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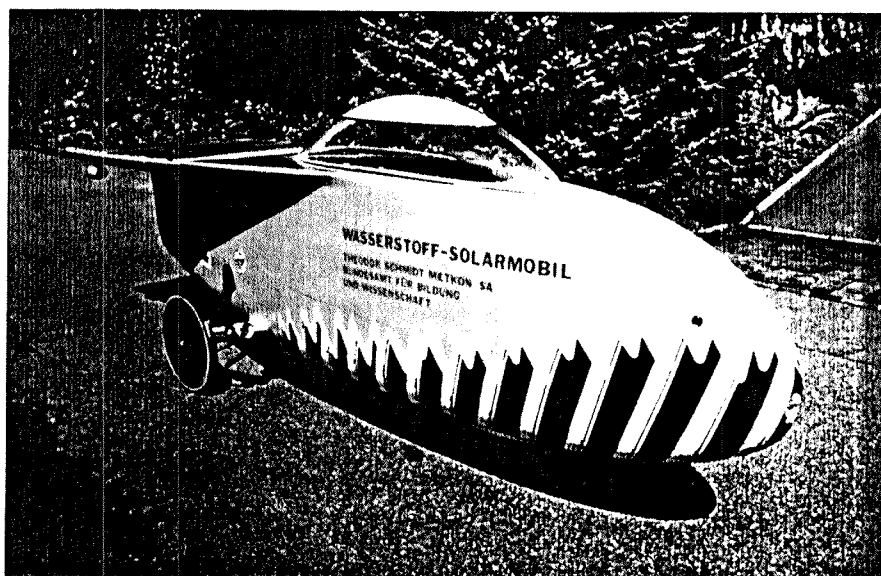
METKON S.A.
ALYZER® DIVISION

CH-6850 MENDRISIO

Windenergie
Energiesparkonzepte
H₂
Solarboote
Solarmobile

Ing. Büro
Theodor Schmidt
Höheweg 23
CH-3626 Hünibach
☎ 033 - 43 16 85
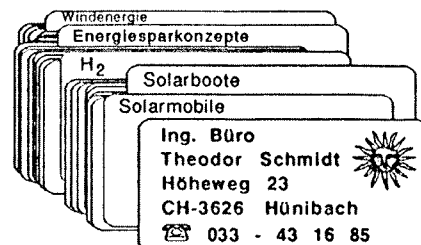
WASSERSTOFF-SOLARMOBIL

SOLAR-HYDROGEN-POWERED VEHICLE

FINAL REPORT

to

Contract no. BBW-PROC (89)37

September 1991

Zusammenfassung

Dieses Projekt hatte zum Ziel, erstmalig ein kleines Experimentalfahrzeug mit ausschliesslich solar hergestelltem Wasserstoff zu betreiben, mit ähnlichen, rein elektrisch betriebenen Fahrzeugen zu vergleichen und das ganze System öffentlich zu demonstrieren. Der gewählte Lösungsweg war: Solarzellen ——> Druckelektrolyseur ——> Druckspeicher ——> Verbrennungsmotor ——> Reibradgetriebe ——> Räder. Es zeigte sich, daß die Fahrleistungen im Vergleich zu ähnlichen Solarfahrzeugen recht bescheiden sind und der Wirkungsgrad sehr viel schlechter ist. Trotzdem ist die erzielbare Reichweite pro Ladung bis zwei Mal grösser. Es wird gezeigt, daß sich die Reichweite mit optimierten Kunststoffdruckflaschen nochmals um einen Faktor 4 vergrössern lässt, und beschrieben, wie sich der Gesamtwirkungsgrad mit einem Hybridkonzept auf akzeptable Werte vergrössern lässt.

Abstract

The aim of this project was to operate a small vehicle exclusively with solar-produced hydrogen, to make comparisons with similar but purely electrically driven vehicles, and to demonstrate the whole system publicly. The chosen procedure was: Solar cells ——> electrolysis under pressure ——> storage in pressure vessel ——> internal combustion engine ——> continuously variable transmission ——> wheels. The driving performance turned out to be rather modest compared to that of similar electrical solar-powered vehicles and the efficiency much poorer. In spite of this, the range can be up to twice longer. It is shown that the range could be increased by a further factor of 4 if optimized composite pressure vessels are used. It is described how the total efficiency could reach acceptable levels if a hybrid drive is used.

MKA Job 15352

1. Foreword

This report constitutes a part of the Swiss hydrogen energy research programme and and describes the development of the work summarizing the results achieved with the research programme "Wasserstoffsolarmobile" promoted by our Company, operating in the field of advanced water electrolysis, in collaboration with Mr. Theodor Schmidt, a specialist in the creation of solar-powered vehicles.

The research has been partially funded within the framework of the CORE projects, under the coordination of Paul Scherrer Institute, on the basis of the Contract No. BBW-PROC (89)37 EPA 217.585.

The economic report of the project will be delivered separately, under the contractual term of 6 weeks from the date of this Report.

Acknowledgements

MKA Job 15352

2. General Remarks

Although at present solar energy is an expensive way to produce hydrogen, it may still prove to be the cheapest one, if environmental factors are properly taken into account. Also, in the long run there is no real alternative.

To power a vehicle, an internal combustion engine is, at present, the simplest solution, because of the high degree of development of such motors. Used in this way, hydrogen is directly comparable to other gaseous and liquid fuels in widespread use.

It is nevertheless much cleaner than any of these. It burns very cleanly, and with air the combustion product is only water, containing eventual traces of nitrogen oxides in dependence of the burning temperature. There are no hydrocarbons, soots, sulphur oxides, carbon monoxide nor other toxic byproducts. In particular, there is no carbon dioxide, which is the product of all organic combustions, and is a controlling factor of the average temperature of the earth's surface.

The only pollutant emitted by the combustion of hydrogen with air, NO_x, can be reduced to relatively low levels by using lean fuel/air mixtures, which is the case of internal combustion engines fed by hydrogen rather than gasoline and other oil derivatives.

Such engines are readily converted to run on hydrogen. Combustion is much quicker, so that ignition timing must be adjusted, while knocking/backfiring must be prevented by injecting water or by other provisions.

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It is more difficult to physically store hydrogen than other fuels due to its low density (≈ 0.09 kg m^{-3} at NTP) and low temperature if liquid ($-252°C$). None of the methods presently available are yet adequate for powering conventional vehicles for long distances.

Storage of H_2 gas (GH_2) in pressure tanks is however suitable for all vehicles for limited ranges and for general use in special vehicles. The energy density of GH_2 stored in conventional steel bottles already exceeds that of conventional electric batteries by a factor of about ten and this can be multiplied several times if composite tanks of fiber-reinforced plastics are used. This can help make up for the poor efficiency of the conversion to mechanical power, which is several times less than in purely electrical vehicles.

Separate consideration should be given to future motive systems where the hydrogen would be burnt in more efficient fuel cells, powering electric motors. A light, silent, zero-pollution car will be the final result.

In the future, solar energy collection and manipulation will be probably concentrated in geographical areas enjoying the best promising characteristics such as light quality, space availability and land cost. Hydrogen will then reach our rainy countries by means of pipelines; it will be stored and distributed in one way or another to the final consumer. Nevertheless the presence of small size photovoltaic fields, spread out on the territory, can be considered an interesting solution for the exploitation of the solar energy in a sort of "domestic" size. This assumption was the basis for proposing the study of the first solar-powered car fueling station, based on GH_2, tailored for solarmobile-type vehicles.

Relying on that, the car may give up the major part of its photovoltaic equipment, which remains stationary on top of the fueling station. In turn, it must install a hydrogen-powered device, say an internal combustion engine or a fuel cell feeding an electric motor.

In this project, the photovoltaic panels generate direct current, utilized to feed a water electrolysis system, operating at 30 bar pressure, and accumulating the produced hydrogen in composite material bottles, at that pressure. Optionally hydrogen can be compressed mechanically to higher levels, in order to increase the volumetric energy "storage density".

This project is composed of two separate parts:

- the development of the solar-hydrogen generating unit, referred also as the "fueling station", filling up hydrogen bottles at the maximum pressure of 30 bar;

- the development of the "solarmobile" based on a hydrogen-fueled internal combustion engine.

The first part of the project has been performed in the laboratories and workshop of our Company. The second one at Mr. Schmidt's laboratory.

3. Goals of the Project

Goals were to operate a small vehicle entirely with solar-produced hydrogen, to measure and possibly improve the efficiencies of the components and study their interactions, and to demonstrate the complete system publicly. The original idea of producing the H_2 on board the vehicle in the manner of a true solarmobile had to be dropped as unrealistic, but the hydrogen charging station was at least to be made transportable.

3.1 Electric Power Generation from Solar Energy

The goal here was to generate electric power either from a portabe solar panel array (nominal power 320 to 480 Wp) or from a rooftop installation (nominal power 1250 Wp), which can be utilized directly or indirectly via a mains-connected hook-up.

3.2 Electrolyzer

The goal was the design and construction of an original electrolyzer conceived to operate at a pressure up to 30 bar, according to the available solar radiation.

3.3 Hydrogen Storage (Th. Schmidt)

a)   30 bar steel bottles

This was selected as a first approach to the storage problem.

b)   200 bar steel bottles with compressor

The goal here was to construct a small compressor with a pressure input of 30 bar and an output of 200 bar, for use with standard steel bottles.

c)   30 bar Kevlar pressure vessel

The goal here was to construct and test filament-wound pressure vessels or to purchase these.

3.4 Vehicle

The goal here was to complete the vehicle and drive it for at least 100 km while making measurements regarding the hydrogen consumption. It was initially intended to do this at the Tour de Sol 90.

3.5 Public Relations

It was intended to demonstrate the vehicle and solar hydrogen charging station in public, in particular during the Tour de Sol 90.

4. Research Work Description

4.1 Electric Power Generation (Th. Schimdt - Metkon S.A.)

The maximum flexibility was given to the photovoltaic system providing the electric power generation.
Three methods of supplying energy to the electrolyzer have been provided:

- a portable solar array of 480 W peak power for use at demonstrations and during the Tour de Sol;

- a rooftop solar array of 1250 Wp for normal running;

- the above rooftop array feeding into the mains and a physically separate mains power supply for normal running at any location with a mains supply.
When no hydrogen is being produced, the rooftop array and mains-hookup are used for supplying most of the electrical energy of a family household.

One of the main problems in using solar energy from a photovoltaic (PV) source is that the quantity of energy available is unsteady and the PV cells develop their maximum efficiency only under certain load conditions.
Furthermore, it is preferred to run the PV-field at relatively high voltage, in order to reduce the size of the connecting cables. Depending on all these reasons it is necessary to condition the PV-power to match the electric requirements of the final user.
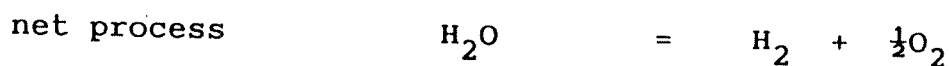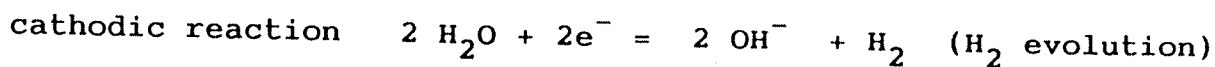
In this project, the DC from the solar cells has been conditioned by a Maximum Power Point Tracker (Australian Research Labs Maximizer 800BLV) having MAXIMIZER(R) as trademark, a device which continually adjusts the

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operating point of the system in such a way as to maximize in all conditions the power available from the PV-panels. The optimal voltage resulting from the PV field is thus not the nominal voltage of the solar array of 48 V, but the one giving the maximum power output as function of the instantaneous DC flow. Using MOSFET chopper technology, the MAXIMIZER(R) transforms this into the required 24 V for the electrolyzer. The originally intended direct coupling of solar cells and electrolyzer cells was not done because the systematic investigation thereof would have taken more time than available. The MPPT unit has been installed as a part of the hydrogen generating station.

4.2   Hydrogen Production (Metkon S.A.)

4.2.1   Basic Process utilized by METKON in the Hydrogen Generator
The unit we refer to is a source of pressurized hydrogen, generated by water electrolysis, that is a process where an electric current flow is used to split water through the following chemical reactions:

cathodic reaction $\quad 2\,H_2O + 2e^- = 2\,OH^- + H_2$ (H_2 evolution)

anodic reaction $\quad 2\,OH^- = H_2O + 2e^- + \frac{1}{2}O_2$ (O_2 evolution)

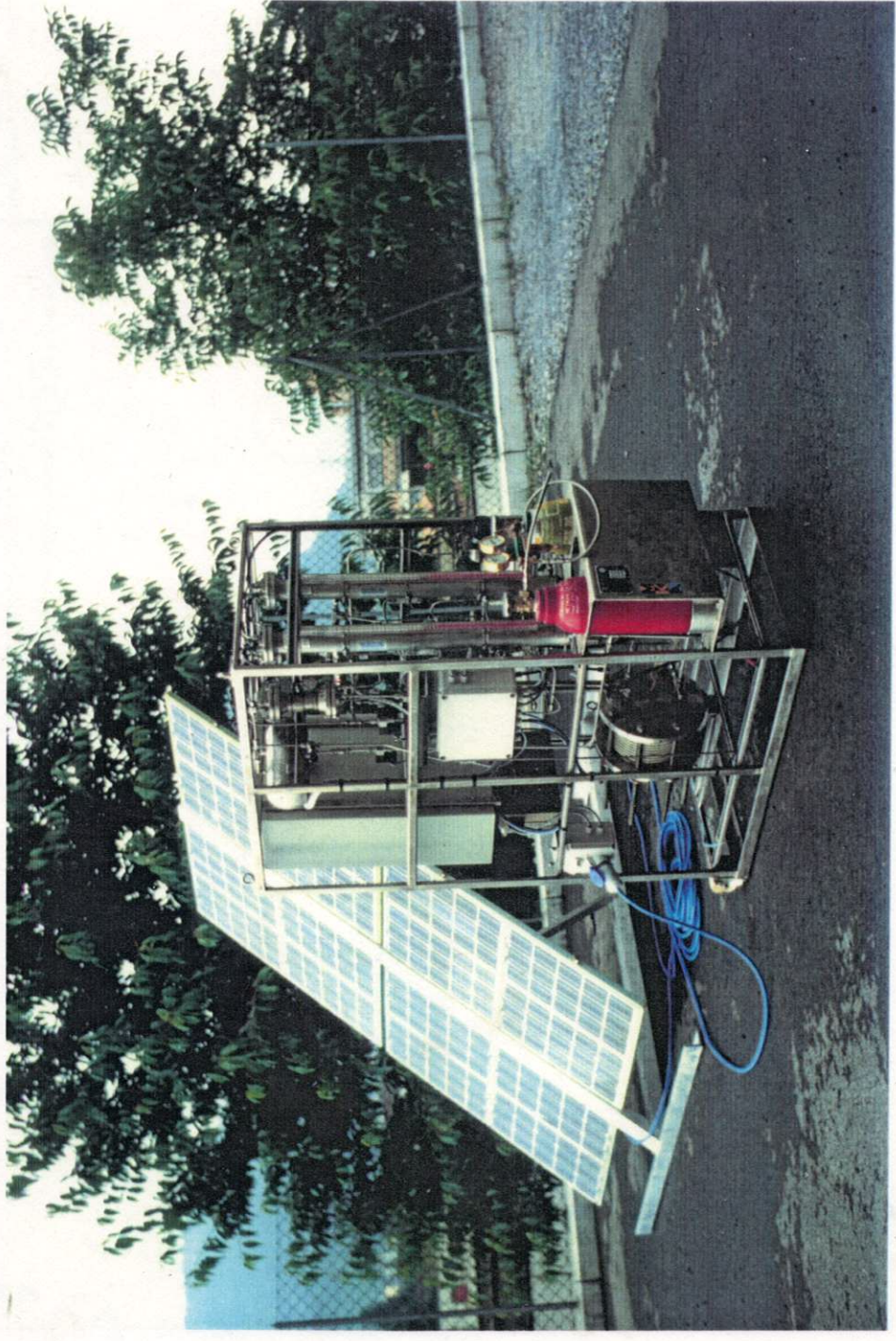net process $\quad H_2O = H_2 + \frac{1}{2}O_2$

FIGURE 1 - The Electrolyzer connected to the PV array

The above reactions are performed inside a new type of electrolysis cell designed and patented by METKON SA, having trade mark ALYZER(R).

4.2.2   System Description

Overall Configuration

The system has been designed as a portable unit for automatic pressurized hydrogen generation (See FIG. 1), consisting of the following subsections:

- DC (direct current from the PV-field, high voltage) to DC (battery voltage) conversion unit

- control section

- process section

- hydrogen storage section.

The control section is enclosed in a metal cabinet with a front transparent door, installed on the same stainless steel structure holding the process section. The DC conversion unit is installed immediately below the control cabinet.

Hydrogen is stored in two steel bottles (the red ones in FIG. 1) which can be alternatively separated from the electrolyzer), to be used onboard of the "Solarmobile".

Electric Conversion Unit

Electrolysis is the splitting of molecules whose energy demand is satisfied by the supply of direct electric current under a proper potential to the electrolysis cells.

In addition, electric power is necessary to operate the control system and the process actuators. The system is then powered through a back-up battery, kept charged by the power generated by a PV-field and conditioned through the Electric Conversion Unit intended to step down the voltage generated at the terminals of the PV-field and making available that power at a voltage acceptable to the battery.

The battery feeds the cell and the process control system in parallel. The conditioning unit is provided with a display showing its actual output voltage, which fluctuates in a range depending on the amount of power coming from the PV-field and on the level of the battery charge.
It is protected against short circuits at the battery by an automatic switch, placed inside the control cabinet.
It is also protected against short circuits at the electrolysis cell by a second automatic switch.

Control Station

Hydrogen generation is performed under conditions monitored and supervised by the control station. This is based on a Programmable Logic Unit (PLC) controlling all process parameters, and keeping them at the set levels through the action of process actuators.
When a parameter deviates too much from its set value, an ALARM condition is raised up, and the unit automatically reverts to a fail-safe status, waiting for a corrective action by the operator.

Monitoring and control items installed on the control panel can be grouped as follows: (item numbers as in FIG. 2).

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	DISEGNATO—drawn AR	APPROVATO—approved	DATA—date 22/12/90		HYDROGEN OXIGEN GENERA
PPR. op'd	SCALA scale %	PESO UNIT unit weight	N.PEZZI quantity	M K A	LAY—OUT
	MATERIALE material		POS. CAD Item 153521		

1

S1–H1   Start
S2–H2   Stop
S3   Emergency
S4   O2–H2 Vent
S5   DW Aut/Man
S6   Lamp test
S7   ACK
S8–H8   Reset
S9   Power on/off
H6   LLA HV–H2
H7   LLA OV–O2

CONTROL PANEL

DC/DC
CONVERSION UNIT

PHOTOVOLTAIC ARRAY INPUT
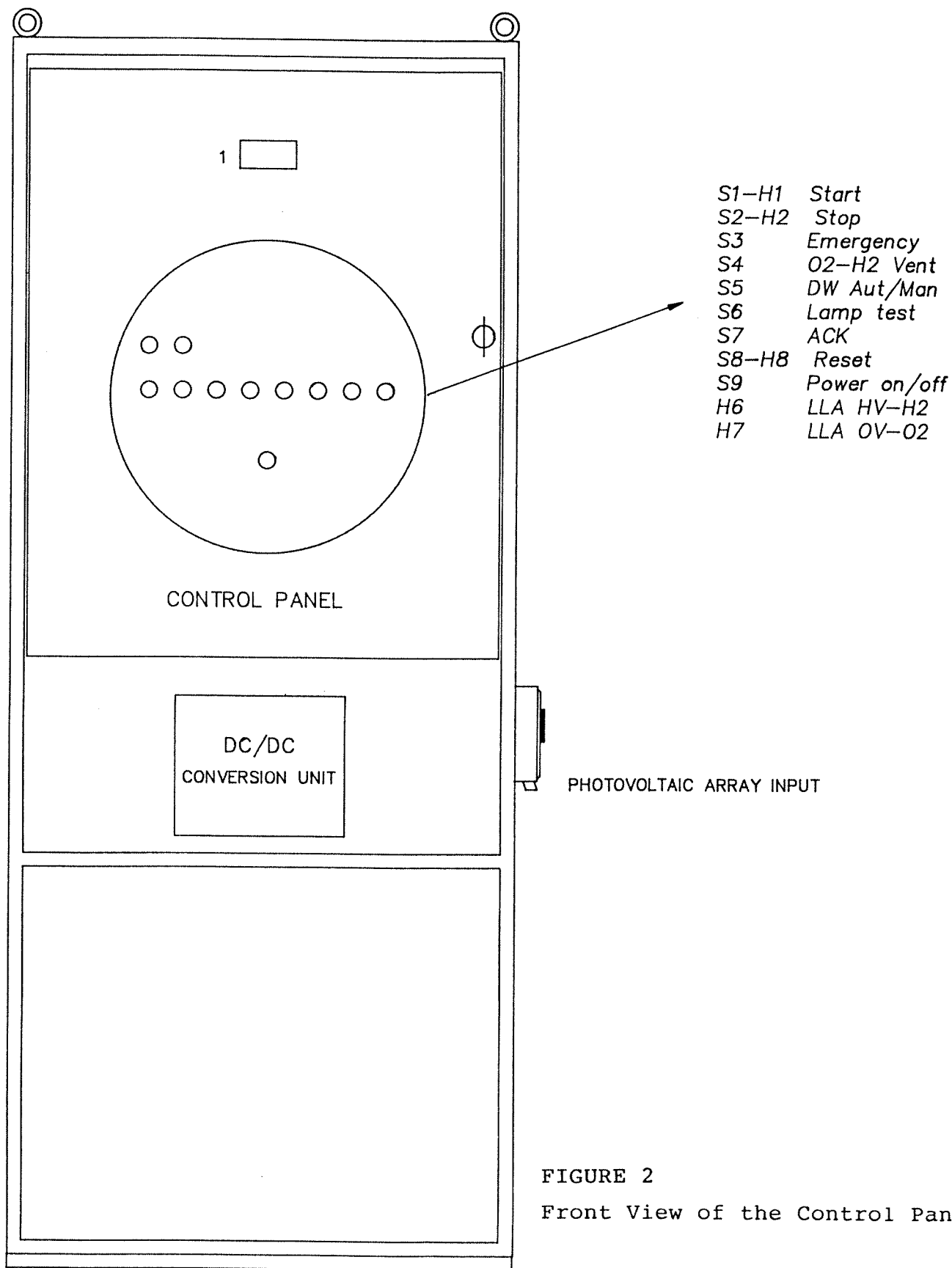
FIGURE 2

Front View of the Control Panel

| D | | E | | F | | G | | H | | | | J |

- **power control**   power ON/OFF switch (item S9)

- **digital indicator**   showing the electrolyte temperature (item 1) (TEMPERATURE).
                             It is provided with 2 set points, the first one for the electrolyte temperature control, the second one for the electrolyte maximum temperature alarm setting.

- **switches**   to vent out the gases from the unit to the atmosphere (item S4) (VENT)

                             to set the feedwater valve under manual or automatic control (item S5) (FEEDWATER)

- **pushbuttons**   to start/stop the hydrogen generation process (luminous pushbuttons) (item S1/S2) (START/STOP)

                             to test the soundness of the signalling lamps and the working of the siren (item S6) (LAMP TEST)

                             to acquire an alarm condition and silent the relevant acoustic signal (item S7) (ACK)

                             to reset the plant to STANDBY STATUS after any corrective action (pushbutton which lights up in

case of plant trip) (item S8) (RE-
SET)

to shut off   rapidly the unit,   in
case of EMERGENCY (item S3)

- **signalling lamps**   H1 for START pushbutton

H2 for STOP   pushbutton

H6 for low level in H_2 vessel

H7 for low level in O_2 vessel

H8 for RESET pushbutton

The PLC unit, installed inside the cabinet, controls   the
system by elaborating a certain number of input signals
through a special built-in software, and producing output
signals used to drive the various process actuators or to
raise alarm situations.
Input and output signals are connected to the various sen-
sors and actuators by means of terminal blocks installed
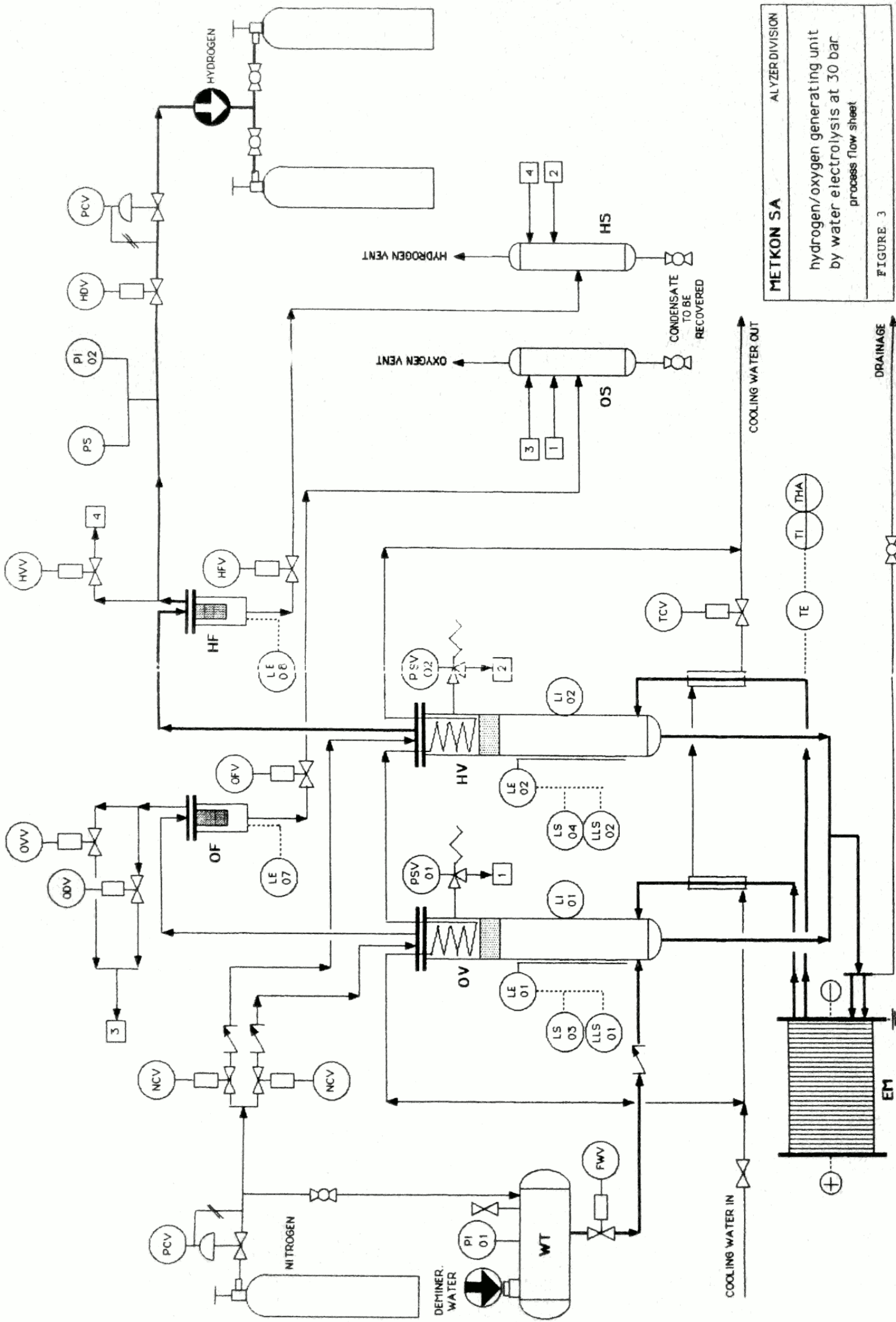in a junction box.

4.2.3   Process Sections

The Piping and Instrumentation Diagram of FIG. 3 shows all
the components of the hydrogen generation, separation and
storage sections.

For clarity reasons we subdivide hereunder the description
of the various process subsections, as follows:

Water electrolysis

The electrochemical cells assembly is indicated by EM
(ELECTROLYSIS MODULE). It is made up by stacking in series
a sufficient number of bipolar ALYZER (R) cells between
two end covers. All cells are crossed by the same DC flow
and perform the electrochemical process indicated by the

HYDROGEN

HYDROGEN VENT

OXYGEN VENT

CONDENSATE TO BE RECOVERED

COOLING WATER OUT

DRAINAGE

HS

OS

PCV

HDV

PI 02

PS

HVV

HFV

HF

LE 08

PSV 02

LI 02

LE 02

LS 04

LLS 02

OFV

OVV

ODV

OF

LE 07

HV

PSV 01

LI 01

LE 01

LS 03

LLS 01

NCV

NCV

OV

TCV

TI

THA

TE

EM

NITROGEN

PCV

DEMINER. WATER

WT

PI 01

FWV

COOLING WATER IN

METKON SA

ALYZER DIVISION

hydrogen/oxygen generating unit
by water electrolysis at 30 bar
process flow sheet

FIGURE 3

reactions set forth at para. 4.2.1 above. The module is not filled up solely by water, whose very low conductivity would lead to an excessive resistance to the DC flow. Water conductivity'is largely increased by the addition of a dissolved substance (potassium hydroxide), which forms an aqueous, very conductive medium, called **electrolyte**.

This is circulated throughout EM by the natural draft provided by the gas evolution inside the cells.

The demineralized water consumed by the electrolysis process must be loaded by the operator into the vessel WT (WATER TANK) through a special cap.

WT is then put under a sufficient nitrogen overpressure (indicated by the pressure gauge PI-01) such as to allow water to feed the pressurized electrolysis section.

WT is also provided with a venting valve, to bring overpressure down to zero before any cap opening.

Hydrogen and oxygen from EM reach the separating vessels HV (HYDROGEN VESSEL) and OV (OXYGEN VESSEL). The two gaseous streams entrain some electrolyte up to HV and OV, wherefrom the electrolyte returns to EM by gravity.

The electrolyte circulation loop is characterized by the presence of cooling jackets on the gas evolution pipes from EM which are used for temperature control purposes of the water electrolyser. The cooling action is controlled by the PLC actuating the TCV (TEMPERATURE CONTROL VALVE).

As it can be noticed from the flow diagram, OV and HV are interconnected on the bottom through a pipe allowing the electrolyte to flow from one vessel to the other. This is an essential condition for the pressure equilibrium in the electrode compartments.

The level reached by the electrolyte in OV and HV is directly shown by visual indicators (LI-01/LI-02).

Oxygen, as generated by the electrolysis module EM, is collected in OV and intermittently vented to the atmosphere by the ODV (OXYGEN DELIVERY VALVE), operating in ON/OFF mode. When ODV is closed, oxygen accumulates in OV and the liquid level tends to decrease until LS-03 opens ODV venting out the gas for a set period of time.

Hydrogen, in turn, separates in HV and, crossing the filter HF, is delivered to the storage bottles.

Before leaving HV and OV hydrogen and oxygen are cooled by water coils located in the upper part of the two vessels, in order to recover the maximum of condensing humidity inside the electrolysis section.

While the level in OV is kept at an almost constant average value by LS-03, the liquid in HV tends to lower continuously, owing to the electrolysis water consumption. When a minimum level defined by LS-04 is reached, FWV is activated to inject water, thus restoring the required average level in HV.

In case of any ODV malfunction or other possible troubles the liquid level in OV or HV could decompensate with possibility of hydrogen-oxygen intermixing through the bottom interconnecting pipe. This is avoided by the presence of the minimum level switches LLS-01 and LLS-02 which trip out the gas production and start an automatically balanced resetting of the system at atmospheric pressure.

OV and HV are protected against overpressures by the respective relief valves PSV-01 and PSV-02.

Gas filtration

Oxygen from OV reaches the upper part of OF (OXYGEN FIL-TER), where a microporous cartridge makes the coalescence of the misty particles entrained by the gas stream in larger liquid drops, which are easily separated and collected at OF bottom.

This vessel is provided with a liquid level sensor LE-07 and a level switch actuating, through the PLC, the drain valve OFV (OXYGEN FILTER VALVE) releasing automatically the collected condensate to the vessel OS (OXYGEN SEPARA-TOR).

The filtered oxygen is vented to the atmosphere by ODV, as explained above, through OS.

Hydrogen from HV is similarly filtered in HF, wherefrom the captured liquid is discharged to HS.

Pressure control

The operating pressure of the electrolysis section is controlled by setting the automatic backpressure controller PCV.

This is a hand-adjustable, spring-loaded controller of the gas inlet pressure.

The clockwise rotation of the handle adjusts the set toward higher pressures. The valve setting can be controlled by means of the pressure switch PS.

Pressure release and venting system - inertization system

It is very important that any variation in the system pressure will keep in balance the hydrogen side and oxygen side pressures, in order to avoid gas intermixing forming hazardous mixtures.

This could occur, for instance, when the operator stops the plant and reverts it to atmospheric pressure venting out the hydrogen and oxygen content.

The depressurization of the plant is also automatic in case alarm situations occur.

In order to perform correctly these venting procedures, the system is provided with a special logics, actuating the pressure release in balanced and safe conditions.

The depressurization, started by the operator or by an alarm situation, is made by HVV (HYDROGEN VENTING VALVE).

The hydrogen venting raises up the liquid level in HV, while it lowers down the level in OV. In case the latter reaches the minimum determined by LLS-01, HVV closes and OVV (OXYGEN VENTING VALVE) opens. The pressure release continues and, if HV gets to the minimum level condition (LLS-01), OVV closes and HVV opens. The level balancing procedure continues up to the whole system depressurization.

During depressurization electrolysis is automatically put out.

The OS and HS vessels collect any liquid entrainment of venting gases, before their release to the atmosphere.

The automatic venting takes place when:
. certain alarm situations occur;
. the operator sets the VENT switch to ON;
. the operator pushes the EMERGENCY button.

Subsequently to the depressurization period an automatic control opens the two nitrogen feeding valves NCV injecting pulses of inert gas for a preset time.

Cooling water system

Cooling water is continuously used for cooling as much as possible the gases evolved from OV and HV by means of coils installed in the upper part of these vessels.

Cooling water is also used to remove the excess heat released by the DC flow to the electrolyte, the temperature of which is measured by TE and controlled by the PLC.

Manual venting valves

Two ball valves are installed on the gas lines connected to the top of the gas filters HF and OF.

The two valves must remain open during the electrolyte loading/unloading operations.

The valves are also left open during maintenance operations, to assure that the system is not under pressure.

They must remain closed during normal operation.

The valves can be used for re-equilibration purposes of the levels in HV and OV.

4.3 Hydrogen Storage (Th. Schmidt)

Direct storage in pressure vessels was chosen as the only method practical for a small vehicle at the present time. This still leaves the choices of material, design pressure, and geometry of the storage vessel.

Material

The broad choice is between metals, plastics, and composite materials.

— **Steel** is widely used for hydrogen storage. Design, manufacture, and testing of vessels are straightforward and follow established procedures. The behaviour of steel is well understood and documented, resulting in relatively narrow safety factors (e.g. Bursting pressure/Test pressure/Working pressure = 5/3/2 from Swiss regulations). Hydrogen embrittlement restricts the use of high tensile alloys (they may not exceed 950 MPa with present regulations). Steel is not suitable for low-pressure bottles (except throw-away ones) as wall thicknesses may not be reduced too much because of rusting and denting. 200 bar bottles are an easily available, relatively cheap product which store approximately 1% of their weight as H_2 (if this sounds like very little, consider that the steel bottle with H_2 stores about *ten times more energy* than a lead-acid accumulator of the same weight).

— Many **plastics** are not suitable for H_2 as their permeabilities for this gas are too great. Table 1 shows the values for H_2 of some materials. The mechanical properties of most of these materials makes them unsuitable for high-pressure vessels. Aging, fatigue, and reaction to chemicals are much less well-defined than for metals. Such polymers can however be very useful as liners for vessels made of other materials.

Table 1

Permeability of some Polymers with GH_2

Unit: 10^{-10} cm^3(STP) s^{-1} cm^{-2} $cmHg^{-1}$ mm

(Data from Angst & Pfister. Values are a rough guide only, as they vary non-linearly with temperature and pressure)

PETP	(Mylar)	4-5
PTFE	(Teflon)	9.5-63
FEP		120
PA6	(Nylon)	8
PVC		33

For example, a 10 liter cylinder with spherical end-caps, 12 cm diameter, 3483 cm^3 surface, filled with H_2 at 30 bar, will lose through a 1 mm thick PETP liner 1% of the gas in 8-9 days.

— Several materials are available as fibers which exceed the specific tensile strength of steel by up to over an order of magnitude, as shown in Table 2. **Composite** bottles can be formed of a filament winding on a separate gas-tight liner. These are however only available

to special order and are very expensive, as is the quite complicated testing procedure necessary (Metal cylinders which are only partially fiber-reinforced are more easily obtainable). Aging and fatigue properties are not yet well known. Therefore larger safety factors are necessary (e.g. Bursting pressure/Test pressure/Working pressure = 10/2.5/2, from American Society of Mechanical Engineers). As this safety factor is currently twice that of steel and a composite vessel also requires a liner and some resin to hold together and protect the fibers (although it is conceivable to do without this), the full potential of these fibers is not yet realised and the ones made store 2-5% GH_2 by weight. With careful quality control and cycle history monitoring it might be possible to raise this value to over 10%, making such vessels no heavier than current automotive ones for the same amount of H_2 in *liquid* form.

Table 2: Properties of some suitable and affordable materials:

Material	Tensile Strength [MPa]	Density [g cm^{-3}]	Specific Tensile Strength *
Steel	300-1300	7.8	1
Steel Wire	2600	7.8	-
E-Glass Fiber	1750	2.5	5.7
Carbon Fiber	2650	1.7	12.8
Aramid Fiber e.g. KEVLAR™	2000-2760	1.45	11.3-15.6
SPECTRA™	2500-3000	0.97	21.2-25.4

*(relative to 950 MPa Steel)

Storage Pressure

The amount of material required to fabricate a vessel for the storage of a given amount of gas is in principle less for small pressures, as ambient atmospheric pressure reduces the vessel's required back-pressure by 1 bar and because the gas becomes less compressible at higher pressures, requiring a higher storgae pressure than theoretically needed for an ideal gas. However low pressure vessels such as bags or bellows use too much room to be practical vehicles and pose severe safety problems. In those very special cases where such containers might be used, they could of course be extremely light, even buoyant!

Medium pressures such as our 30 bar Electrolyzer system pressure are well suited for efficient vehicles, as only little energy is wasted for compression. Except for throw-away cans, no light-weight vessels are commercially available. Steel vessels which are available (e.g. butane bottles) are considerably heavier than they need be.

Higher pressures waste less interior vehicle space and vessels use material more effciently and are thus lighter as well. Only at extremely high pressures would they become heavier again, due to the increasing incompressibility of a real gas. Although the result of such vessels bursting would be catastrophic, they are so thoroughly tested and so strong that the probability of this occurring, even in a crash, is very small.

The energy required for isothermal compression of an ideal gas is $nRT \ln(P_1/P_2)$. n is the number of moles, R the molar gas constant and T the temperature in K, so that this works out to about $101 \ln(P_1/P_2)$ kJ/Nm^3 at 0°C or $110 \ln(P_1/P_2)$ kJ/Nm^3 at 24°C. However several times this value is usually lost in practice.

Geometry

Many shapes which utilise materials efficiently, e.g. spheres for homogeneous materials, various forms of "endless cylinders" for fibers, utilise vehicle space poorly, where the cylinder with end-caps is usually optimal. In special cases the vehicle structure itself can be used, but here problems of safety arise.

Solution chosen

From the above, many combinations are possible, and two were chosen:

1) Standard 200 bar steel bottles for immediate use

With 30 bar H_2 available from the Electrolyzer, the required 6-7 fold compression can be done in a single stage with a modest energy requirement. Theoretically the oxygen available at 30 bar, which is presently wasted, contains enough energy to power this compressor up to 164 bar. A device was conceived which could do this, but its construction would have been difficult mechanically and therefore a simple compressor was built which can be powered by a 150 W electric motor or by hand. The two opposing pistons are balanced and work rather slowly, so that compression is nearly isothermal. High-quality valves and piston seals ensure practically zero leakage.
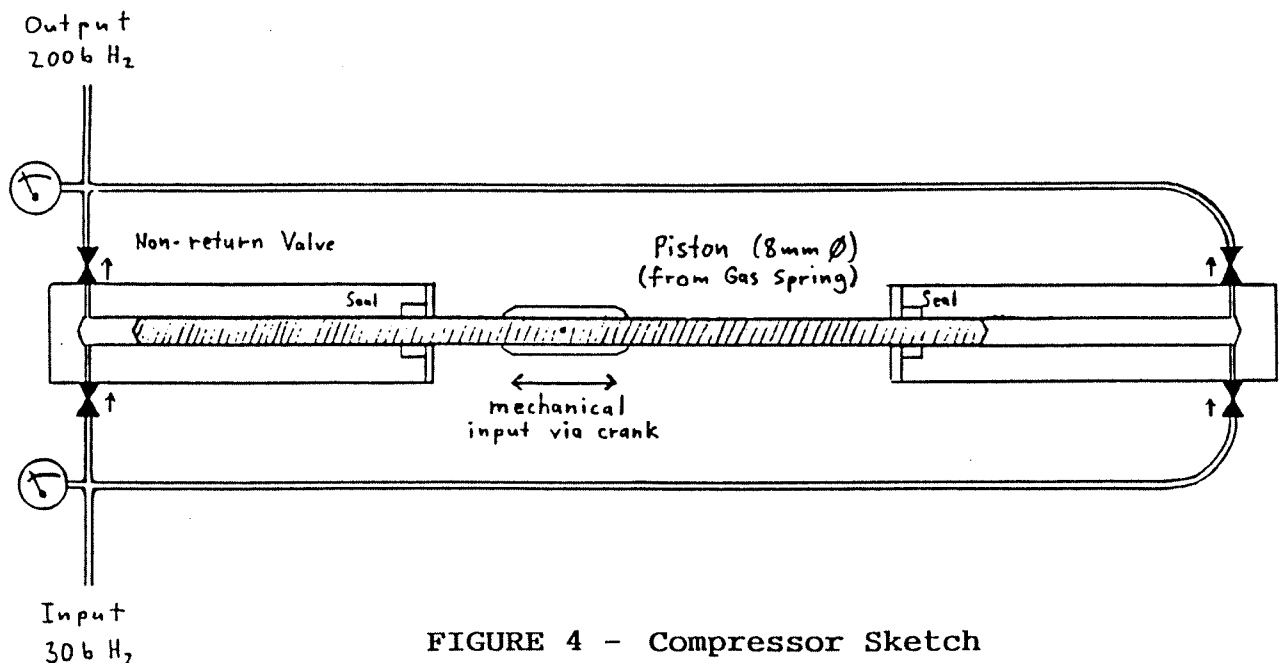

Output
200 b H₂

Non-return Valve

Piston (8mm Ø)
(from Gas Spring)

Seal

Seal

mechanical
input via crank

Input
30 b H₂

FIGURE 4 – Compressor Sketch

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2) 30 bar composite vessels for future use

Quotes were obtained from MMD (Mulhouse) and HM International (Hyeres) for filament wound bottles. The problem of constructing such bottles lies not in the winding, but in the liner, which must be as light as possible yet capable of withstanding the forces of the winding machine and those occuring when the bottle undergoes pressure cycling. Metallic liners such as aluminium are less elastic than the filament winding, even when high-modulus fibers are used, so that they will tend to leak after repeated cycling unless very carefully constructed, or rather thick. Plastic liners are elastic, but difficult to use in winding machines, unless rather thick. For these reasons, standard filament winding techniques are not suitable for low pressures, unless disproportionally heavy liners are used.

Therefore a new technique was invented which is especially suited for hand-laminating low to medium pressure bottles:

Commercially available pre-woven tubing material is placed around a liner, which can be as flimsy as a rubber balloon, and fastened at the ends. Under pressure, the structure automatically assumes the theoretically optimal shape. The laminating resin, which has no real mechanical function other than to keep the integrity of the shape and protect the fibers, is then added and this is repeated for as many layers as needed for the given pressure. Before the resin hardens, the mean angle of the fibers should be adjusted to become slightly less than the theoretically required 54.75° (see further below), either by having chosen a sub-diameter liner or with outside mechanical force. This is in order to ensure that if the cylinder bursts, it will do so by a more or less longitudinal split so that the structure stays together and does not shoot off like a rocket. This point must be especially carefully considered when many layers are added, as the angles will not be the same in different layers. This method is thus well suited for manual fabrication of medium-pressure vessels but probably less for mass production of high-pressure vessels, unless tubing with very thick rovings is available.
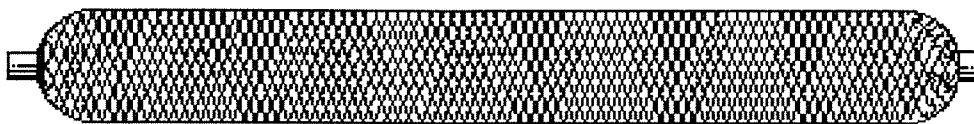
Correspondence with and visits to EMPA showed that there were not yet any standards for fully filament-wound pressure vessels in Switzerland, only for a certain type of fiber-reinforced cylinder. If the Swiss regulations for steel vessels and the ASME standards for filament-wound vessels mentioned earlier are compared, composite vessels wound from the aramid fiber Kevlar (up to15 times higher specific tensile strength than steel) can legally be made to be 5 times lighter than steel ones if it is assumed that the weight of the liner and the laminating resin is 1/2 of the total and that the vessel can pass the thousands of pressure cycle tests done to check the fatigue resistance. Additionally, filament-wound cylinders have an advantage of 25% over homogeneous cylinders, as circumferential

stresses are twice the longitudinal stresses and fibers can be oriented such that this is exactly compensated (angle to axis = $\tan^{-1}(\sqrt{2}) \approx 54.75°$).

Composite bottles made by MMD, ABB and others used in passenger jet airplanes all store up to 4.5% H_2 by weight (steel bottles up to 1.2%), albeit at pressures of several hundred bar, where the percentage weight of liner and fittings is small.

Accordingly, it was attempted to make a 30 bar bottle, using the method described above, which could at least achieve 2-3%.
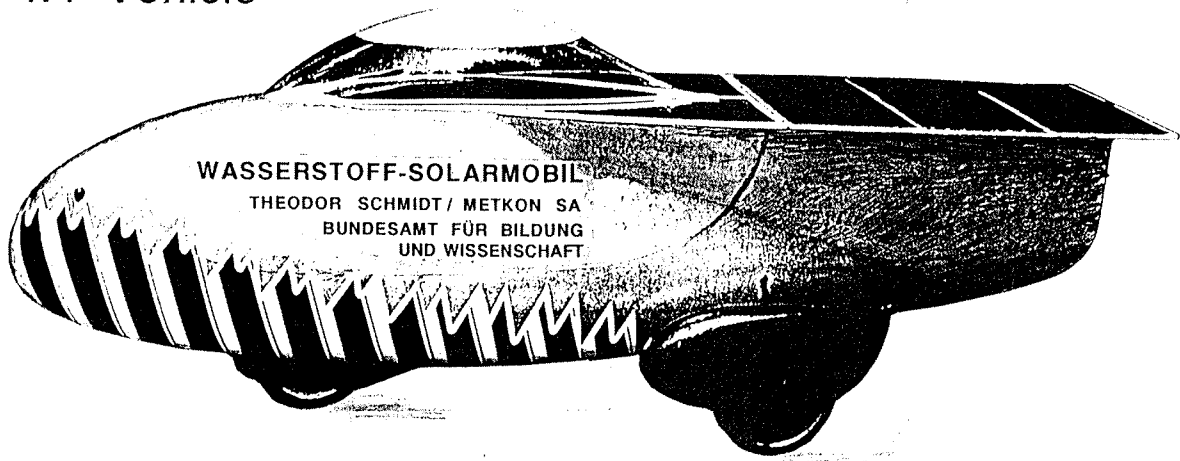
4.4 Vehicle

FIG. 5

The test vehicle is a modified racing solarmobile with reasonably low mass ($\approx$125 kg) and rolling resistance and very low aerodynamic resisitance ($C_D \cdot A \approx 0.15$ m^2). Some of the onboard solar cells were retained in order to power the engine's starting motor and the vehicle's lights and ancillary equipment.

A solarmobile was used rather than a standard car for two reasons:

— The amount of hydrogen required by a standard car running any appreciable distance could never be provided by solar means within a project of this magnitude.

— A hydrogen car with little direct air pollution is only a small improvement on a conventional one and remains one of the worst ways of transporting people in an urban or suburban environment, as the problems of the enormous waste of energy, of the thousand or so people killed annually in Switzerland alone, of noise, and of suburban sprawl remain unsolved. Any useful solution must take all these into account and not just ease a single symptom, so that it is insufficient to merely use a modern power source in an unsatisfactory and outdated concept.

Motor

A small internal-combustion otto-cycle 4-stroke engine was chosen as the only presently available practical heat-engine usable in this size, in spite of the many disadvantages. A

suitable engine was supplied by Romeo Gridelli, who had used this to win the 1982 World Mileage Marathon (0.15 l Petrol/100 km).

The initial conversion to GH_2 proved easy and straightforward. External mixture formation in the intake manifold is the classic method of operating such small engines with low-pressure GH_2:

— replacement of carburetor with long intake manifold in order to store the continually formed H_2/air mixture until the next intake stroke. Supply of H_2 near the intake valve.

— making the timing adjustable. Several references recommended retarding ignition timing to TDC (Top Dead Center) and after because of the higher ignition speed of H_2 compared to petrol.

— removal of the crankcase ventilation connection from the intake manifold in order to prevent explosive mixtures forming in the crankcase. ([1] stresses this as important and goes to great lengths to provide forced crankcase ventilation.)

Although it was easy to get the engine to run on H_2 in some manner, it proved much more difficult to avoid frequent flashbacks of the mixture into the intake manifold, resulting in very loud bangs and sometimes flames. Various things were tried:

— A timed valve in order to admit H_2 only during the actual intake stroke. This seemed to make no difference, probably because its construction was insufficient.

— Water induction for cooling. Although this worked, the water quantity used was considerable and some of it ended up in the engine oil.

— Different spark plugs seemed to make no difference.

— Removal of the unwanted ignition spark between exhaust and intake strokes which small engines generally have, because contacts are worked by the crankshaft rather than by the camshaft. For petrol this makes no difference, but with H_2 operation, this spark can come just at the time when both intake and exhaust valves are slightly open at the same time. A proper H_2 engine would probably also need different valve timing, but this was considered too difficult to modify. The ignition modification improved matters noticeably but not considerably.

— As most of the initial problems occurred during starting, the greatest improvement was achieved by fitting an electric starter and cranking the engine for a second or so before admitting any H_2.

— A flowmeter was essential, in order to be able to admit exactly the right amount of H_2, especially for starting.

— The air intake was adjusted with a variable restriction in the intake manifold. This was an initial setting and subsequent control of the engine was by amount of H_2 admitted only.

Eventually the engine behaved and measurements could be made with a simple dynamometer consisting of a braking element (Kevlar tape) connected to spring scales. Engine speed was measured by stroboscope and H_2 flow with the flowmeter (conical gapmeter).

Table of measurements of first engine. With corrections from December 2022 using $\lambda = 0.418 * Air\% / H_2\%$

H2 consumed	Motor Speed	Torque	Power	Efficiency	Air Number
[Nl/min]	[min^{-1}]	[Nm]	[W]	[%]	lamda λ
4	1500	idling	—	—	≈~~4~~ 4.8
7.5	3000	idling	—	—	≈~~4.5~~ 5.3
10	~~3600~~ 3800	idling	—	—	≈~~4.5~~ 5.0
8	2400	1.0	260	18	≈~~3~~ 3.9
10	2850	1.0	309	17	≈~~3~~ 3.6
14	3400	1.0	368	15	≈~~2~~ 3.1
14	3000	1.6	520	21	≈~~2.5~~ 2.6

(using: 1 Nl H_2 ≈ 3 Wh, l Nl/min H_2 ≈ 180 W)

Because of several mechanical problems and the rather low power of this motor, a nearly identical new one was purchased, but with 107 cm^3 rather than 67 cm^3 cubic capacity. Used with petrol, the manufacturer gives 2.6 kW at 3600 min^{-1} and a maximum efficiency of 25%. The compression ratio is given as 8.7. The new motor was converted in a similar manner to the old one, however it seemed for a while impossible to get rid of frequent flashbacks, no matter how the ignition was adjusted. Much time was wasted in trying out various different ignition systems. I later found out that there were three regions of ignition timing angle:

1. The region after TDC produced smooth but inconsistent running with occasional flashbacks.

2. The region around TDC. Here the engine would not run at all, but it was not dicovered why.

3. The region before TDC. Here the engine runs well without flashbacks, but sounds rough.

In the end, the engine's original electronic magneto ignition was used in spite of having a fixed non-adjustable timing angle of 25° before TDC, which seems rather early. However

this ignition system proved more reliable than the experimental one and flashbacks no longer occured.

NO_x in the exhaust was not measured because equipment for this was not readily available and because all references agree that NO_x levels at a λ of 2 and above are extremely low.

The engine was then installed in the vehicle and first driving tests done. It was quickly apparent that even this motor was very prone to stalling when loaded too much. In contrast to petrol operation, where more torque is generally available by introducing more fuel, injecting more GH_2 displaces the same volume of air, limiting maximum power more quickly than with a liquid fuel. At the stochiometric ratio (where λ, the air/fuel ratio, is defined to be 1) the mixture contains about 30% H_2 by volume, limiting the maximum power to some 70% of that with liquid fuels or even other heavier gaseous fuels, e.g. propane, where only 4% is required for a stochiometric mixture. A simply modified engine like this one won't run near $\lambda=1$ in any case, as the combustion temperature becomes so high, that preignitions and flashbacks become uncontrollable without special measures, e.g. water induction. It runs well on very lean mixtures ($\lambda \approx 5$ idling, ≈ 3 working), but stops well before $\lambda=1$, again limiting the maximum power to a value well below that available with heavier fuels.

Gearing

With such a relatively weak engine, a very wide range of gearing is required if the vehicle is to be capable of both climbing an incline and running on the level at a reasonable speed. Such a gear was developed and constructed from two "Deltamats" in tandem, a continuously variable transmission (CVT), developed by Willi Lanker and manufactured by Delta AG, which was used with great sucess in the early Tours de Sol. The ratio is adjustable from 0.33 to 4.5, giving a total adjustment range of over 13. The vehicle is geared from 6 km/h to 80 km/h at maximum motor revolutions.

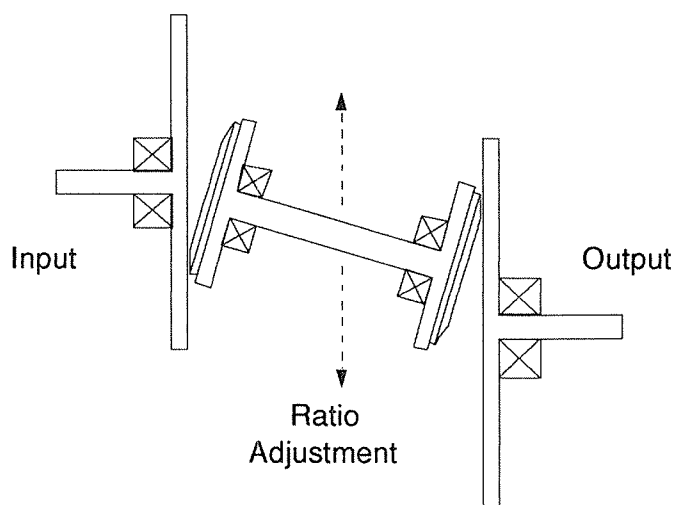Input   Output

Ratio
Adjustment

FIG. 6

This shows the principle of the CVT. Not shown are cams which set the pressure of the rubbing surfaces proportional to the torque and the spring-loaded carriage which sets the gear ratio automatically to the de-sired input torque.

5. Results

5.1 Electric Power Generation (Th. Schmidt)

The solar panels were indeed able to work at the efficiency given by the manufacturer (max 14% photovoltaic cell efficiency) but it must be noted that the specific conditions (1 kW/m2 insolation and 25° cell temperature) are quite rare, but this was not further investigated as ample literature exists. With the rooftop array, maximum power available on a cloudless day was usually around 900 W rather than the specified 1250 W peak, which could only be approached in winter (cool cells) and with reflecting clouds.

The mains inverter (NEG 1400) worked at a maximum efficiency of 90%. Maximum daily harvest into the mains was 6 kWh in summer, 3 kWh in winter. Extrapolated from 11 months continuous running, the yearly harvest is 1100 kWh, the equivalent of 310 Nm3 of H_2.

Very few problems were encountered with the solar installations or with the portable panels.

5.2 Hydrogen Generation (Metkon)

Preliminary measurements of the cell electric characteristics have been performed by feeding the electrolyzer with a conventional AC/DC converter, where the DC flow can be set in the range 0-30 ADC.

Table 4 summarizes the results.

MKA Job 15352

TABLE 4 : Preliminary electrolytic cell characterization

Module of 13 cells type 0010 – reinforced type for high pressure

Electrode nickel extended plate – Raney nickel activated

Diaphragm HS

Elastic element nickel corrugated net

Electrolyte KOH concentration 30 %

Temp	Current	Current density	Module Voltage	Cell Voltage	Pressure	Analysis %	
C	A	A/m^2	V	V	kg/cm^2	$O_2 in H_2$	$H_2 in O_2$
39	10	1087	23.7	1.82	atm	0.50	
32	20	2174	26.4	2.03	atm	0.25	
36	30	3260	27.5	2.11	atm	0.18	
46	10	1087	23.2	1.78	8	0.60	
44	20	2174	25.0	1.92	8	0.35	
45	30	3260	26.2	2.01	8	0.24	
49	10	1087	22.7	1.75	20	0.70	
47	20	2174	24.8	1.91	20	0.40	
48	30	3260	26.0	2.00	20	0.28	
54	10	1087	22.3	1.72	30	0.75	
54	20	2174	23.9	1.84	30	0.42	
55	30	3260	25.5	1.96	30	0.30	

Notes

The electrolyte temperature has been set at various levels, ranging from 32 to 55 °C.

The operating pressure was set at values from atmospheric to 30 bar. At the highest temperature (54-55 °C) the voltage efficiency ranges from 76% to 86% at current density decreasing from 3260 to 1087 A/m2. The effect of the temperature on the performance is substantial, as expected: the electrolyzer has been designed to operate up to 80 °C.

When operating above the thermoneutral cell voltage of 1.48 V, as in the usual case, the voltage excess over 1.48 V is turned out as heat increasing the electrolyte temperature. This phenomenon is used to raise the electrolyte temperature up to the desired value, removing then the excess heat to keep constant the temperature at the desired value.

This usual practice was not well applicable to this project, due to the strong influence of heat losses in the very small scale of the unit, despite the insulating characteristics of the cell materials. Added to that, the natural discontinuity of the solar power does not allow to achieve operating temperatures sufficiently high to give reasonably high electrolysis cell efficiency.

The maximum practical temperatures recorded by Th. Schmidt are in the range of 30 °C.

This limitation will be obviously removed in larger scale units, where heat losses are significantly less influent.

The stability of the cell performance is a second important aspect. The already mentioned discontinuity of the solar radiation has a strong importance on the life time of the electrode coatings. These are electrocatalysts having the aim of lowering the electrode overvoltage with

respect to the use of solid metal electrodes, increasing the cell power efficiency.

Electrocatalysts developed for the industrial water electrolysis and normally used at constant load suffer for the discontinuous load characteristic of the solar radiation. This load can vary broadly in very short time (even a few seconds) from full load to zero or vice versa, and this many times in a day.

The result is a progressive decrease in the cell efficiency, which can be noticed for instance by comparison of Th. Schmidt's measurements (FIG. 7) with the preliminary data of Tab. 4.
We achieved two long tests, in which a lot of frequent changes of current load and different periods of unsteady shut down from 3 to 42 hours have been deliberately operated, in order to emphasize better the behaviour of said electrocatalysts under discontinous load operations.

The electrolysis module used in these tests was exactly alike to the one installed in the water electrolysis system described in 4.2. In particular the electrodes (the anodes and the cathodes) were composed by nickel extended plates on which an electrocatalyst was put.
Said activation was obtained by covering the electrodes with a thin layer of Nickel-Alluminium alloy by a plasma spray technique. Later the Alluminium was leached by a hot aqueous NaOH solution bringing to the formation of an active Raney-Nickel layer.

This module was tested for about 9 days on a pilot electrolyzer: the only difference with the plant supplied to Th. Schmidt was the operating pressure that could not exceed 6 bars. The results (see Table 5 and FIG. 10) show an evident increase on cell voltage with the time, sign of a

loss of activity of the electrode surface, followed by a period of constant values.

When the module was dismantled it was possible to see on the surface of anodes an overwhelming decrease of the catalyst layer and at the same time a black suspension, probably due to Nickel or Nickel oxides, was visible on the discharged electrolyte. The cathodes did not apparently show any remarkable modification.

In a later test, which lasted 11 days, we used the same kind of activated Raney-Nickel cathodes. Sand-blasted nickel extended plates were used as anodes, without any activation. The results (see Table 6 and FIG. 11) show that cell voltages are quite constant during the test period and practically like the ones obtained in the previous test after the activation loss. No black suspension was found in the electrolyte.

This subject needs a specific detailed investigation, not included in the scope of the present project.

Further problems are raised by the solar variations in the produced hydrogen purity. It can be seen from Table 4 how the concentration of oxygen in hydrogen is varying with cell load, and how the contamination increases at low load.

This is a combined effect of the cell diaphragm physical characteristics and current density. The cross diffusion of the gases through the diaphragms increases also with the electrolysis pressure and becomes critical as much as the DC flow approaches the zero, which happens often with the solar radiation variations.

Also this subject requires future investigation, outside the scope of this project.

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Finally, the control logics for water electrolysis plants fed by photovoltaic fields requires further developments. The presence of a DC/DC converter as the MAXIMIZER used in this project introduces limitations in the power transfer to the electrolysis cells.

Other ways must be investigated for a direct coupling of the PV-field to the electrolysis unit, in order to optimize the system efficiency.

TABLE 5 : Cell behaviour versus time with activated electrodes

Module of 13 cells type 0010 - reinforced type for high pressure

Electrode nickel extended plate - Raney nickel activated

Diaphragm Polisulphone - type HS

Elastic element nickel corrugated net - type Italfim

Electrolyte KOH   concentration 30 %

Time	Temp.	Current	Module Voltage	Cell Voltage	Pressure	Analysis %	
h	C	A	V	V	kg/cm^2	O_2inH_2	H_2inO_2
0	45	20	24.8	1.91	4	0.20	
1	48	5	22.2	1.71	4	0.30	
1.5	44	30	26.2	2.01	5	0.20	
3	51	10	22.5	1.73	5	0.18	
4	50	5	22.3	1.71	5	0.26	
6	48	30	26.3	2.02	6	0.21	
7.5	54	10	23.0	1.77	6	0.21	
11	50-35	0	(shut down for 3.5 hours)				
14	46	20	25.0	1.92	4	0.19	
16	51	30	26.5	2.04	5	0.18	
17.5	54	10	23.2	1.78	5	0.20	
20.5	53	5	22.6	1.74	4	0.28	
24	55	30	26.6	2.05	5	0.18	
32	55-28	0	(shut down for 8 hours)				
36	43	10	23.5	1.81	4	0.22	
39	48	20	25.2	1.94	5	0.20	
42	53	30	26.8	2.06	5	0.18	
82	53-22	0	(shut down for 40 hours)				
85	32	5	22.9	1,76	4	0.33	
90	41	20	25.5	1.96	5	0.22	
93	47	30	27.2	2.09	5	0.20	
95.5	51	10	23.6	1.81	5	0.21	

Notes

(Continue)

Time	Temp.	Current	Module Voltage	Cell Voltage	Pressure	Analysis %	
h	C	A	V	V	kg/cm^2	O$_2$inH$_2$	H$_2$inO$_2$
96	53	20	25.6	1.97	4	0.20	
101	50	5	23.1	1.77	4	0.30	
104	52	30	27.3	2.10	5	0.20	
112	51-30	0	(shut down for 8 hours)				
115	44	10	23.8	1.83	5	0.26	
118	48	30	27.5	2.11	6	0.18	
128	54	20	25.8	1.98	6	0.21	
137	54-31	0	(shut down for 9 hours)				
141	46	20	25.8	1.98	4	0.22	
143	49	30	27.4	2.11	5	0.18	
148	49	10	23.8	1.83	5	0.20	
152	53	30	27.4	2.11	6	0.18	
162	55-24	0	(shut down for 10 hours)				
166	44	20	25.8	1.98	5	0.20	
168	48	10	23.7	1.82	4	0.22	
171	51	30	27.4	2.11	5	0.18	
173	50	5	23.2	1.78	4	0.28	
185	50-25	0	(shut down for 12 hours)				
189	42	10	23.8	1.83	4	0.26	
192	49	20	25.7	1.97	5	0.22	
195	52	30	27.4	2.11	5	0.20	
198	50	5	23.3	1.79	4	0.27	

Note 1 – The electrolyser was runned continuously except for the indicated shut down periods. On the graph (see Fig.10) was reported the effective running time.

Note 2 – The cell voltage correspondes to the average value for each considered period.

Note 3 – The temperatures were not constants as they depend on the current load.

TABLE 6 : Cell behaviour versus time with activated cathodes and pure nickel anodes

Module of 13 cells type 0010 – reinforced type for high pressure

Electrode   cathode: nickel extended plate – Raney nickel activated
            anode : nickel extended plate – sand blasted

Diaphragm Polisulphone – type HS

Elastic element nickel corrugated net – type Italfim

Electrolyte KOH   concentration 30 %

Time	Temp.	Current	Module Voltage	Cell Voltage	Pressure	Analysis %	
h	C	A	V	V	kg/cm^2	O$_2$inH$_2$	H$_2$inO$_2$
0	42	10	23.8	1.83	4	0.30	
3	45	5	23.2	1.78	3	0.33	
11	48	20	25.8	1.98	5	0.20	
21	50-33	0	(shut down for 10 hours)				
26	52	30	27.3	2.10	5	0.18	
31	48	10	23.8	1.83	5	0.21	
34	50	5	23.3	1.79	4	0.31	
46	49-35	0	(shut down for 12 hours)				
50	46	10	23.9	1.84	5	0.28	
54	51	30	27.5	2.11	5	0.18	
57	50	5	23.4	1.80	4	0.33	
59	53	20	25.7	1.97	4	0.28	
70	52-31	0	(shut down for 11 hours)				
75	49	5	23.5	1.81	4	0.31	
78	52	10	23.7	1.82	4	0.22	
84	48	30	27.6	2.12	5	0.18	
126	53-28	0	(shut down for 42 hours)				
131	46	20	25.8	1.98	5	0.25	
134	45	10	23.8	1.83	4	0.29	
140	41	5	23.5	1.81	4	0.30	
152	40-28	0	(shut down for 12 hours)				
155	51	30	27.7	2.13	5	0.21	

Notes

(Continue)

Time	Temp.	Current	Module Voltage	Cell Voltage	Pressure	Analysis %	
h	C	A	V	V	kg/cm^2	$O_2 in H_2$	$H_2 in O_2$
159	50	10	24.0	1.85	4	0.22	
161	47	50.0	23.3	1.79	4	0.30	
165	53	30	27.8	2.14	5	0.18	
179	51-27	0	(shut down for 14 hours)				
183	47	20	25.9	1.99	5	0.22	
188	49	5	23.5	1.81	5	0.28	
191	50	10	24.0	1.85	4	0.21	
193	54	30	27.9	2.15	6	0.17	
205	46-25	0	(shut down for 12 hours)				
209	46	5	23.4	1.80	4	0.30	
211	49	20	25.8	1.98	5	0.21	
214	53	30	27.8	2.14	5	0.18	
224	52-24	0	(shut down for 10 hours)				
229	44	10	24.2	1.86	4	0.20	
231	48	20	25.8	1.98	5	0.22	
234	46	5	23.5	1.81	4	0.28	
237	50	30	27.9	2.15	5	0.19	
251	50-23	0	(shut down for 14 hours)				
254	42	5	23.5	1.81	4	0.32	
257	51	30	27.8	2.14	5	0.20	
261	47	10	24.1	1.85	5	0.24	
264	49	20	25.8	1.98	4	0.21	

Note 1 – The electrolyser was runned continuously except for the indicated shut down periods. On the graph (see Fig.11) was reported the effective running time.

Note 2 – The cell voltage correspondes to the average value for each considered period.

Note 3 – The temperatures were not constants as they depend on the current load.
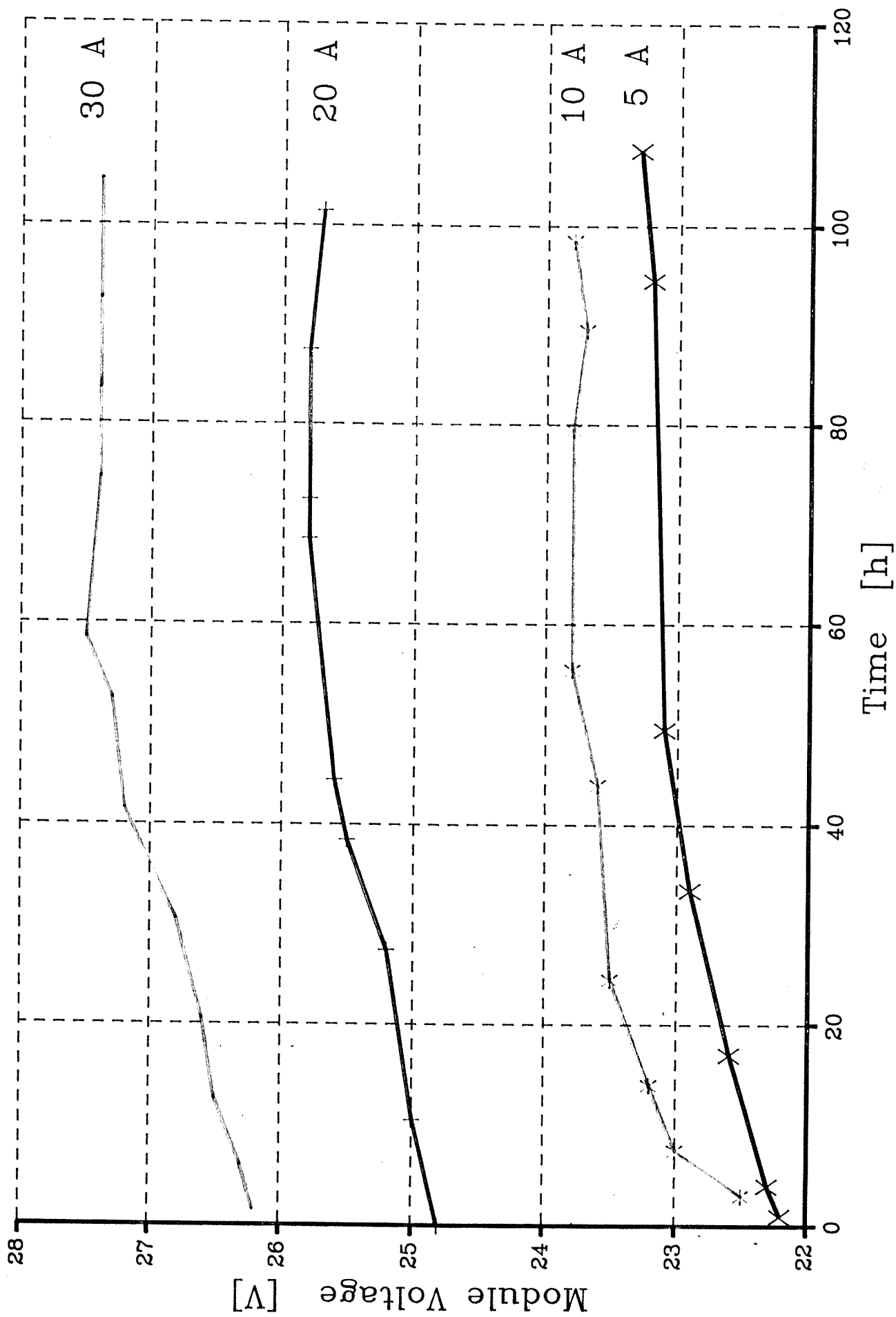
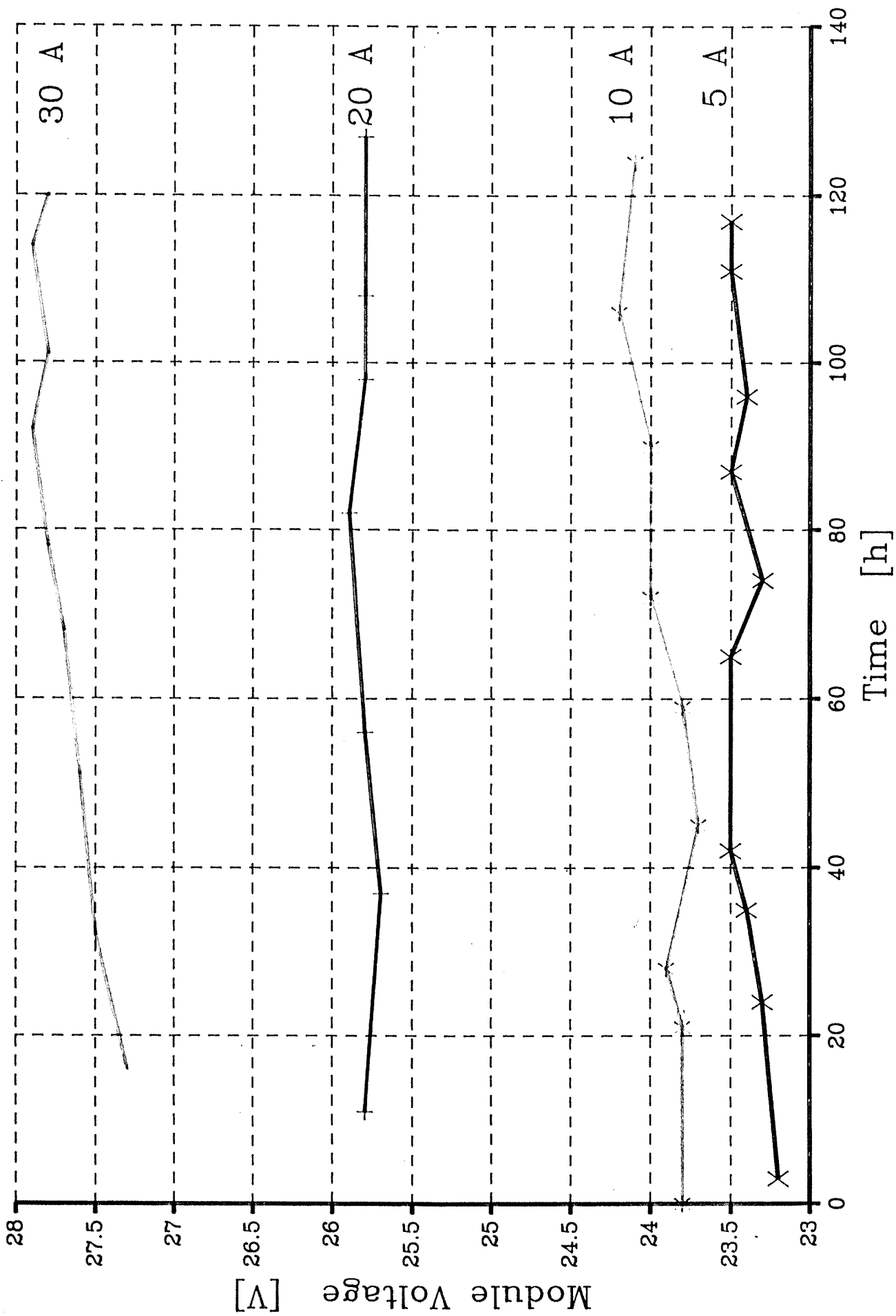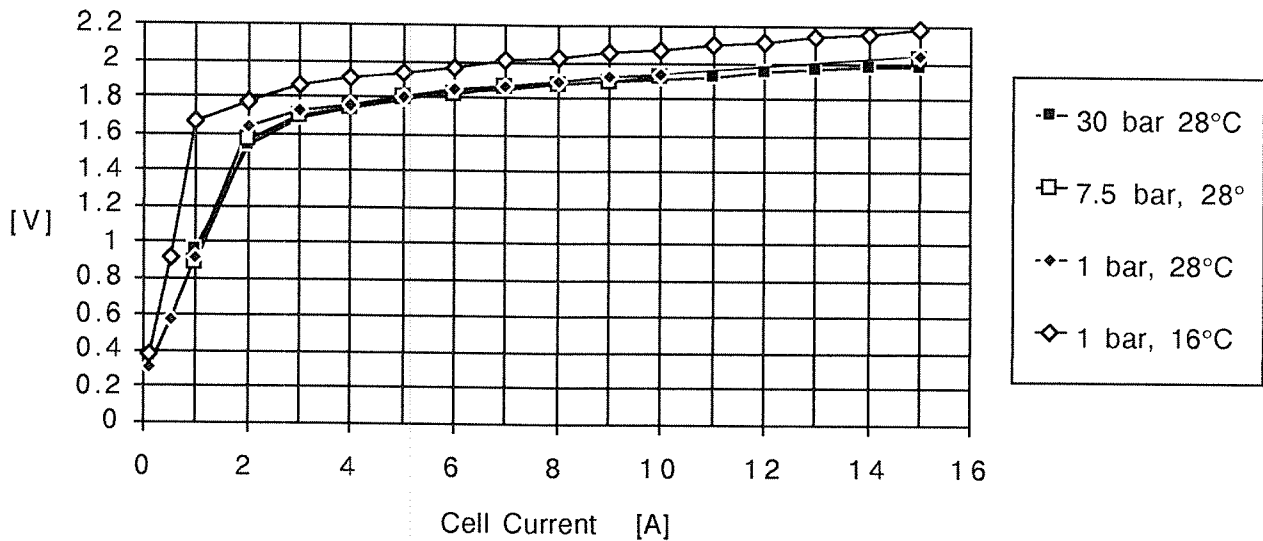FIGURE 10 - Module Voltage Versus Time Behaviour with Activated Electrodes

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FIGURE 11 - Module Voltage Versus Time Behaviour with Activated Cathodes and Pure Nickel Anodes

FIG. 7   Cell Voltage


5.3 Hydrogen Compression (Th. Schmidt)

FIG. 7 shows measurements of the electrolyzer cell voltage at several pressures and temperatures for one cell (total stack was 13 cells). The effect of pressure is seen to be negligible, even though energy considerations (see formula for energy of compression on page   ) would require a cell overvoltage of about 0.05 V at 30 bar. As this is not observed and indeed the values indicate a very slightly *lower* voltage at 30 bar, the electrolytic compression in this case is more than completely "free". This may be due to the higher conductivity of the electrolyte with smaller gas bubbles.

The mechanical compressor which is used to increase pressure from 30 to around 200 bar works well except that its non-return valves sometimes stick in the open position after a period of not being used. Because of the rather small cylinder volume and the dead spaces in the valves, volumetric efficiency drops to very low levels around 200 bar, effectively limiting the maximum pressure to a bit over 200 bar. FIG. 8 shows that, when starting from 30 bar, the cumulative efficiency is between 40 and 50% for a wide pressure range and drops to 35% at 200 bar (this is the efficiency compared to an ideal compressor and must not be confused with the efficiency of the whole process of storing GH_2 under pressure). The most efficient bottle pressure with this compressor is 100-120 bar, where the electrical energy required for the compressor is only 2-2.5% of the energy stored in the hydrogen.

Due to the low power and the temporary nature of this compressor, no filters, lubricating system, cooling system, or vapor traps were included. It is used in the following manner: When the Electrolyzer system pressure reaches 31-32 bar, the compressor, which is connected between the Electrolyzer and a steel bottle, e.g. a 4-liter one as shown in the measurements in the graph overleaf, is switched on until the input pressure drops to about 28 bar. This only takes a few seconds to begin with, so an additional 4-liter bottle is connected to the input as a capacitor, in order to permit longer running.

[%,Wh]

Pressure [bar]
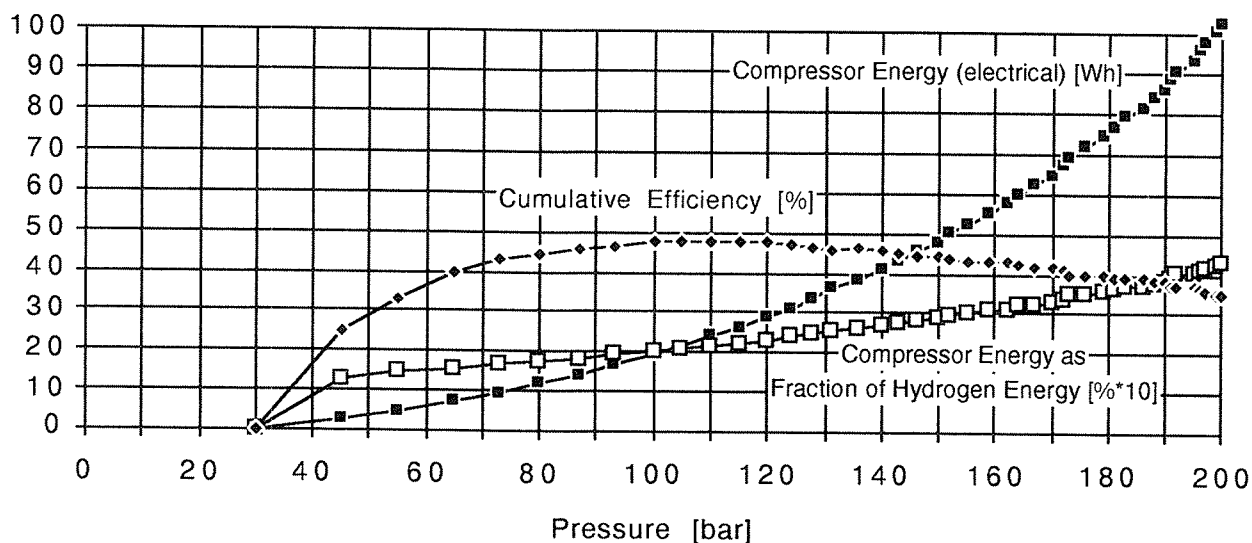
(using Hydrogen Energy=3.55Wh/Nl; theoretical (isothermal) Energy of Compression= 0.028 ln(P2/P1) Wh/Nl)

5.4 Hydrogen Storage

Three sizes of 200 bar steel bottles were used: 4 liter and 5 liter bottles each weighing 7 kg and 10 liter ones weighing 14-15 kg, depending on make. Only one bottle was used in the vehicle at a time, but it would be possible to put up to eight 10 liter bottles in the vehicle, giving a total amount of 16 Nm^3 H_2.

One composite bottle using the described invention was made. It was designed for a working pressure of 30 bar and a bursting pressure of 150 bar. A thin aluminium liner was chosen in order to acchieve "leak before burst" characteristics. Construction was purposely done in a slovenly manner in order to assess the importance of quality control.

At 1 kg for a volume of 4.75 liters (giving 1.28% H_2 storable by weight at 30 bar), the bottle has not turned out lighter than a good one made of steel, mainly due to an excess of epoxy resin and the fixed weight of valve and end fittings. The bottle was tested destructively at EMPA, resulting in its bursting at 150 bar, exactly as calculated, in spite of the slovenly construction. The desired leak-before-burst characteristic was also achieved, but far too early. Leaking started at 15 bar instead of around 100 bar as intended. Severe leaking started at 70 bar. It appears that only a carefully made one-piece liner would offer a predictable leaking characteristic.

For this reason, the next bottles will be made with plastic liners. A full safety certification by EMPA (to "exemption-type" rules, as no definite Swiss rules yet exist) would require 10-15 bottles for destructive testing, which would take longer than the time available. Any further bottle development will have to be done in a follow-up project. Then it might also be desirable to raise the working pressure to about 100 bar, a pressure probably reachable by electrolytic compression in the near future (or easily reached by a waste-O_2-powered compressor) and a good compromise in bottle weight and storage efficiency. Also, the bottle would not burst if inadverently filled to the standard 200 bar pressure.

5.5 Hydrogen Vehicle

Measuring equipment used

Bottle and system pressures were measured with standard Bourdon-type pressure-guages. H_2 flow was measured with conical gapmeters made by Gloor AG and Platon Ltd, measuring up to 18 Nl/min at 1.5 bar and 44 Nl/min at STP, respectively. These do not easily provide an electrical signal, so that in addition a standard certified bellows-type household gasmeter was converted to give one impuls per N liter. For instantaneous reading with an analog output, a sensitive solid-state pressure transducer (Honeywell 163 PC) was fitted with a pneumatic shunt (several lengths of thin tubing connected in parallel) to read flow. This was calibrated using the flowmeters and checked later on against the bellows gasmeter.

Measurements were stored by a MODAS 84 32k Datalogger (Neue Energie Systeme) which can read 4 channels at up to once per second.

This was also connected to a digital wheel sensor to give speed and distance and a solid-state inclinometer (Schaevitz Accustar) to give the angle of road steepness, as longer stretches of level road are very rare in Switzerland.

The datalogger was set up to record continuously while driving so as to be able to concentrate on the road. An additional electronic speedometer and odometer was fitted with an easily visible display. After a run, the data could be transfered to a portable computer and later to a desktop computer, where it could be evaluated and graphed with the program Excel.

Results

The graphs in FIG. 9 show a typical run. The inclinometer data is seen to be sensitive to road vibration, acceleration and braking and had to be verified with a mechanical inclinometer. Only data at points where acceleration is near zero could be used. The coefficient of rolling resistance was measured with a spring scale at about 1%, twice the value anticipated, probably because the wheel arms are not rigid enough to keep the rear wheels exactly parallel.

Average consumption on the level, from the run shown and two others, all at speeds from 40-45 km/h, was 31 Nl/km, or 93 Wh/km. Earlier measurements at 25 km/h gave 24 Nl/km, or 72 Wh/km.

Climbing a gradient of 3.9°, or $\approx$6.8%, gave a consumption of 170 Nl/km. Climbing a gradient of 3.1°, or $\approx$5.4%, gave 132 Nl/km. If regarding as useful work the potential energy gained of driver and vehicle (total 1990 N), this works out to efficiencies of 7.4% and 7.5%, respectively, using the lower heat of combustion of H_2 ($\approx$3Wh/Nl) as input. Two measurements were also made driving up a hill with varying gradients with maximum power. With a vehicle weight here of 1900 N including driver, 100 m of altitude were gained in 10 minutes using 300 Nl H_2; another test working out to 500 Nl/100 m in 14 minutes. The efficiencies here work out to 5.9% and 3.5%, showing the large drop of efficiency when average and not peak driving conditions are regarded.

Because no long enough stretches of level road could be found, average values for driving on the level could not be measured. It was originally hoped that the acceleration and the gradient effects could be seperated in the inclinometer data, which would allow the isolation of that proportion of
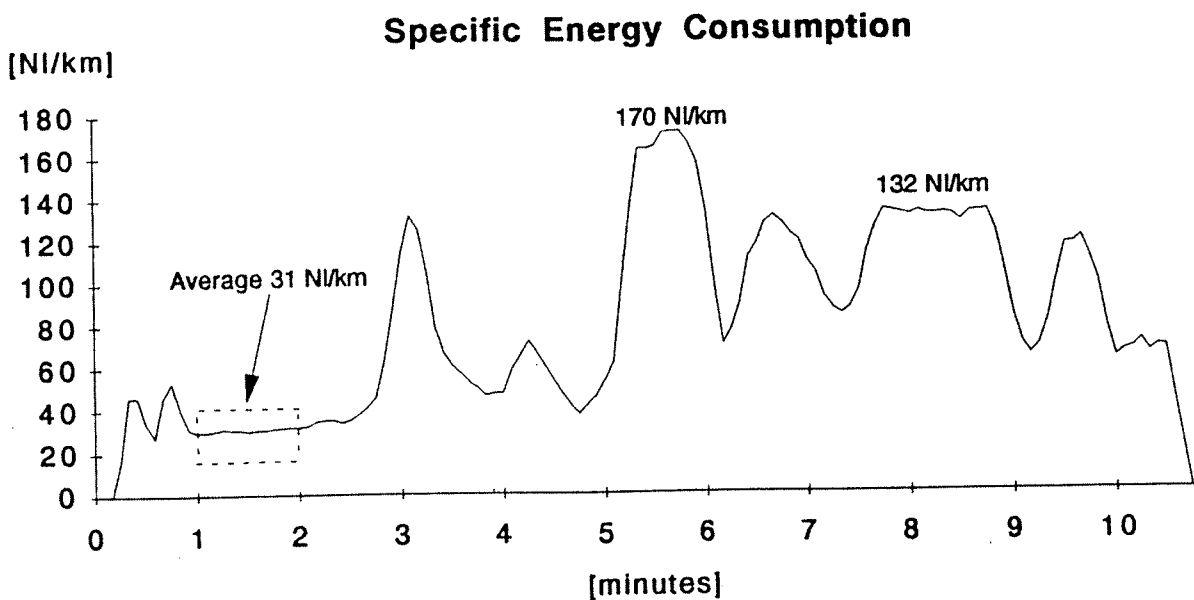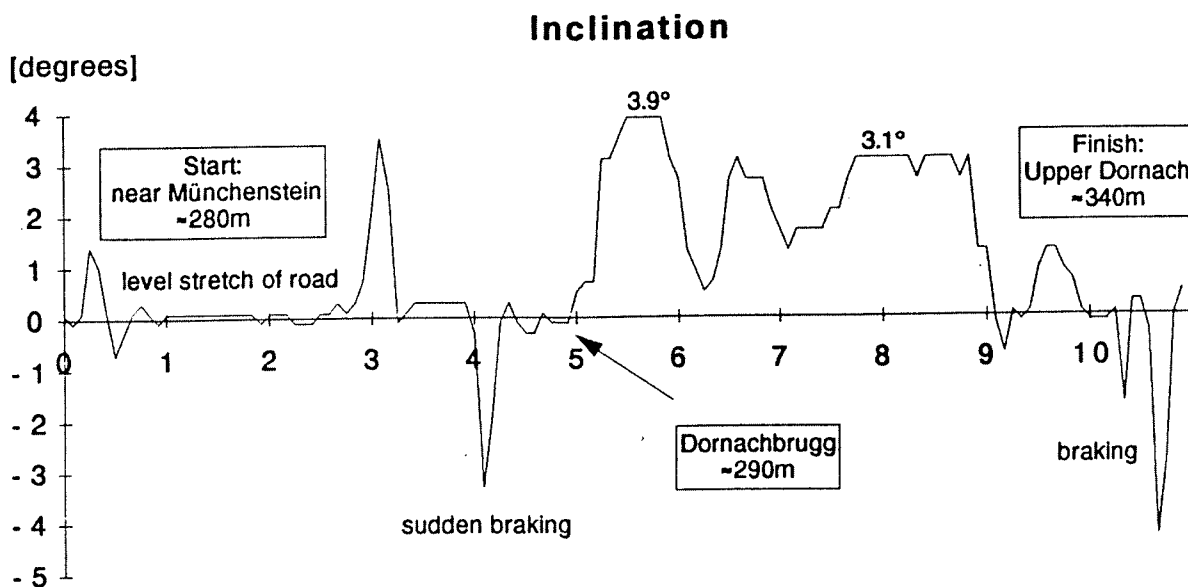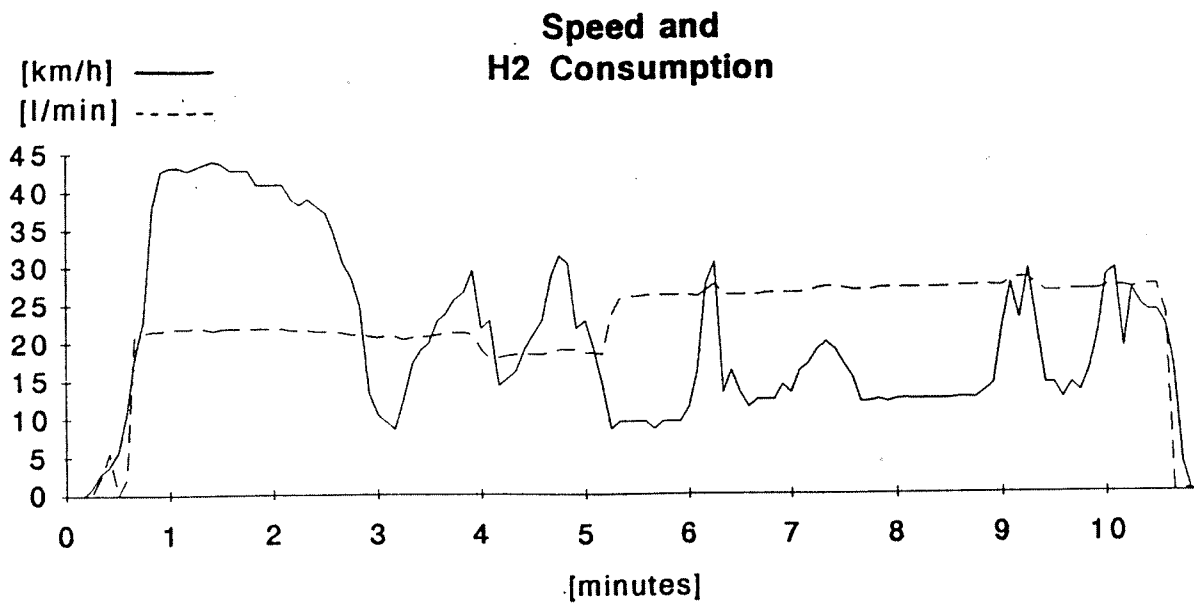
Speed and H2 Consumption

[km/h] ———
[l/min] - - - -

[minutes]

Inclination

[degrees]

Start:
near Münchenstein
~280m

level stretch of road

3.9°

3.1°

Finish:
Upper Dornach
~340m

Dornachbrugg
~290m

sudden braking

braking

[minutes]

Specific Energy Consumption

[Nl/km]

170 Nl/km

132 Nl/km

Average 31 Nl/km

[minutes]

FIGURE 9 – Typical Data of a Vehicle Run

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power required for climbing. Because of the vehicle's springs, the general bumpiness of the road, the relatively low temporal resolution of the data, and the large effect of even small changes of gradient, it was then decided that this would not give any meaningful results unless the measurements were done in much greater depth with much higher accuracy. For example, altimeter data could be incorporated, but this would again have to be isolated from aerodynamic pressure effects...

Handling

The vehicle is not very practical to drive, but with practice it is possible to drive safely on public roads. The vehicle is equipped with pedals to accelerate to about walking speed, after which the motor can be started. The pedals are otherwise not used, except for low speed manoeuvring, in order not to falsify measurements and driving impressions. There is no clutch and speed is adjusted mainly through the CVT. H_2 quantity is adjusted with a valve, but only flows as long as a spring-loaded trigger is depressed. There is no idling; the motor is stopped for every halt. Being connected through a freewheel, the motor can be stopped at any time and the vehicle can coast or be pedalled if the traffic situation demands it. There is no braking with the motor. Acceleration is automatic, the CVT acting to keep the torque loading on the motor constant at a value adjustable with a lever, irrespective of speed or the slope of the road. In spite of this, acceleration is sluggish because the motor has no overload capability like an electric one. Even worse, the motor will stop suddenly without warning if overloaded only briefly, quite unlike the petrol 2-stroke motors used on mopeds. The automatic CVT doesn't always react quickly enough to prevent motor stalling if the road steepness increases suddenly. Top steady-state speed measured on the level was about 50 km/h. Caution tempered the desire to go faster by exploring the limits of engine speed.

Noise

The motor exhaust passes through two silencers connected in series and the exhaust noise is slight. As the motor itself is completely inside the vehicle, it is quite quiet outside when driving with the top shut. According to observers, the noise is less than that of most motor vehicles, and even less than that of some electric vehicles.

It is completely different inside the vehicle. In spite of being rubber-mounted, the noise from the motor's casing and from the air intake is considerable. A separate motor enclosure or a silencer for the intake manifold was not considered in order to avoid the possibility of the accumulation of explosive mixtures.

Exhaust Emissions

These were measured with the motor idling with garage type equipment, showing no CO, CO_2, and HC emissions to the sensitivity of the equipment, as was to be expected.

O_2 content of the exhaust was measured at idling and under full load to be 17-18% and 14-15%, respectively, corresponding to $\lambda \approx 6$ and $\lambda \approx 3$.

NO_x emissions, the only ones of interest, were not measured, but with the very lean mixtures used, these emissions are negligible and only a tiny fraction of the values reached under stochiometric operation, as for example with petrol. [4]

6. Safety

6.1 Electrolyser

Hydrogen-Oxygen Mixtures

The main point to be stressed out is the potential danger represented by the presence, in the plant, of hydrogen and oxygen, the two gases being the products of the water electrolysis process. When they are mixed together, they have a strong natural tendency to react with each other forming water, the reverse reaction with respect to the electrolysis process. This reaction does not occur spontaneously, but it can be started by any flame or spark or high temperature surface and leads to a deflagration.

In normal operating conditions, the produced hydrogen contains few tenths of volume percent oxygen. This oxygen concentration is not hazardous, being it largely lower than the Low Explosion Limit (LEL) of the gas mixture, which corresponds to 6% by volume of oxygen in hydrogen.

In turn, oxygen is normally released containing few tenths of volume percent hydrogen, which is not a hazardous mixture, being it largely lower than the LEL of the gas mixture, which corresponds to 4% by volume of hydrogen in oxygen.

From their generation at the electrodes the two gases are kept accurately separate from each other.

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Intermixing of hydrogen with oxygen through displacement of the electrolyte is carefully prevented by a system of liquid level controls and alarms.

The only practical possibility of massive intermixing is the breakage of the cell diaphragms, a failure very unlikely to occur.

The last possibility of hydrogen and oxygen mixing is due to the tendency of the two gases to migrate by diffusion through the cell diaphragms. This phenomenon takes place very slowly and is responsible for the usual and very limited cross contamination of the two gases during normal operation. When the plant is stopped during operation, this diffusion, which is promoted by the gas pressure, gives in the long run a substantial cross contamination of the gases to be avoided for safety reasons.
This is why, after any plant stop, the unit is automatically reverted to atmospheric pressure, in order to slow down this diffusion phenomenon.

The same contamination effect, which is independent from the cell current density, becomes more evident when the electrolysis is run at very low DC flow, an event which can occur when it is directly powered by the solar field.

The electrolysis unit has been equipped with a portable gas analyzer, useful for a periodical check of hydrogen quality.

Hydrogen-Air Mixtures

Hydrogen in air forms flammable mixtures above a LEL of 4% by volume.

Air should never be present inside the process vessels of the hydrogen generating unit, which must be inertized by nitrogen (by depressing the EMERGENCY button) before the first hydrogen generation run will be started.

Hydrogen leakage in the atmosphere can also form flammable mixtures, which can be prevented by ventilation or can be revealed by a proper hydrogen-in-air sensor connected with a LEL % monitoring and alarm unit.

Overpressure relief

Pressure vessels are protected against overpressure by relief valves (PSV-01 on OV, PSV-02 on HV).
They are set at a cracking pressure (starting gas relief) of 32 bar.

Lack of Energy

In case of lack of energy from the PV-field, the battery installed in the control unit will assure the running of all controls up to when, becoming insufficient the battery charge, the plant will revert to atmospheric pressure, in fail-safe condition.

6.2 Compressor

Due to the ratio of dead space in the valves to cylinder volume, the volumetric efficiency decreases with increasing pressure and eventually reaches zero, after which a further increase in pressure is not possible. In our case, the maximum pressure obtainable is approximately 220 bar,

well within the design limits of tubing, fittings and valves.

6.3 Storage Bottles

All bottles used were EMPA-approved. The experimental bottles were not used except for tests at EMPA.

6.4 Vehicle

In the following, only points are listed which pertain to the use of hydrogen in this particular vehicle:

- The hydrogen system was deliberately kept simple and the volumes kept small, so that no appreciable amounts of explosive mixtures could form, with the exception of a commercial gas meter built strong enough to withstand an internal detonation.

- Several pressure reduction stages and no other pressurized gases ensure that no air can get into the system while it is operating.

- A normally closed solenoid valve operated by a spring-loaded trigger prevents any inadvertent release of H_2.

- The system is periodically checked to be absolutely leak-free.

- The motor cannot be kept idling while the vehicle is stationary, except when the top has been raised and the driver has got out. The motor can only be started when

the vehicle is already moving. While driving, air is forced through the vehicle from front to back. Thus there is always sufficient ventilation to prevent the formation of explosive mixtures within the vehicle.

- The whole system was subjected to the scrutiny of an expert on the safety of flammable gases.

Two main risks were present:

1. Nearly invisible flames from leaks or from the motor's air intake (after a motor malfunction) could ignite other flammable materials. For this reason, the most flammable parts of the air filter were removed and a fire extinguisher carried.

2. Detonations within the air intake manifold could possibly rupture this (made of plastic) and cause injury. During driving, any such shrapnel would however be contained within the rear part of the vehicle, away from the driver.

In view of the short term experimental nature of this vehicle, these risks were considered tolerable and indeed never manifested themselves.

7. Conclusions

7.1 Solar arrays

The 480 W portable array could be adjusted to track the sun by hand. In spite of this, not enough H_2 could have been produced to completely autonomously run the vehicle during the Tour de Sol, except perhaps on easy stages with perfect weather.

Due to problems described, it was not possible to utilise the full power of the directly connected1250 W rooftop array, but this was the most efficient way of running the Electrolyzer.

With the 1250 W array feeding into the mains (at > 90% efficiency) and a separate mains power supply for the Electrolyzer (at 50% effciency), the best rate of H_2 production could be realised. The efficiency of the power supply should however be raised to > 90% by using toroidal transformers and/or high frequency transformation. In spite of the double energy conversion, the mains hook-up concept is more effcient over all, because the Electrolyzer can operate continuously and because electricity is not wasted during the times the Electrolyzer is not operating.

7.2 Electrolyzer

The electrolyzer performance under the typical conditions of coupling to a PV-field gave rise to the following problems, which are not noticed when the unit is fed from the AC mains:

— Difficulty in reaching the higher temperatures at which the system operates with maximum efficiency.

— Decrease in cell efficiency owing to electrocatalysts deactivation under variable loading conditions.

— Reduced purity of gases in low current loading periods due to low insolation.

Problems were encountered because initially the same 24 V power supply was used for the control computer, actuating valves and relays, and the Electrolyzer cells, with a floating battery across all these. It was thus not possible to regulate the power to the cells sufficiently, in particular the full power of the 1250 W array could not be used. Later control and power circuits were separated, solving this problem.

7.3 Vehicle

Comparison to Electric Drive

As the same vehicle was previously raced while fitted out with an electric motor, both quantitave and qualitative comparisons could be made:

— At speeds on the level of 40-50 km/h, the electric version required 650-900 W electric power, the hydrogen version 3600 W (using 1 Nl/min $H_2 \approx$ 180 W). At about 25 km/h, the electric version 250-300 W, the hydrogen version 3100 W. The vehicle is thus about 4 times less efficient in the hydrogen mode than in the electric mode and roughly10 times less efficient during partial load. These values are for steady-state driving; in real traffic conditions with inclines and stop-and-go condtions, both modes suffer unless the condtions can be exploited, e.g. by accelerating and switching off the drive during coasting.

— The range with 30 kg of lead-acid batteries is 50-90 km, the range with 30 kg of steel hydrogen bottles would be 165 km (at even 45 km/h). The range with hydrogen is thus about twice the range with lead batteries under ideal conditions. In real traffic the ranges would probably be about about equal, but the hydrogen system has the advantage that it does not deteriorate with age and that it provides heating in winter. Lead batteries perform poorly in cold weather and have to be replaced every few years and much sooner if abused.

— A 500-1000 W electric motor is sufficient to give the vehicle a perfectly acceptable driving performance, as the motor can be overloaded for accereration and hill-climbing. The 1000-1500 W hydrogen motor is adequate for constant driving on the level but unsatisfactory for accelerating and hill-climbing. It would have to be larger, giving even worse partial-load efficiency.

Feasibility of concept

The poor overall efficiency is in part due to the inherent poor effciency of this type and size of engine (max. 25-30%), in part due to the not completely satisfactory conversion (giving10-20%), but also because it is difficult to operate any such engine at its best operating point. With the required power output varying considerably, the engine is often running at less than peak efficiency. Because of its poor overload capability, an engine correctly sized for steady-state driving on the level (as in our case), is underpowered for acceleration and hill-climbing. If a large engine is chosen, as is the case with most motor vehicles, efficiency is poor during the frequent partial-load conditions. The larger engine also requires a heavier chassis and drive components, further decreasing efficiency.

Viewed in this perspective, the internal combustion engine is a very poor motor for driving road vehicles, especially if the fuel is precious solar hydrogen. Although engine manufacturers strive to improve such engines and can build good GH_2 engines, they cannot solve the problem of poor efficiency at partial load and additionally a great deal of fuel is wasted by vehicles which are standing still or even going downhill! A lot more can probably be gained with a different concept as described in the next section.

8. Future Projects

8.1 Electrolyzer

As explained at para. 5.2 above, coupling of the electrolyzer to a PV-field originates different problems owing to variable loading conditions, mainly:

- deactivation of electrocatalysts;

- reduced efficiency of diaphragms at low current densities.

The first problem in particular requires a deep investigation in the field of possible coatings which can be different for anodes and cathodes, and have to keep their catalytic efficiency even under variable loading conditions. Said investigation has to be carried out into different methods for obtaining such electrodes, their physicochemical evaluation, and long-term tests in suitable electrolyzers operating under a simulated feeding through PV arrays.

Our research programs for the near future envisage such an investigation which shall be an object of a financing request to BEW in the frame of the Swiss Hydrogen Energy Research Programme.

8.2 Vehicle

If an engine correctly sized for steady state running on the level, or even smaller, is used to continuously charge a short-term energy accumulator, it can be tuned to work at peak efficiency at all times. The short-term accumulator and its associated motor are designed to have a high efficiency even if worked at high and quickly varying loads. This is of course the "range extender" hybrid concept which has been proposed by a number of people and even implemented in some prototypes using petrol or butane. The short term accumulator is usually an electric battery, NiCd systems being ideal for this, especially as they can be replaced by directly comparable non-toxic Nickel Hydride systems when these become available. Such batteries can operate at high specific loadings, as can electric motors, without undue degradation. Also possible are fluidic or mechanical systems such as flywheels.

The charging hydrogen engine can be an i.c. one and should achieve several times the average efficiency than if used normally, judging from the experience of this project. How much depends very much on the duration and type of driving. For very long-distance, steady-state driving there may be little or no advantage to this hybrid concept, as 2 or 4 additional energy conversions are involved, and a direct coupling would be advantageous. For usual driving conditions the overall efficiency would however be considerably better, probably around two times. Eventually Stirling engines can be used, solving the noise and pollution problem completely. Even further into the future, fuel cells will allow at least another two-fold increase of efficiency.

For short trips, the short-term power system is usable by itself and can be charged efficiently from outside sources, e.g. directly by solar energy. The lightweight but less efficient hydrogen charging system need only be used for longer distances or as a safety backup. For example, an electric vehicle can be equipped with a fraction of the usual amount of batteries plus the described hydrogen system weighing less than the batteries replaced. Such a vehicle could offer similar driving performance to a comparable conventional motor vehicle yet use over ten times less fuel on short trips and perhaps twice less on longer trips. It can be very much quieter with virtually no pollution.

It is proposed to investigate this option with a Stirling generator in a follow-up project, which would also continue the work on composite GH_2 bottles.

9. Public Relations

9.1 Tour de Sol

Although a goal was the participation in the Tour de Sol 90, this was in fact limited to an exhibition of the complete system during one day while the Tour de Sol was stationed at Olten. It was felt that the vehicle was, after all, not sufficiently efficient, powerful, or reliable enough to be able to complete the Tour with its over 3400 m of altitude to be climbed and 560 km distance in sometimes heavy traffic. At least 5 Nm^3 per day would be required according to the data measured. Although this is just within the capability of the Electrolyzer when properly installed with a powerful power supply and running continuously, it would not

have been possible to do this during the Tour. Instead, about ten public demonstrations were given on June 29 and 30 on a racetrack in Olten. The system was also described during a panel discussion on the subject of solar hydrogen, also in Olten.

9.2 Presentations and Publications

A paper was presented by Dr. Sioli during the 3rd Tour de Sol symposium "Solarmobile im Alltag" in Bern on 18. Feb 1989 ("Fueling your Car with Solar Hydrogen", pages 81-94 of the proceedings)

A paper was presented by Th. Schmidt during the 7. International Solar Forum in Frankfurt, 9-12 Oct 90, organised by the German Association for Solar Energy. ("Wasserstoffsolarmobil", pages 2205-2212 of the proceedings)

A similar presentation was given by TS during the 5th Tour de Sol Symposium "Solarmobile im Alltag" in Basel on 23. March 1991. ("Wasserstoffsolarmobil", pages 257-262 of the proceedings)

A lecture on the subject of solar hydrogen was given by TS on 16/10/90 during an environmental study week at the Kantonsschule Aarau.

The entire system was presented on Swiss TV during a 45 minute program on alternative energy, including an interview of Dr. Sioli ("Nautilus" RTSI 28/10/90)

The project was described in "Basler Zeitung" (20/10/90, Nr. 246, Part III)

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[4]   Hydrogen Engines: A View to the Past and a Look into the Future
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[5]   Summary of 42 Research Projects done from 1984-1989 by students of
       Fachhochschule Wiesbaden, Projekt Wasserstofftechnik

11. Appendices 1 and 2

Appendix 1: Conversion of the Honda GX110 107 cm³ engine to H2 (Th. Schmidt)

Step 1

Removal of the petrol tank.

Step 2

Removal of the tube for crankcase ventilation going into the air filter assembly; plugging the hole in this.

Step 3

Removal of all parts of the throttle linkage.

Step 4

Taking away the intake manifold with air filter and carburetor and removing the throttle valve from this.

Step 5

Drilling a small hole in the engine casing close to the inlet valve and fitting a nipple to take the H_2 supply tube.

Step 6

Replacing the air filter and carburetor assemblies, having removed the foam rubber filter element (because it burns easily).

Step 7

Closing the choke.

Step 8

Connecting a low-pressure H_2 supply with flow set to about 8 Nl/min.
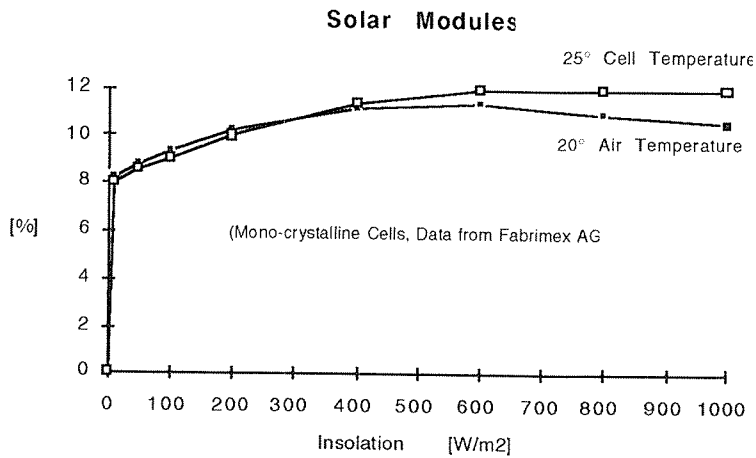
Step 9

It is now possible to start the engine by hand by switching on H_2 flow just at the right moment (which could be done automatically with a centrifugal switch, a good safety feature anyway). However this is difficult and it is easy to damage ones back and ears before achieving sucess.

Step 10

Therefore an electric starter was fitted. As none was available for this model (only for the next size up), a special modification had to be made. The engine now starts well and reliably if cranked for a second before introducing H_2.

Appendix 2: The Efficiencies (Th. Schmidt)

Solar Modules

25° Cell Temperature

20° Air Temperature

(Mono-crystalline Cells, Data from Fabrimex AG

[%]

Insolation   [W/m2]

The values shown are with respect to the solar module, i.e. including the area between the cells, and assuming normal incidence. The upper curve is only achieved in winter or if the cells are cooled. Potential: A new generation of laser-etched cells will soon raise efficiencies by about 3%(absolute). Hybrid collectors utilising the waste heat of course realise much higher efficiencies.

Maximiser

Average: 95%   (Manufacturer gives 95-97%)

[%]

Power Input   [W]
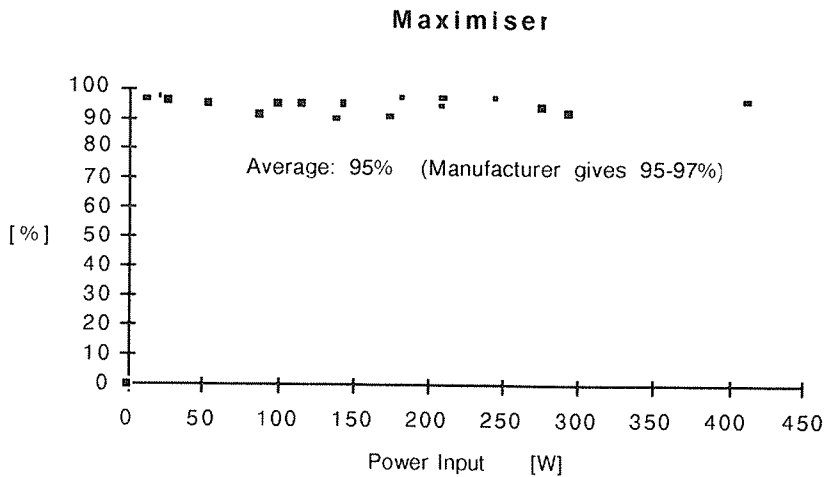
The Maximiser (Maximum Power Tracker) automatically operates the solar cells at their best operating point and provides a defined output voltage for direct connection to the electrolyser.

Potential: The best MPTs available can achieve 99%.

Solar Mains Inverter (NEG-1400)
(Manufacturer's Data)

[%]

Power Input   [W]
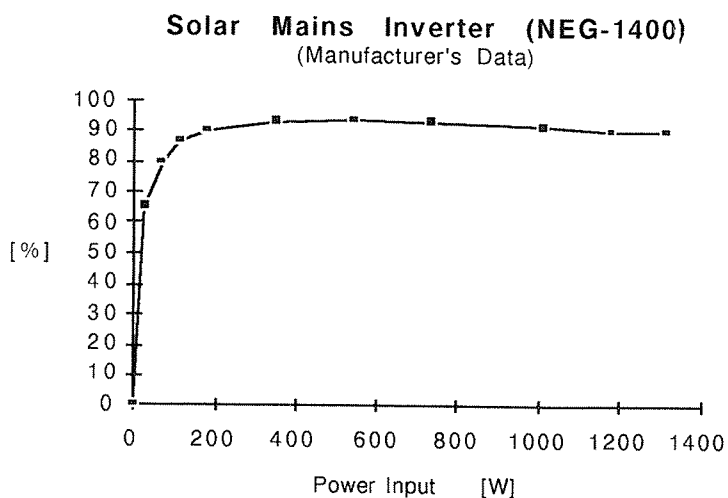
The Solar Mains Inverter (which also contains a MPT) is used together with the Mains Power Supply (instead of the Maximiser) when the solar generater and the electrolyser are far apart or not operated simultaneously. The 230 V AC mains are thus not just a power connection but also a virtual storage medium. The efficiency of the inverter is mainly limited by its internal transformer required for safety reasons. Potential: Future high power inverters with no or with large transformers could reach 97%.

Mains Power Supply

Standby Power: 36 W

Power Input   [W]
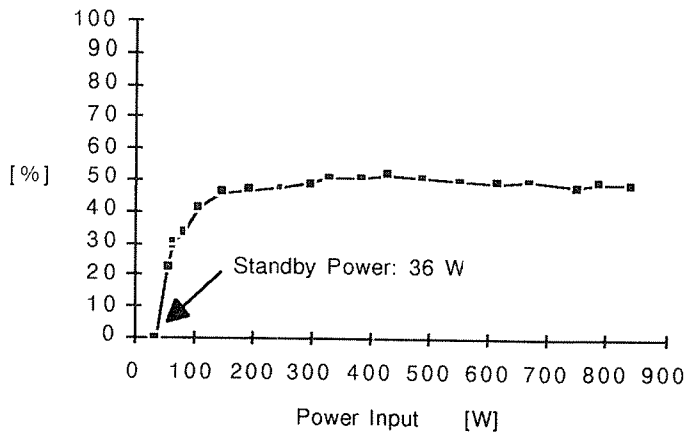
These values are typical of the efficiencies of millions of power supplies used throughout the country. **Potential:** The best available power supplies use toroidal and/or high-frequency transformers and reach 90-95% efficiency. Accordingly there is an enormous energy saving potential achievable if old power supplies are replaced by modern ones and if they are not left running when not in use.
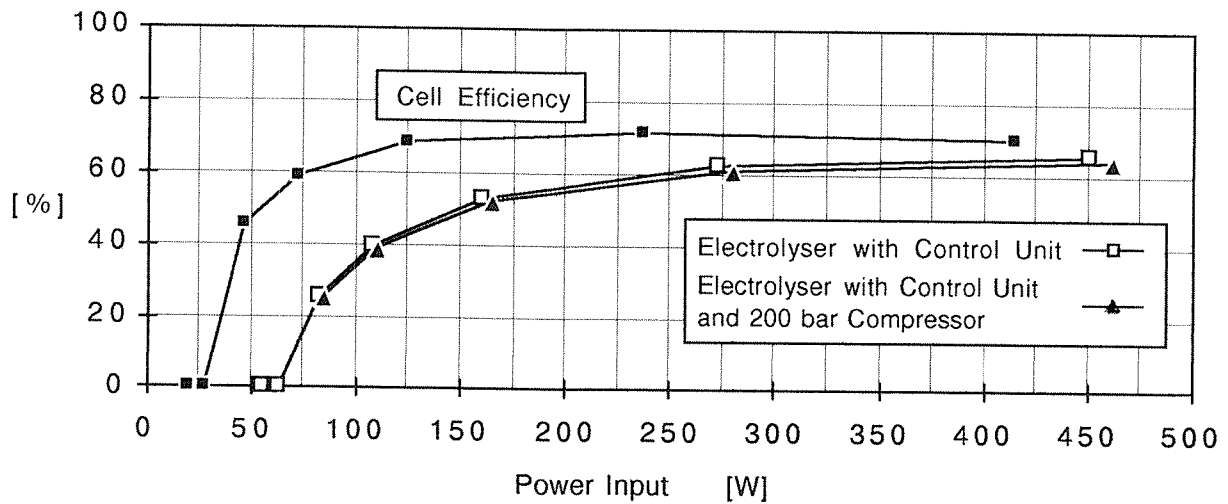
Electrolyser Cells
(at ≈16°C and 1 bar)

Voltage Efficiency

Current Efficiency

Total Efficiency

Power Input   [W]
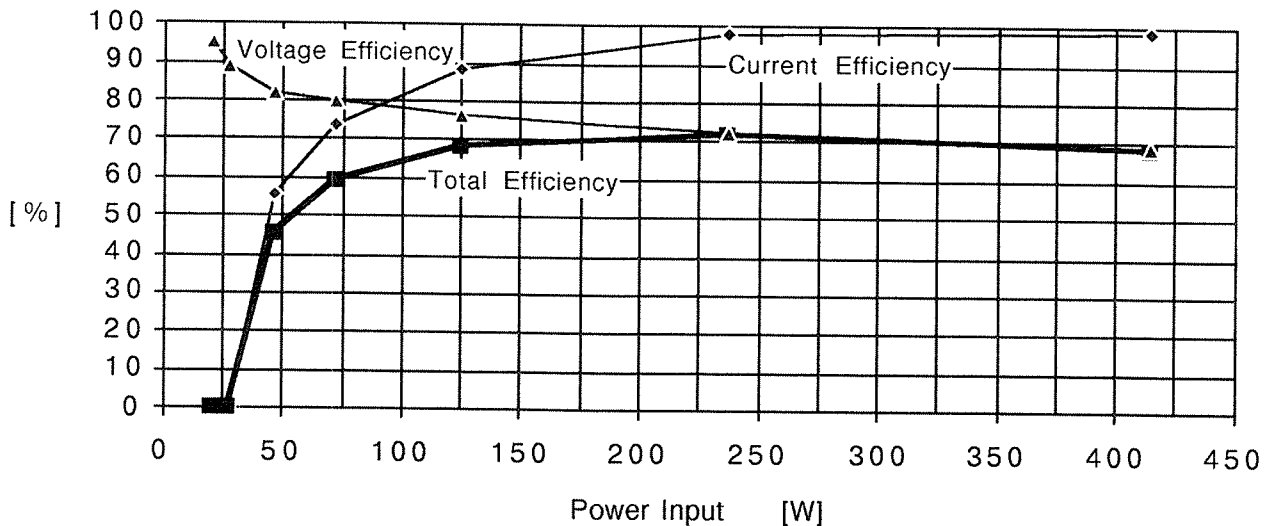
The efficiency of the electrolyser cells is the product of the voltage and current efficiencies. The voltage efficiency is defined to be 100% at a cell voltage of ≈1.47 V, and indeed such values are approached at very low current loadings, but electrode effects and the ohmic series resistance of the electrolyte decrease this efficiency with increasing current. The current efficiency is defined to be 100 % when all current is available for electrolysis, i.e. when 1 A produces ≈0.415 Nl/h H_2 per cell. This is seen to be low or zero at small currents because of the parasitic shunt resistance of the electrolyte, but approaches 98-99% at higher currents. The overall result shows that low powers are to be avoided and 70% is achievable over a wide power range. **Effect of temperature:** The voltage efficiency increases with rising temperature (see cell voltage graph), but the current efficiency decreases (measurements not shown). This can however also be seen on the cell voltage graph, as the parasitic shunt resistances are indicated by the slopes of the plots at voltages smaller than 1.47 V (An ideal cell would have infinite resistance below 1.47 V). Not enough measurements were done to show a trend, but those done indicated a relatively constant total cell effciency of about 70% (at higher powers) at temperatures ranging from 15-40°C.

Electrolyser

The complete electrolyser contains a control unit consuming 10 W on standby and an additional 12 W for a relay and 12 W for a valve when it is operating. The compressor uses about 150 W but is only used for very short periods. The total efficiency (from DC input to 200 bar H_2 output) is seen to be best at maximum power, approaching 65%.

Potential: Using low power electronics, solid state relays, and special valves, the power consumed by the control unit could be reduced by an order of magnitude. The efficiency of the compressor could be increased considerably, but the effect would be small, thanks to the "free" 30 bar electrolytic precompression.

From all the above, the total maximum efficiencies of producing pressurised H_2 are approximately:

	Input: Solar Electricity	Input: Solar Radiation
via Maximiser	61%	6.6%
via Mains Connection	29%	3.2%
via Mains C. with 90% efficient Power Supply	53%	5.8%

Although the mains connection has a worse maximum efficiency than the DC connection, its average efficiency is better, as the electrolyser can always be used at its most efficient power. Also, the solar mains feed works reliably every minute of daylight and no energy is wasted even when no hydrogen is being produced. With a direct connection, the average efficiency is poor, as the electrolyser is often working inefficiently at partial load and must also be completely shut down every night and during poor winter weather, giving rise to cell corrosion unless a small but energy-consuming protective current is imposed and requiring a startup from cold every morning.

The best engine efficiency measured was **20%**, but the amount of gas used while driving indicates a far smaller average efficiency, certainly below 10%. In contrast to the electrical devices discussed so far, whose optimum operating points are relatively easily identified, the engine is only efficient if both torque and speed are chosen correctly. Even with the automatic CVT gearing, this is not easy to do, as real driving involves a very large range of rapidly changing power and all energy expended in acceleration or climbing is lost, since regenerative braking is not possible. **Potential**: All references claim higher efficiencies with H_2 than with petrol, and carefully converted or purpose-built engines can be expected to reach **30-40%**, depending on size. Average efficiencies in real traffic could be *greatly* increased by using a short-term energy storage accumulator (e.g. flywheel) so that the engine can run at its best operating point.

A single Deltamat-type CVT has an efficiency of **90-94%** over most of its operating range and **85%** at very extreme ratios, extrapolated from manu-facturer's data. Our double Deltamat CVT has overlapping ranges such that the efficiency is pretty constant between **70** and **75%** over all ratios and powers.

The drive train (2 HTD tooth belts, 2 chains) is assumed to be **80-85%** efficient.

The best efficiency from H_2 to the wheel is thus ≈**12.8%**, the best efficiency from solar electricity to the wheel ≈**6.5%** and from solar radiation to the wheel ≈**0.7%** (6.6%·20%·75%·85%·85%). The last 85% are introduced because the electro-lyser efficiencies used the higher heat of combustion of H_2 and the engine efficiency the lower heat of combustion. The value of 0.7% seems surprisingly low, especially considering that the average value will be a lot less and that there is not a great deal of scope for improvement. It is all the more important to save as much as possible in the absolute quantities (e.g. by using small vehicles) and to realise extremely low levels of pollution, as is done by many biological systems which are highly sucessful in spite of even lower efficiencies.

Except when hill-climbing, a value of efficiency cannot be given for a complete vehicle, as an ideal vehicle would use no power at all. Here the speed obtainable on the level is given as function of the propulsive power at the wheel, assuming no tire slip.

Vehicle Speed
(Vehicle Weight = 2000 N)