a RSTOIC block as shown in Figure 1. The reactor temperature is set according to the carbon content of the feed using the linear relationship as given by Takahashi [12]

$$\%\text{ of carbon in feed} = -0.65 \times \underset{\text{temperature}}{\text{oxidation}} + 194 \qquad (11)$$

The mass and energy balance information of the streams involved in the process is shown in Table1. It is to be noted that all these values are for a basal case of a crew consisting of 1 man of age 25 years weighing 60 kg resting at basal metabolic rate.

Table 1: Properties of streams involved in wet oxidation process

Stream	Mass flow rate (lb/hr)	Total enthalpy (Btu/hr)	Total entropy (Btu/hr°R)
S1	3.44×10^{-4}	12.91×10^{-4}	23.56×10^{-7}
S2	9.16×10^{-4}	-1.4×10^{-3}	-2.64×10^{-3}
S3	1.26×10^{-3}	-4.77	-3.63×10^{-6}
S4	1.26×10^{-3}	-4.85	1.72×10^{-5}
S5	0	0	0
Q1	Heat duty = -4.77 Btu/hr		
Q2	Heat duty = -0.08 Btu/hr		

The lost work analysis of each unit operation block comprising the Solid waste oxidizer is given in Table 2.

Table 2: Lost Work estimation of the Solid Waste Oxidizer

Unit operation block	Lost Work (Btu/hr)	% of total lost work
Wet oxidizer	4.71	98.1
Depressurizer	0.091	1.9

Total lost work	4.801	

$$W_{ideal} = 530\,(1.72\times10^{-5} + 26.36\times10^{-7} - 23.56\times10^{-7}) - (-4.85 - 12.91\times10^{-4} + 14.05\times10^{-4})$$

$$= 4.86 \quad \text{Btu/hr}$$

W_{ideal} being positive, this is a spontaneous process. Hence

$$\eta_2 = \frac{0.059}{4.86}$$

$$= 1.21\ \%$$

CATALYTIC OXIDATION OF CONTAMINANT GASES :

The Catalytic oxidation process is chosen for trace contaminant removal. This design was proposed by Ammann, [13]. In this subsystem, the incoming trace gas is split into two fractions depending on its methane content (i.e higher the methane content, the greater the volume of gas which goes into the high temperature oxidizer). One portion of the incoming trace gas is oxidized in a high temperature catalytic oxidizer (HTCO) which is maintained at a temperature of 400 - 450 °C. Prior to entering the HTCO the gas is heated in an electric heater. Remaining portion of the gas is oxidized in a low temperature catalytic oxidizer (LTCO) which is maintained at ambient temperature of 70 °F. ASPEN model of this subsystem is shown in Figure 2.

ASPEN results for this model is shown in Table 3.

Table 3: Stream properties of Catalytic oxidation subsystem

Stream	Mass flow rate (lb/hr)	Total enthalpy (Btu/hr)	Total entropy (Btu/hr °R)
S1	35.66	- 3291.38	1.17
S2	3.45	- 318.44	0.113
S3	3.45	135.9	0.71
S4	3.45	309.64	0.86
S5	3.45	309.33	0.86
S6	3.45	-145.0	0.39
S7	32.21	-2972.98	1.05
S8	32.21	-2975.56	1.05
S9	35.66	-3120.25	1.49

Q1 Heat duty : 173.7 (Btu/hr)

Q2 Heat duty : - 0.297 (Btu/hr)

Q3 Heat duty : - 2.56 (Btu/hr)

The lost work analysis of each unit operation block comprising the Catalytic Oxidizer is shown in Table 4.

Table 4: Lost Work estimation of Catalytic Oxidizer System

Unit opreation block	Lost Work (Btu/hr)	% of total lost work
Diverter	0	0
Heat Exchanger	67.31	38.2
Heater	79.5	45.1
HTCO	0.297	0.17
LTCO	2.56	1.45
Mixer	26.5	15.04
Total lost work	176.17	

$$W_{ideal} = 530 (1.49 - 1.17) - (- 3120.25 + 3291.38)$$

$$= - 1.53 \text{ Btu/hr}$$

This is a nonspontaneous process. Hence

$$W_s = 1.53 + 176.17$$

$$= 177.7 \text{ Btu/hr}$$

$$\eta 2 = \frac{1.53}{177.7} = 0.86\%$$

BOSCH SUBSYSTEM :

The Bosch subsystem was chosen for CO_2 reduction. The design for our model is based on a design proposed by Minemoto et al, [14]. A series of two reactors are used. The first reactor is at a temperature of 1300 [K] while the other reactor is operating at a temperature of 900 [K]. The reactions are given by :

Reactor 1

$$CO_2 + H_2 \leftrightarrow CO + H_2O \qquad (12)$$

Reactor 2

$$CO + H_2 \leftrightarrow C + H_2O \qquad (13)$$

Since all the CO_2 is eventually converted to C a stoichiometric ratio of H_2 to CO_2 is maintained.

The properties of the streams present in the Bosch subsystem as obtained from our model is shown in Table 5.

Table 5: Stream properties of Bosch subsystem

Stream	mass flow rate (lb/hr)	total enthalpy (Btu/hr)	total entropy (Btu/hr °R)
S1	0.048	-183.79	-6.04×10^{-4}
S2	4.37×10^{-3}	-54.16×10^{-6}	-5.98×10^{-7}
S3	0.398	-677.1	- 0.139
S4	0.398	515.04	0.778
S5 solid	1.3×10^{-2}	4.51	4.27×10^{-3}
S5 vapor	0.385	-130.4	0.436
S6	3.9×10^{-2}	- 268.11	- 0.087
S7 solid	1.3×10^{-2}	-0.08	-1.5×10^{-4}
S7 vapor	0.346	-507.11	-0.177
S8	1.3×10^{-2}	-0.015	-2.87×10^{-5}
S9	0.398	- 677.1	-0.139

Q1 Heat duty: 1192.14 Btu/hr

Q2 Heat duty: -640.93 Btu/hr

Q3 Heat duty: -649.41 Btu/hr

Table 6 indicates the amount of lost work in each functional unit comprising the Bosch subsystem.

Table 6: Lost work analysis of unit operation blocks of Bosch subsystem

Unit operation block	Lost work (Btu/hr)	%lost work
Mixer	6.89	0.55
Reactor 1	486.01	39.04
Reactor 2	461.95	37.11
Condensate Remover	276.13	22.18
Solid carbon remover	13.78	1.11
Total lost work	1244.76	

$$W_{ideal} = 530\,(-2.87\times10^{-5} - 0.087 + 6.21\times10^{-4} + 5.98\times10^{-7} - 1.72\times10^{-5}) - (-286.11 - 0.015 + 178.94 + 54.16\times10^{-6} + 4.85)$$

$$= 38.53 \quad \text{Btu/hr}$$

Hence this is a spontaneous process.

$$W_s = 38.53 - 1244.76 = -1206.23$$

This is an example of a highly nonideal process. The actual process is spontaneous however under simulated working conditions the process requires external work to be supplied.

STATIC FEED WATER ELECTROLYSIS :

This technique is used for O_2 generation. Our model is based on a design proposed by Fortunato et al [15]. In this method the water from the water regeneration system is electrolyzed in a water retention matrix to produce H_2 and O_2. The electrolysis chamber is maintained at 30psia. The ASPEN model for the process is shown in Figure 4. The water from the water regeneration unit is pressurized to 30 psia before being fed into the electrolysis chamber. A cooler is used prior to the electrolysis chamber to remove the heat generated due to compression of water. The compressed water is cooled to ambient temperature before being fed into the electrolysis cell. Since there are no tailor made blocks to simulate the reactions occuring at the electrodes in ASPEN, the reaction was simulated using a RSTOIC block.

Table 7: Properties of streams present in the Water Electrolys subsystem

Stream	Mass flow rate (lb/hr)	Total enthalpy (Btu/hr)	Total entropy (Btu/hr °R)
S1	9.6×10^{-2}	-654.8	-0.21
S2	9.6×10^{-2}	-654.83	-0.21
S3	9.6×10^{-2}	-654.86	-0.21
S4	9.6×10^{-2}	-0.38	-0.27
S5	1.07×10^{-2}	-0.25	-4.76×10^{-4}
S6	8.52×10^{-2}	-0.13	-2.46×10^{-4}

Q1 Heat duty: - 0.03 Btu/hr

Q2 Heat duty: 654.55 Btu/hr

Table 8 presents an analysis of the lost work within each subsystem.

Table 8: Lost work analysis within the Water Electrolysis subsystem

Unit operation block	Lost work (Btu/hr)	%lost work
Pump	0.427	0.38
Cooler	0.03	0.03
Electrolyzer	96.99	87.08
Gas separator	13.93	12.51
Total lost work	113.38	

$$W_{ideal} = 530(-4.76\times10^{-4} - 2.46\times10^{-4} + 0.21) - (-0.13 - 0.25 + 654.8)$$

$$= -543.5 \text{ Btu/hr}$$

Thus this is an example of a nonspontaneous process.

$$W_s = -656.88 \text{Btu/hr}$$

$$\eta_2 = \frac{543.5}{656.88}$$

$$= 82.74\%$$

HUMIDITY CONDENSATE SEPARATOR :

In order to maintain the cabin humidity at a desired level, the exit air from the trace removal subsystem is cooled to a temperature such that the amount of moisture in the air leaving the condenser separator is equal to the amount of moisture desired in the cabin. The condensate is removed and treated to obtain water of potable quality. For the ASPEN model the condenser separator is modeled as a single unit using a SEP block.The temperature of the condenser is set in a user incorporated Fortran subroutine which takes into account the humidity levels of the incoming and outgoing streams.

Table 9: Stream properties of streams ocuuring in Humidity Condense Separator

Streem	Mass flow rate (lb/hr)	Total enthalpy (Btu/hr)	Total entropy (Btu/hr °R)
S1	35.66	- 3120.22	1.49
S2	7.18 × 10-2	- 489.58	- 0.154
S 3	35.59	- 2783.35	1.35
Q1	Heat duty:	- 152.71 Btu/hr	

Since the heat of condensation is not being used to do any useful work, hence

Lost work = 530 (1.35 +0.154 -1.49) + 152.71

= 160.13 Btu/hr

Wideal = 530(1.35 +0.154 - 1.49)
- (-489.58 - 2783.35 +3120.22)

= 160.13 Btu/hr

This is a spontaneous process.

Ws = 0

Thus η_2 = 0

This is valid since we had assumed that the heat of condensation is not used for doing useful work, thereby the amount of work which can be obtained from the process is zero.

CONCLUSIONS :

As shown in Tables 2, 4 and 6 lost work analysis provides a means of identifying areas within a subsystem where maximum work is lost due to irreversibilities. The magnitude of second law efficiency of some subsystems like the Catalytic Oxidation process or the Bosch subsystem reveal that these subsystems merit considerable attention to redesign their functional units from an energy conservation viewpoint.

For example, our study shows that percentage of lost work in the reactors used for CO_2 reduction is between 35 to 39 %. It is hopeful that this will provide some insight to the design scientists to redefine the operating conditions so as to optimize between yield of desired product and lost work.

The overall conclusion to be drawn from this paper is that there exists a potential for energy conservation in the currently used ECLSS technologies which warrants evaluation of the present operating conditions.

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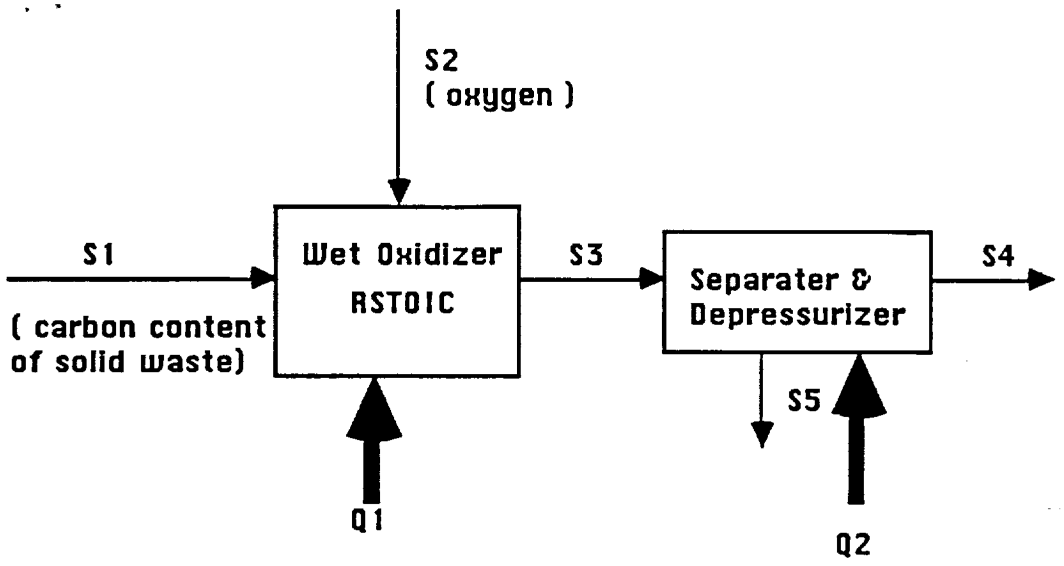

Figure 1: Schematic of Solid Waste Wet Oxidation Subsystem.

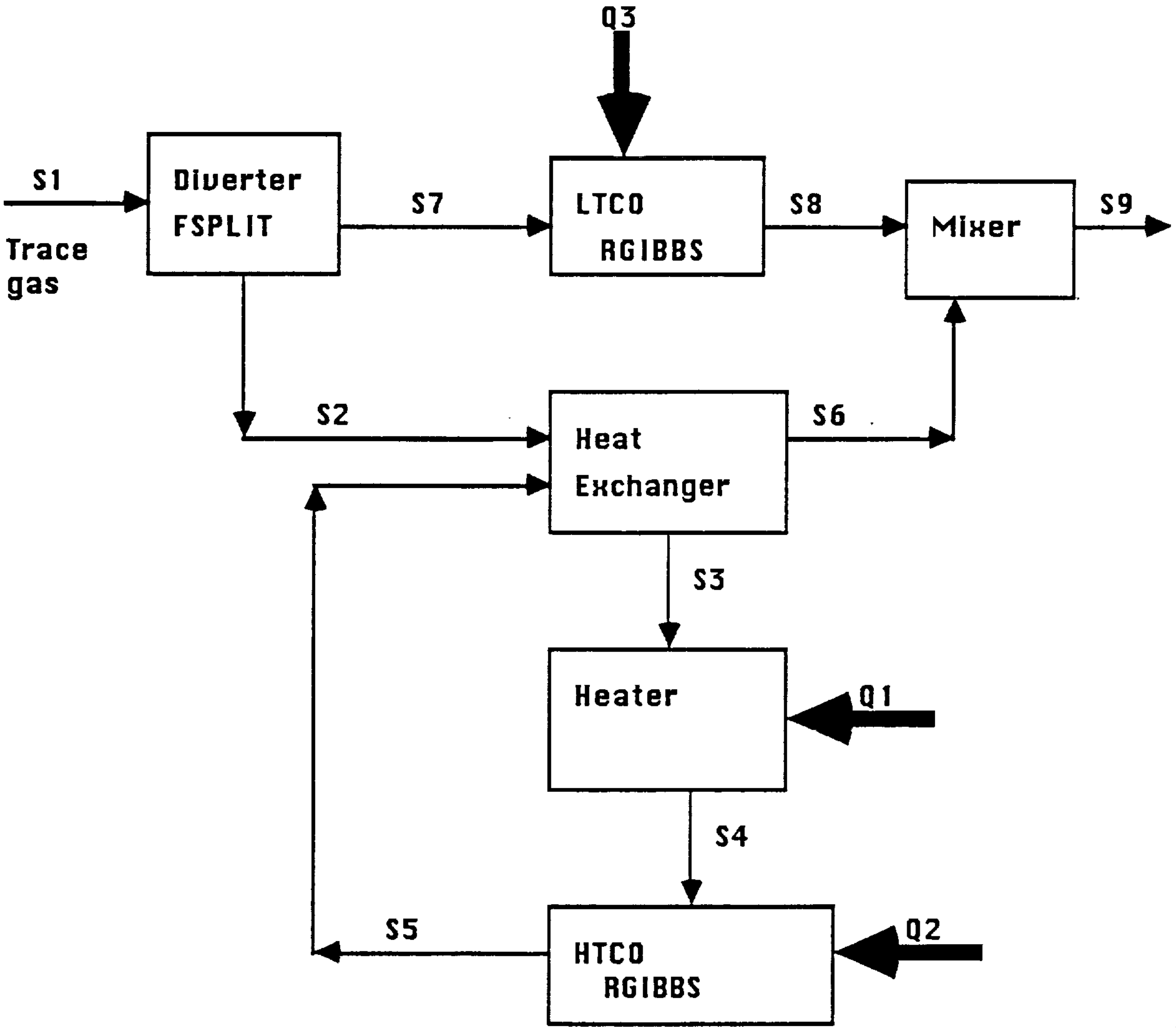

Figure 2: Schematic of Catalytic Oxidation Process

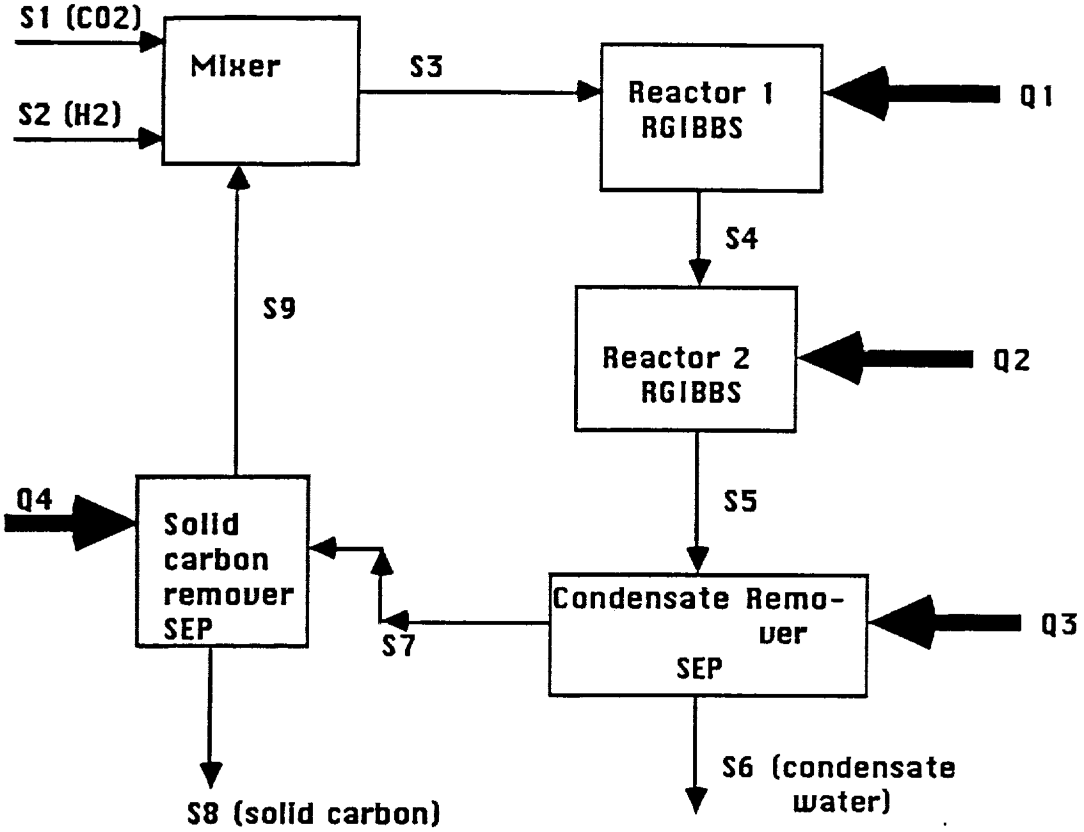

Figure 3: Schematic of Bosch subsystem

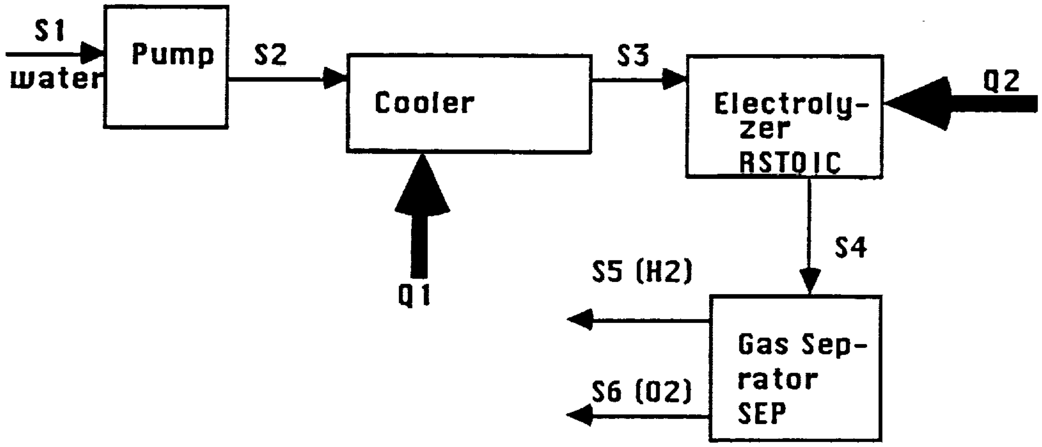

Figure 4: Schematic of Water Electrolysis process

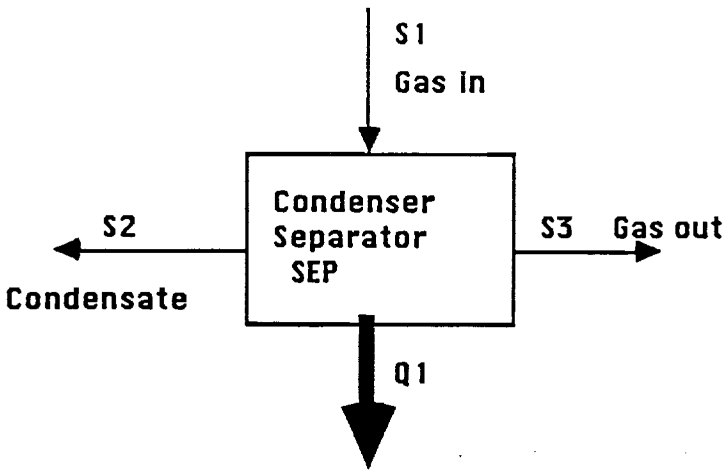

Figure 5: Schematic of Humidity Condensate Separator