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A System of Hydrogen Powered Vehicles with Liquid Organic Hydrides

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A SYSTEM OF HYDROGEN POWERED VEHICLES WITH LIQUID ORGANIC HYDRIDES

(MTH - System)

2nd revised edition

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ABSTRACT

A complete system for storing and using energy in the form of hydrogen organic liquid is discussed. The recycable liquid carrier is

$$\underset{\text{(liq)}}{\text{Methylcyclohexane}} \underset{\text{hydrogenation}}{\overset{\text{dehydrogenation}}{\rightleftarrows}} \underset{\text{(liq)}}{\text{Toluene}} + 6\ \underset{\text{(gas)}}{\text{Hydrogen}}$$

(The system is called MTH for Methylcyclohexane, Toluene, Hydrogen). All the technical processes proposed here are well established. The dehydrogenation reaction occurs in a catalytic reactor (>400°C, ∿20 bar) on the vehicle. The hydrogenation occurs in a regional plant, servicing ∿ 195 vehicles in which the hydrogen is produced by the electrolysis of water (22 MW (el)) and catalytically bonded into toluene, transforming into methylcyclohexane.

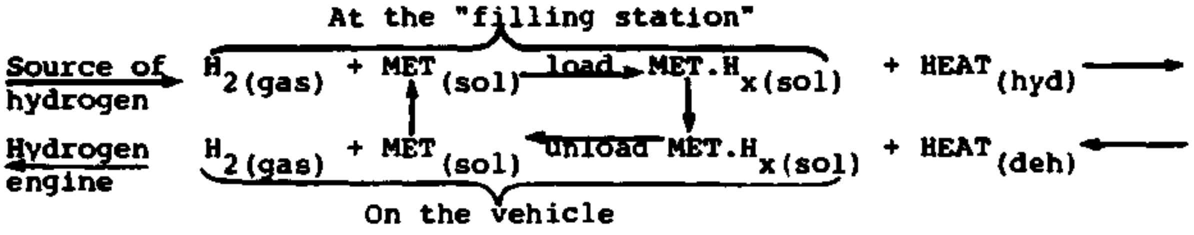
As a reference vehicle a 17 ton lorry having a 150 kW (mec) engine and a operation radius of ∿ 250 km daily for 250 days per year is taken. The catalytic reactor for the dehydrogenation on the vehicle has a volume of ∿50 liter. The tank for methylcyclohexane, the carrier of hydrogen, is ∿710 liter (equivalent: 100 kg gasoline). The cold start is based on the direct burning of toluene. The overall energy consumption is split up as 90 % from hydrogen (electrical energy) and 10 % from the direct burning of toluene (fossile fuel). The complete MTH-system after 30 years with approx 15'000 lorries consumes 5.4 TWh (el) per year during the night and at weekends during 235 days of "summer". A seasonal storage for rest of year ("winter" appr. 115 days) is included here. The calculated economic parameters for the proposed MTH-system are as follows (prices 1981)

- the cost of an equivalent 1 liter gasoline 0.70 SFr/liter (assuming the electricity price, during summer night 0.04 SFr/kWh)
- the cost of an equivalent 1 liter heating oil 0.31 SFr/liter (low price because of difficulties of selling during summer)
- the capital cost for the system (excluding annual storage), calculated for an equivalent barrel of oil 75'000 SFr per barrel daily
- corresponding capital cost of MTH-system equals: (Prices: 1981)
  ∿ 26 SFr per barrel-equivalent, that is
  ∿ 12.5 US $ per barrel-equivalent ,

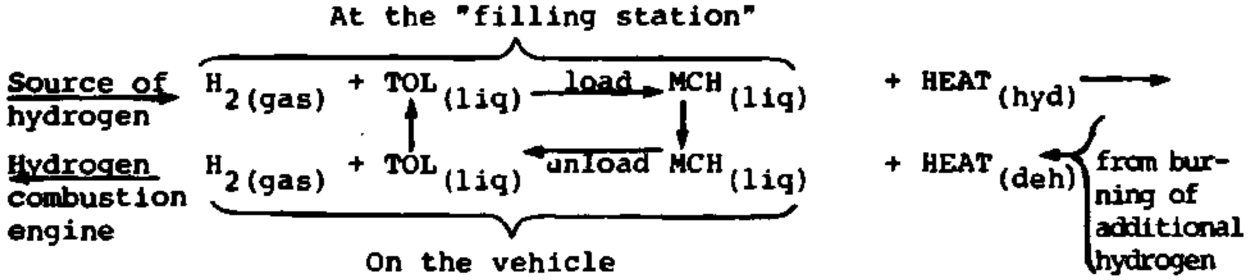
1. Liquid organic carrier of hydrogen

The use of nuclear energy for the source energy for automobiles is shown in the simplified diagram on the Fig. 1.

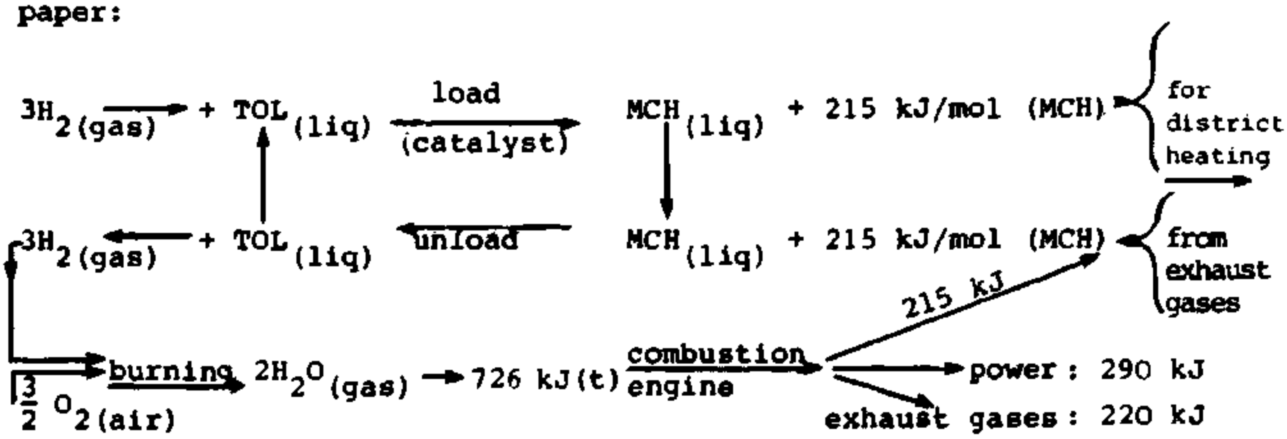
The known system of hydrogen storage, e.g. using metal hydrides MeH_x for automative purposes is



Sultan and Shaw *) have proposed as an alternative the following system including the organic hydride (for symbols see below):



The corresponding chemical reaction (for 600 K) is: including the management of the "heat-waste" proposed in this paper:



The system is in this paper called MTH (Methylcyclohexane, Toluene, Hydrogen).

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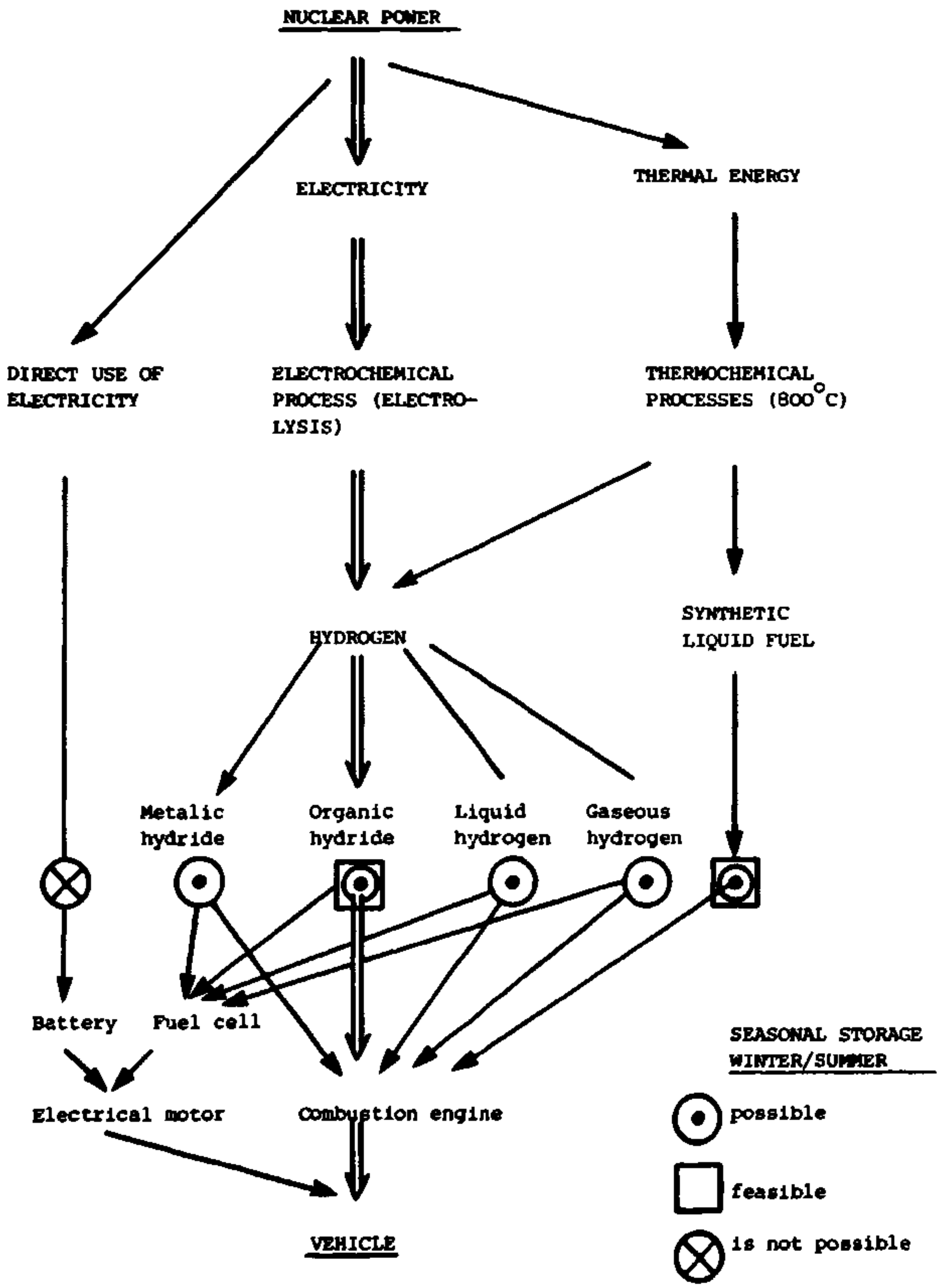
*) Sultan O., Shaw M., Study of automotive storage of hydrogen using recyclable liquid chemical carriers. TEC-75/003, ERDA, Ann Arbor 1975

Figure 1: FROM NUCLEAR POWER TO A STORED FUEL FOR AUTOMOBILES



Note: the symbols used in this paper:

(gas): gaseous
(liq): liquid
(sol): solid
x: stoichiometric coefficient
MET: metal
MCH: methylcyclohexane
TOL: toluene
EXG: exhaust gases
HEX: heat exchanger

y = year
d = day
h = hour

(tot): total (energy)
(elc): electrical
(che): chemical
(the): thermal
(mec): mechanical
(deh): dehydrogenation
(hyd): hydrogenation
(com): combustion

Remark: all prices in 1981

SFr: Swiss Francs = 0.48 US$

MSFr: Mega SFr = 10^6 SFr

2. Selected properties of the components

Both components of the proposed MTH-system, MCH and TOL are liquid at ambient temperature and pressure and very similar to the typical gasoline (see Table 1). In this paper a lean burning system is postulated with equivalence ratio $\emptyset = 0.46$ which corresponds to $\lambda = 2.17$.
The corresponding combustion reaction:

$$H_{2(gas)} + 1.09\ O_{2(gas)} + 4.07\ N_{2(gas)} \longrightarrow H_2O_{(gas)} + 0.58\ O_{2(gas)} + 4.07\ N_{2(gas)}$$

The amount of exhaust gases (EXG) equals $\sim$ 75g for 1 g of hydrogen burned. The specific heat capacity of the exhaust gases in the appropriate temperature range is calculated to be ~ 1.2 J/(g.K). The net heat of combustion is $\sim$ 120 MJ/kg(H_2):

$$H_{2(gas)} + \frac{1}{2}\ O_{2(gas)} \longrightarrow H_2O_{(gas)} + 242\ \text{kJ/mol}(H_{2(gas)})$$

The MTH-system has the following properties which significantly influence its feasibility:

a) The heat of dehydrogenation, that is of the production of the free gaseous hydrogen from methylcyclohexane, is rather large in relation to the net combustion heat:

$$\frac{\text{Dehydrogenation heat}}{\text{Net combustion heat}} = \frac{215\ \text{kJ/mol(MCH)}}{(3 \times 242\ \text{kJ})/\text{mol(MCH)}} = 0.30$$

b) This amount of heat must be extracted from the exhausted gases to drive the catalytic reaction since the amount of FXG equals 75 g EXG/g(H) and the specific heat:

$C_p^{EXG} = 1.2$ kJ/(kg.K). From this the required temperature range is:

$$\Delta T^{EXG} = \frac{0.30 \times 120\ \text{MJ/kg}(H_2)}{75\ \text{kg EXG/kg}(H_2) \times 1.2 \times 10^{-3}} = 400\ \text{K}$$

c) Postulating the catalytic reaction of dehydrogenation by T = 400 °C and T_{out}=20°C, the temperature of the exhaust gases coming to the reactor equals:

$$T^{EXG} = 400 + 400 + 20 = 820\ ^{o}C$$

Note: the exhaust gases of present day combustion engines have a much lower temperature and therefore in first period some amount of TOL must be burned for "heating" the exhaust gases.

d) The dehydrogenation of methylcyclohexane is a very well known operation. Approximately a hundred million tons of this component are processed in catalytic reforming plants because of the significant increase of octane number (see Table 1). The catalyst for this reaction has the liquid hourly space velocity, LHSV, as follows:

$$\text{LHSV} = \frac{\text{rate of liquid feedstock (MCH)} \left(\frac{\text{vol}}{\text{h}}\right)}{\text{volume of catalytic reactor} \left(\text{vol}\right)} = 1...10h^{-1}$$

The value LHSV = 5 will be used in the calculation below.
This process occurs in the MTH-system on the vehicle and therefore is doubtless the most crucial step in the whole system.
The efficiency ot this step has been estimated to be ∿ 90 % (in the first period even as low as 70 %).

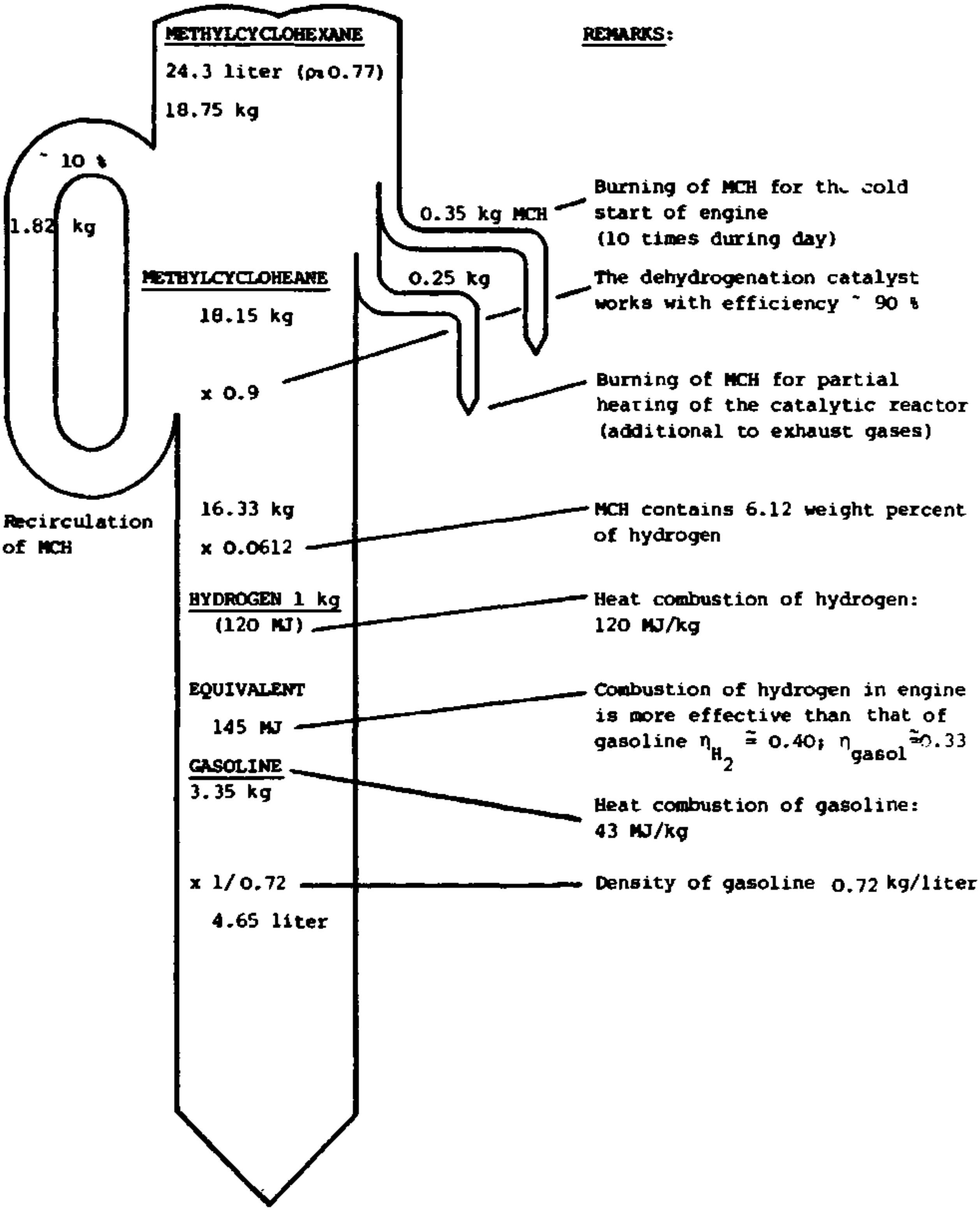
Table 1. SELECTED PROPERTIES OF MTH-COMPONENTS AND TYPICAL GASOLINE

Property	Unit	Toluene (TOL)	Methylcyclohexane (MCH)	Hydrogen (H_2)	Gasoline	Diesel oil
Formula	-	C_7H_8	C_7H_{14}	H_2	C_6H_{16}	C_xH_y
Molecular weight	kg/kmol	92.15	98.19	2.016	115	.
Hydrogen content	weight %	.	6.2	100		.
Boiling point	°C	110.6	101.2	.	125	35..200
Freezing point	°C	- 95	- 126.6	.	-56	.
Heat of vaporization	kJ/kg	347	321	.	300	.
Vapour pressure (20 °C)	bar	0.05	0.07	.	0.03	.
Density	kg/L	0.867	0.769	.	0.72	0.815
Heat capacity						
- liquid	kJ/kgK	1.738	1.83	.	1.8	.
- gaseous (250°C)	kJ/kgK	1.84	2.48	.	.	.
Heat of combustion (25 °C)						
- gross (mass)	MJ/kg	42.44	.	142	45	45
- net (mass)	MJ/kg	40.53	.	120	43	42
- net (volume)	MJ/L	-	5.72 (hydrogen only)		31	34.5
Octane number	MON	112	84		92	.
Explosion lower limit	vol %	.	.	18	.	.
Flammability limit	vol %	1.3/6.8	1.2	1.4/76		1.4/6.4
	°C	535	260	550	260	55
Toxicity	ppM	100	400	.	300	.
Price						
USA May 1981	$/kg	0.43		.	0.7	
Switzerland, July 1981	SFr/kg	0.88			Switzerland tax free	

. not relevant here.

Fig. 2 shows the proportions of the substances discussed here, which take part in the appropriate fuel cycle.

Figure 2: RELATION BETWEEN MASSES AND ENERGY OF USED SUBSTANCES NORMALIZED TO 1 KG OF GASEOUS HYDROGEN (20 BAR)



Ratios: weight $\frac{\text{MCH}}{\text{gasoline}} = \frac{21.0}{3.35} \cong 6.26$

volume $\frac{\text{MCH}}{\text{gasoline}} = \frac{27.3}{4.65} \cong 5.90$

f) The cold start of the vehicle has been postulated by direct injection of the TOL (liq) to the carburetor (TOL has octane number 112). This increases the direct burning of TOL by 1.9 weight percent (see also below).

e) The hydrogenation of toluene (methylbenzene) to methylcyclohexane is very similar to the well established hydrogenation of benzene to cyclohexane which has a turnover of about ten million tons annually.
In the MTH-system this step occurs in a regional hydrogenation plant and causes no problems. The best process is the hydrogenation in a liquid phase. A licence for this process can be obtained.

g) Each step, hydrogenation and dehydrogenation, results in the production of by-products, which can be undesirable in this system.
Because a steady state system is proposed in which approx 2 % or more of the weight of TOL is burned in each cycle the production of by-products can be controlled.

h) The purity of hydrogen in the system is not too significant. The electrolysis of water giving hydrogen of 99.8 % purity is probably more than satisfactory.

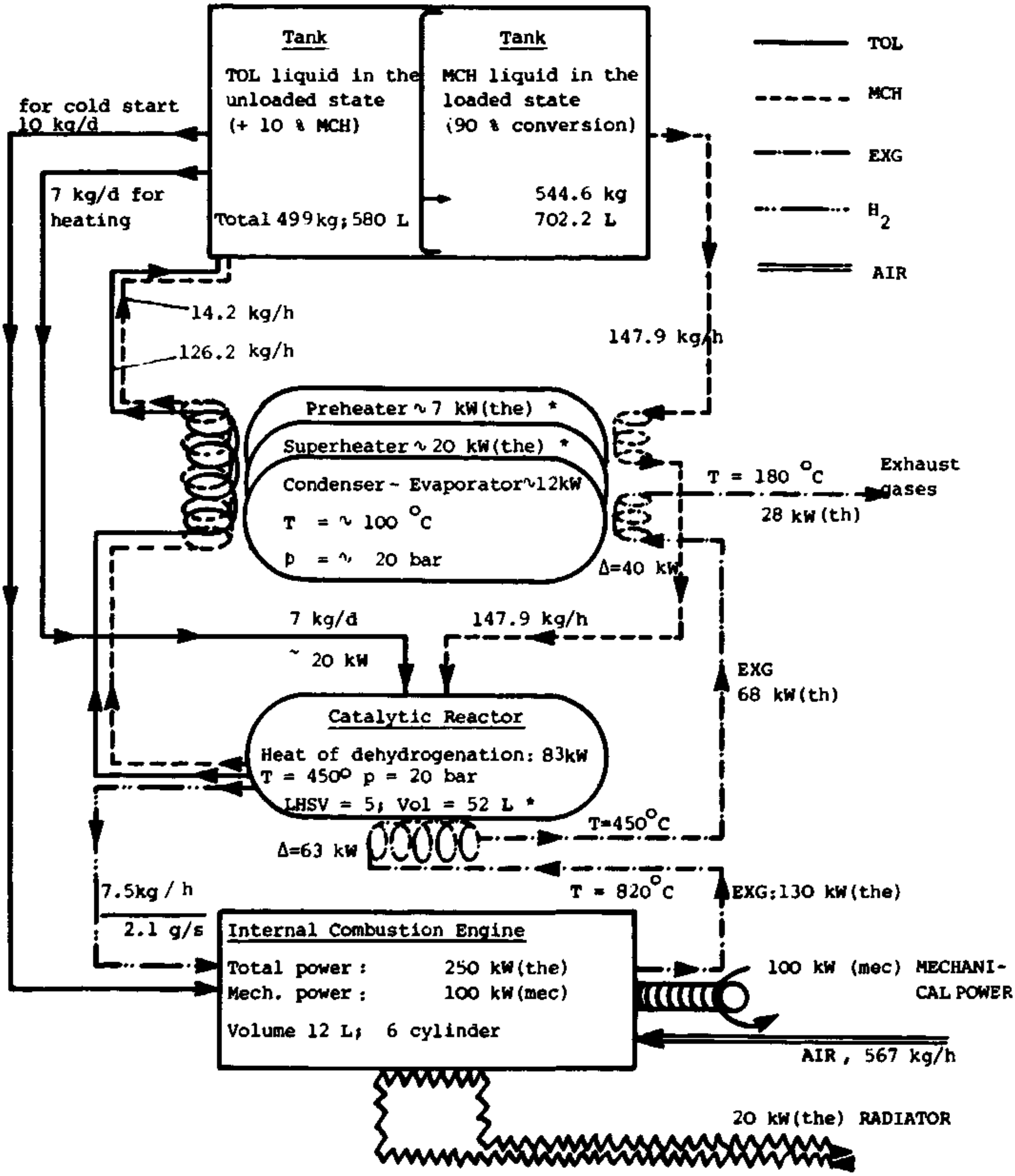
i) The seasonal summer - winter storage of hydrogen in form of methylcyclohexane in conventional, pressureless, non insulated tanks.

3. <u>The reference vehicle with hydrogen burning engine</u>

The significant data for this vehicle are shown in Table 2.
The mass flow and the energy flow data for this vehicle are given in Figure 3. A rather important problem is the cold start for all hydrogen driven vehicles. In the proposed MTH-system the following schemes have been proposed:
<u>Cold start</u>: A certain amount of liquid toluene is pumped directly into the carburretorfor the start. For a start sequence lasting 6 minutes the following amount of toluene will be burned directly

Figure 3 SIMPLIFIED ENERGY AND MASS HOURLY FLOWS AT AN AVERAGE POWER OF 100 kW(mec)

Note: Tank for 250 km
Dieseloil = 4.3 GJ/250 km (η = 0.33)
Hydrogen is 1.2 more effective = 3.6 GJ/250 km (η = 0.40)



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* These apparatus are designed for the maximum power, that is for 150 kW(mec) and therefore all here calculated values must be increased by 1.5.

Table 2. REFERENCE VEHICLE

Parameter	Source	Unit	Type of fuel	
			Diesel oil	MTH fuel (hydrogen)
Vehicles (17 tons)				
Weight without fuel		kg	17000	18000
Weight with fuel	SAURER	kg	17100	18500 (incl.catal.)
Engine	D2K-G gas engine 6 cylinder in line 12.5 liter	kW (mec)	150	
Operation				
Operating distance	arbitrary	km/d	250	
Mean power	150 kW(mec)x(2/3)	kW (mec)	100	
Thermal energy		GJ/ 100 km	1.72	1.44 (hydrogen is 1.2 more effect.)
Fuel				
Net heat of combustion	from Table 1	MJ (the)/kg	43	120
Amount of fuel				
Fuel consumption		kg/d	100	30
Fuel carried		kg/d	100	544.6(see Fig.3)
Volume of tank	from Table 1	liter	∿ 120	710
Ratio of weight effect.	MTH fuel/dieseloil	weight ratio	∿ 5.5	
Weight difference (fuel only: no catalytic reactor)	MTH fuel minus dieseloil	kg/vehicle	445	
Annual consumption of fuel	250 day/year	ton/year	25	MCH 136 H_2 7.5
	250 day/year	GJ(ch)/y	1'075	900
Refuelling time	assumption	minutes	5	$\lesssim$ 15
Catalytic Reactor (for 100 kW (mec)				
Flow of MC	see Fig. 1, Fig.3	liter/h		190
LHSV	assumption	LHSV		~ 5
Volume of reactor (max)	(190L/5) x 1.5	liter	not relevant	~ 53
Weight of reactor	effect.density ∿ 0.8	kg		42
Weight of platinum	1 % weight	kg		0.4
Lifetime for 62000 km/y	desired	h		~ 1'000
Change of catalyst	desired	time/year		1
Cold start				
with automatic switching from toluene to H_2			not relevant	toluene combustion
Exhaust gases temperature (heating above 400°C)	see page 6	°C	not relevant	820°C (not reached in today's vehicles)
Possible improvement of exhaust gas heat			Smaller compression ratio reduced heat losses to walls delayed ignition timing.	

in the engine:

$$20\ \text{kW(mec)}\ \frac{1}{0.25\ \text{efficiency}}\ \times 6\ \text{minutes} = 28\ \text{MJ (the)}$$

This corresponds to the combustion of approx 0.7 kg of toluene. For some cold starts per day and for idling a total of 7 kg toluene will be used, that is approx. 2 weight percent of the total amount of toluene in the tank.

Warm start: After a longer period of full power the engine and the catalytic reactor are hot. The heat losses for a well insulated reactor have been estimated as a few kW(the).
For 1 hour of "warm" waiting the heat equivalent of toluene directly burned will be some tens of MJ (the) which corresponds to the use of ∿ 1 kg toluene.

4. Regional MTH-station hydrogenation and electrolysis plant and filling station

The regional MTH-station is based on the following six units:

1. A fleet of 195 vehicles (buses and lorries each of 17 tons)
2. 6 filling pumps, totalling 140000 liter MCH/day.
3. A tank for longer storage at the regional hydrogenation plant, e.g. from weekend to working day and especially from summer to winter (∿ 10'000 m^3).
4. A hydrogenation plant with average production rate of ∿ 7.5 tons MCH per hr (in real situation the daily production will vary from working day to weekend).
5. An electrolysis plant of approx. 22 MW (elc), including 2 modules of electrolysers.
6. A central heating station for using the waste heat of hydrogenation and of electrolysis with an average power of ∿ 6 MW(the).

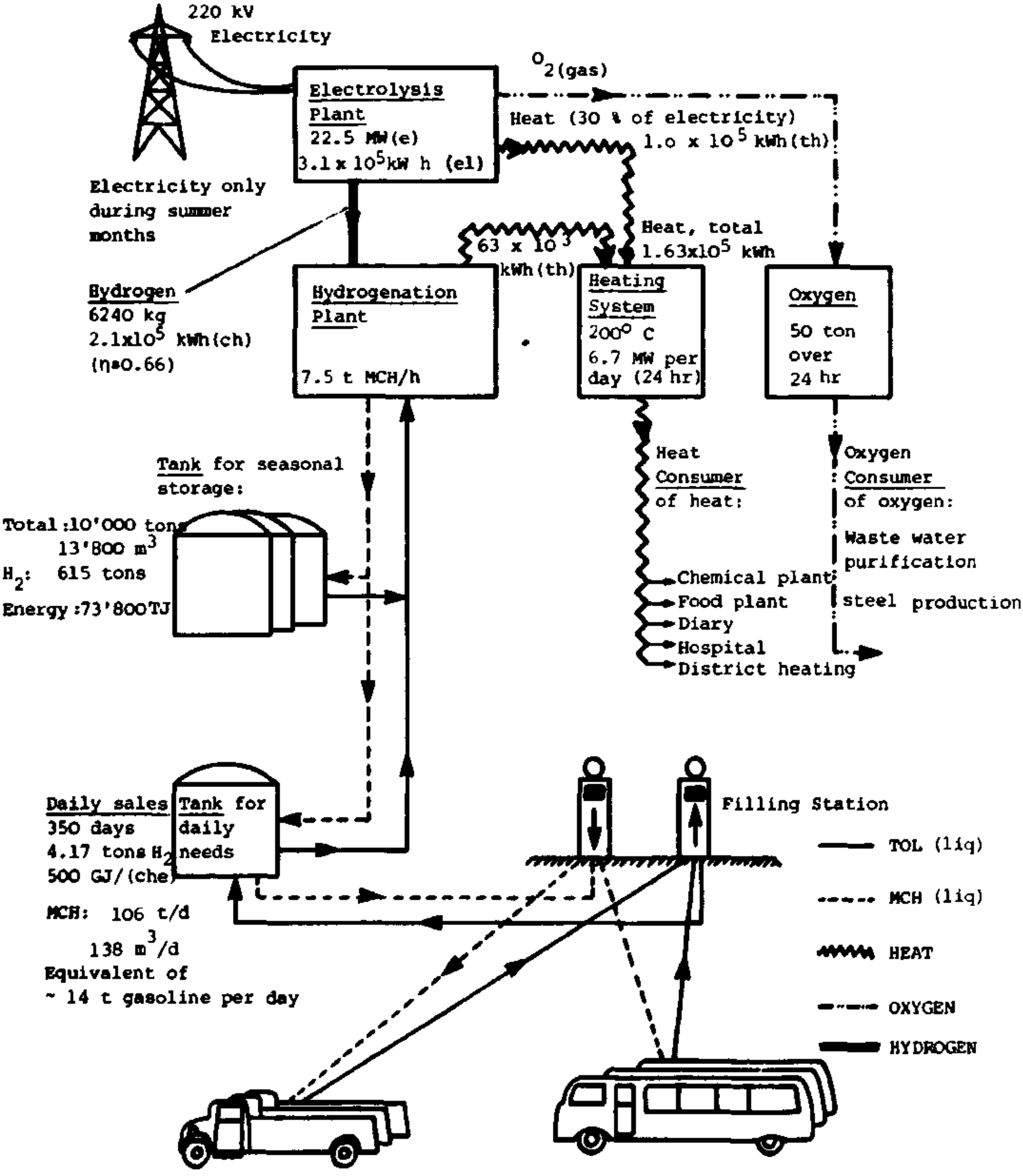
Table 3 shows the most important data for this regional MTH-station. Fig. 4 and Table 4 gives the economic data for such a regional MTH-station.

Table 3. REGIONAL MTH-STATION HYDROGENATION ELECTROLYSIS AND FILLING STATION

Parameter	Unit	Value	Notes
Electrolysis plant			
Total electric power	MW(elc)	22.5	Two electrolytic modules
Efficiency of H_2 production	%	66.7	
Hydrogen production	$t(H_2)/h$	0.45	
Duty time during night (in summer)	h/working day	10	
Duty time during weekend (summer)	h/weekend	35	
Number of working days	days/y	200	
Number of weekends, holidays	weekends / year	35	total 235 days/year
Total duty time	hours/year	3'200	
Total hydrogen production	ton/year	1'460	$1460 \div \frac{7.5}{\text{vehic}} = 195$ veh.
Electricity used in "summer" (3'200 h/year)	GWh(elc) TJ(elc)	72 260	no electricity during winter
Price of electricitiy on 220 kV grid	SFr /kWh(elc)	0.04	optimistic
Cost of electricity	MSFr /year	2.90	
Rate of MCH hydrogenation	ton MCH/h	7.5	
Heat flow for district heat			
Heat from plant	TJ(the)/y	138	optimistic
- price of heat	SFr /GJ(th)	~ 10	very low price
Oil equivalent ($\eta = 0.75$)	ton/y	4400	
Mass flows during year			
Hydrogen production	ton/year GJ/year	1'460 175'000	
Methylcyclohexane	ton/year	23'500	
Daily sale (250 days), hydrogen	ton (H_2)/day	5.85	
Methylcyclohexane	ton (MCH) / day	94.8	
Gasoline equivalent (*)	ton/y GJ(che)/y	4'800 210'000	(*)Hydrogen is a more effective fuel than gasoline (see Fig 2)
Heating energy (1.6x 10^5 kWh/d)	GJ/J	200'000	
Heating oil equivalent ($\eta = 0.70$) (**)	ton/y	4'400	(**)Burning of oil results in 30 % losses in chimney
Total equivalent 9300 t/y	barrel / year	63'700	
(1 barrel = 146 kg)	barrel / day	212	
Seasonal storage			
Production of MCH	t/y	23'700	
Sale of MCH(350 d/y)	ton/day	67.8	
Sale during summer 235 d/y	ton/summer	15'900	
Excess for storage for winter	ton MCH m^3 MCH	7'800 10'000	

Figure 4 REGIONAL MTH-STATION (AVERAGE DAILY BALANCE FOR 14 h/d)

Electrolysis: 3200 h/year, during 235 days/year
Selling: 35o day/year = 8400 h/y



Total vehicles 195 per day (each ~ 17 tons; 250 days/y)

Table 4: Regional MTH-Station: Economics (a)

Parameter	Source	Unit	Value	
Capital Cost				
1) Electrolysis plant	BROWN BOVERI (b) (a)	MSFr	8.0	
2) Hydrogenation plan production	LONZA (b)	MSFr	4.0	
3) Filling station distribut.	MIGROL (b)	MSFr	1.0	16.1
4) Vehicles,adaptation	195 lorries x 15'000 SFr	MSFr	3.1	
5) Storage tanks storage	(10'000 m^3)x(100 SFr/m^3)	MSFr	1.4	8.3
6) Toluen cost	(7'800 t) x (880 SFr/t)	MSFr	6.9	
Total capital cost		MSFr	24.4	
Annuity + other				
1) Annuity for 1, 2, 3, 4	arbitrary 13 per cent/year	MSFr/y	~ 2.1	
2) Annuity for 5, 6 c)	arbitrary 5 % and 3 %	MSFr/y	~ 0.3	
3) Electrical energy	see Table 3	MSFr/y	2.9	
4) Maintenance	estimated	MSFr/y	0.5	
5) Cost of toluene burried	17 kg/dx250x195x0.88 Fr./kg	MSFr/y	0.7	
Total annual cost		MSFr/y	6.5	
Sales	195 vehiclesx250 dx100 kg/d			
Gasoline (equivalent)	(4900 t/y)x(980 SFr/t)(f)	MSFr/y	~ 4.8	
Heating oil (equivalent) d)	(4400 t/y)x(390 SFr/t)(g)	MSFr/y	~ 1.7	
Total annual sales	4900+4400 = 9300 t/y	MSFr/y	6.5	
Balance				
Sales minus annual cost			~ 0	

a) Prices, June 1981 : 1 US$ = 2.15 SFr = 2.35 DM

b) See reference list

c) The low annuity of stored toluene, results from the governmental support for long-term fuel storage

d) The very low price of oil equivalent results from the difficulties of consumption of this heat during summer

e) Projected cost for new generation electrolyzer

f) Price: 980 Fr/t ~ 0.70 Fr/liter (Remark: price without taxes etc.)

g) Price: 390 Fr/t ~ 31 Fr/100 liter

5. The future complete MTH-system in Switzerland

(some economic considerations are given in Table 5)

It is of interest to examine the optimal size of the proposed system for a country such as Switzerland. Table 5 gives the appropriate data.

It must be stressed that this MTH-system is based exclusively on the existing or planned nuclear power stations. No new power station is needed or proposed.

One of the most attractive aspects of the MTH-system is the inherent capability for seasonal storage of hydrogen. Particularly in the case of Switzerland the production and consumption patterns based on the mix of hydro-electric and nuclear plants means that there tends to be a surplus of production in the summer especially in the night. The structure of the electrical market must cover the case of a "low" hydraulic year (once every 5-20 years) or in case of an extended nuclear plant outage with a reserve capacity of approx 1 GW(elc).

This is best met by a nuclear station. In normal years this summer surplus is sold abroad.

The proposed MTH-system is able to consume this surplus produced by the 1 GW (elc)reserve plant, because the MTH-system requires 5400 GWh (elc) per year (in 2015).

Among all consumers of electricity only the MTH-system is able to totally survive for a period of several months without needing electricity and able to change in a very short time (in one second) to using toluene as a liquid fuel gasoline (with octane number of 112).
The amounts of toluene stored in the MTH-system allow the trucks to be drive for about 1.5 years without external supply. This, of course, is an extreme case, but demonstrates the strength and flexibility of the system. The MTH-system needs toluene. Assuming a 30 year period building up the total system to 5.4 TWh. (el) the amount of toluene required for the seasonal storage and for direct burning (cold start and low power operation) is approx 22000 tons per year. The world production of pure toluene at the present time is ∿ 8 million tons annually.

Table 5. MTH-System in Switzerland

	Unit	Year	
		2000	2015
Regional MTH-Station	Number	∿ 40	∿ 75
Electricity consumption during summer	TWh(el)/y	2.88 (see Fig. 5)	5.4
in relation to the Swiss summer production	%	8.0	12.5
Total installed power in MTH-System	GW(el)	0.90	1.7
In relation to the Swiss nuclear power generation during the summer night	%	∿ 20	∿ 30
Capital cost for MTH-System cumulative up to appr. year (without annual storage)	MSFr	∿ 645	1'200 (see Fig. 6)
Oil substituted by MTH-System (9300 t/y per station)	tons/y	372'000	697'000
Oil substituted by MTH-System (300 days/y)	barrel/day	8'500	~ 16'000
Oil substituted by MTH-System in relation to the Swiss oil consumption	%	3.3	∿ 6 (?)
Capital cost of total MTH-System (645×10^6 Fr/8500 barr. p.day	SFr / (barrel per day)	76'000	76'000
Capital cost (76000 Fr/(10y x 300 barr./y	SFr / (barrel)	26	26
Capital cost	US$ (1981) / (barrel)	12.5	12.5
Vehicles based on MTH-System (each 17 t)(250 d/y)	Number	7'800	15'000
Vehicles based on MTH-System in relation to total swiss heavy vehicles	%	5	~ 10

Figure 5 **APPROXIMATE SCHEME FOR INTRODUCTION OF MTH-SYSTEM IN SWITZERLAND**

Production of electrical energy in Switzerland during summer half year

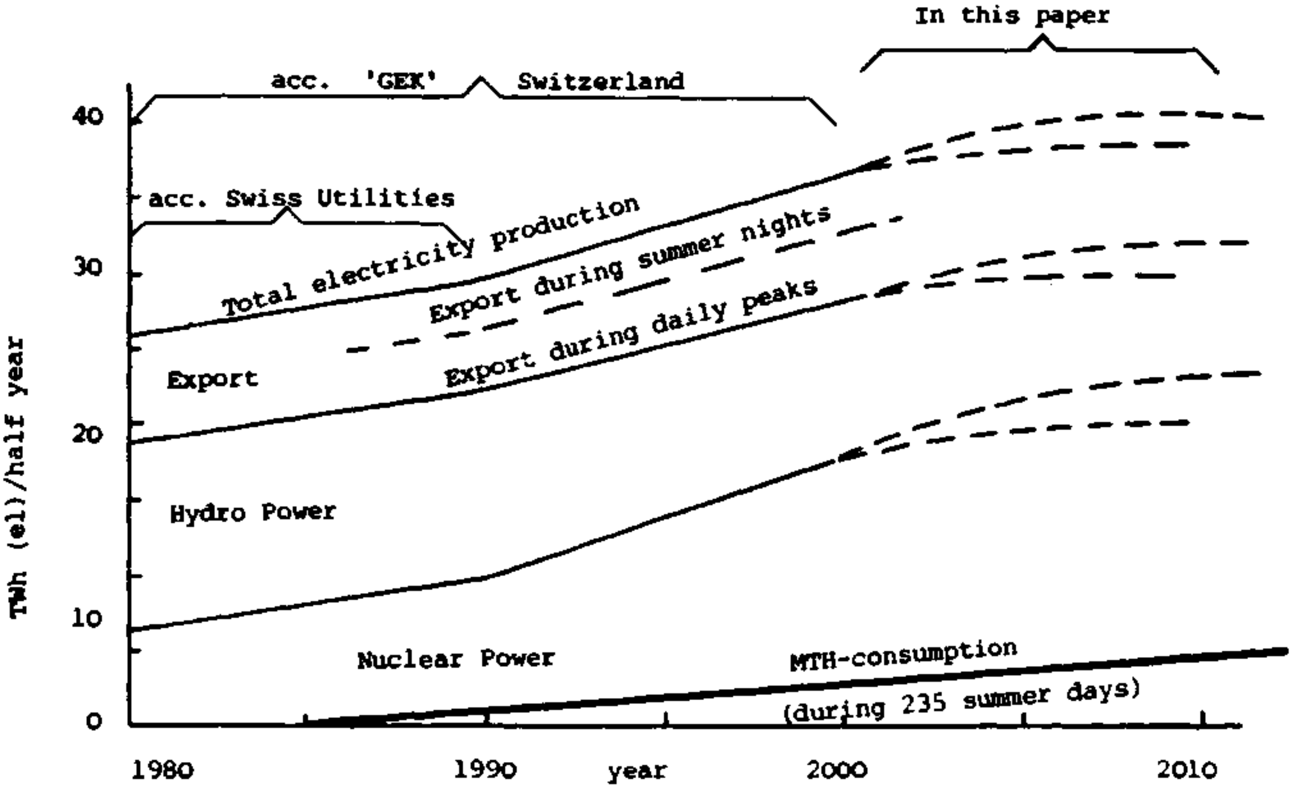
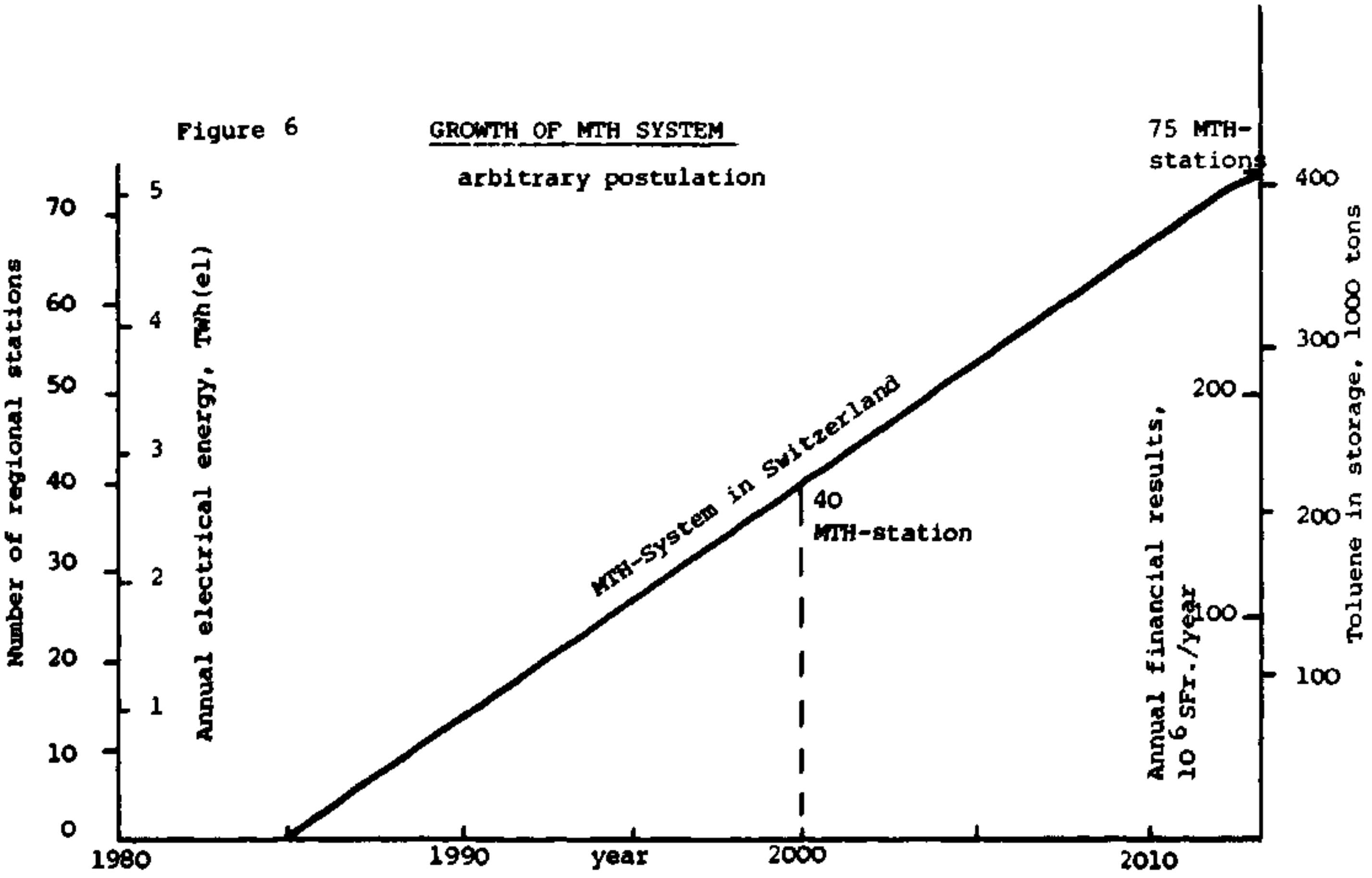


Figure 6 GROWTH OF MTH SYSTEM

arbitrary postulation



Remark: Annual production of toluene in USA (1980) only: 5.4×10^6 tons

7. Environmental problems

Last but not least are the excellent properties of this type of fuel for vehicles from the point of view of environmental protection.

It is enough to mention that in the proposed MTH-System

a) the emission of carbon dioxide, carbon monoxide, sulphur dioxide, hydrocarbon and smoke are reduced by a factor of 10, and in the future may be reduced to zero,

b) the emission of nitrogen oxide is significantly lower,

c) the thermal pollution is approx. 6 times lower than for gasoline driven vehicles,

d) the re-use of the heat of exhaust gases diminishes the amount of heating oil burned for space heating,

e) significant amount of free oxygen are produced and can be used e.g. in local aqueous waste purification stations (35 g(O_2)/ m^3 waste or garbage)

f) the possibility to use fuel cells (direct transformation of hydrogen energy to electrical energy for electrical motor,(see Fig. 1) is not negligible. The appropriate reduction of noise is of higher importance for the populated areas.

8. Conclusions

A motor car system based on the hydrogen produced by nuclear power stations during the night in the summer an coupled with organic liquid hydride seems to be a feasible system in the near future.

The pros and cons are as follows:

Pro: a) formidable chance for the seasonal storage of the electricity "surplus",

b) liquid organic hydride can be adapted to existing Otto-engine vehicles,

c) the concept of catalytic reactors on board vehicles, seems to be reasonable with reference to cost, weight, size and maintenance,

d) the radius of normal action of 250 km per day is possible and increases the weight of buses of 17 tons by only ∿1.5 tons, that is ∿ 9 %,

e) the cold start and the "warm start" are possible due to the direct burning of toluene (octane number 112).

This results in losses of some weight percent toluene per cycle. The deficiency in dehydrogenation heat for the catalytic reactor is covered by direct burning of toluene.

f) chemical and thermal pollution is significantly reduced,

g) the toxicity and flammability of the components toluene and methylcyclohexane are the same as those of gasoline,

h) the MTH-system is competitive still today with present prices of gasoline and heating oil. But the selling of the heat in summer could be a problem, even at a price of 1/3 of the market price.

i) the first step in market penetration can be a rather small system, with rather low capital cost. Big decisions are not needed here. The pilotsystem for 2-3 heavy vehicles could be realised the next 3 years.

j) the capital cost corresponds to 26 SFr per equivalent barrel of gasoline (not the crude oil) that is ~ 12.5 US$/barrel (during 10 years, 300 d/y).

<u>Cons:</u> a) use of electricity for production of hydrogen is a rather bad system from the point of view of the thermodynamical efficiency,

b) the lifetime ot the catalysts in the cars can be prohibitively short because ot the non-continuous regime. This must be proved experimentally,

c) the location of regional hydrogenation plants is limited because of the complex character of the system: Neighbourhood of electrical grid, work during the night, need for tanks, neighbourhood of consumer and even of oxygen consumer, increasing traffic of vehicles.

d) the MTH vehicles use approx 80 % of energy from hydrogen (electrolysis) and approx 20 % from toluene.

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