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OS81016/VOD06
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GRENSÁSVEGUR 9,
108 REYKJAVÍK ICELAND

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Princeton University

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ÚTDRÁTTUR (SUMMARY IN ICELANDIC)

Í skýrslu þessari er sýnt fram á að framleiða megi 35.000 tonn af metanóli á ári hverju úr sorpi sem safnast á Stór-Reykjavíkursvæðinu. Stofnkostnaður metanólverksmiðjunnar, sem auk sorps þarf vetni og súrefni til framleiðslunnar, sýnist vera $26,2 milljónir. Rafgreiningarbúnaðurinn er hér ekki talinn með en hann myndi kosta $7-8 milljónir til viðbótar. Framleiðslukostnaður metanóls í verksmiðju þessari er þá $280/tonn (verðlag 1980). Þessi kostnaður er ekki nema eilítið hærri en núverandi innflutningsverð á bensíni ef miðað er við "virkar orkueiningar" (þ.e. eldsneytiskostnaður á hvern ekinn kílómetra er einungis örlítið meiri fyrir metanólbifreið en bensínbifreið ef bifreiðarnar eru sambærilegar að öðru leyti). Ástæðan er einkum sú að orkunýtni metanólvéla er 25-30% betri en bensínvéla og vegur þessi góða nýtni næstum að fullu upp þann verðmun sem er á hverju tonni af metanóli og bensíni.

Þótt þekktar og líklegar olíubirgðir jarðarinnar geti dugað jarðarbúum næstu 30-40 árin er óvíst hvort olíuframleiðsla muni svara til eftirspurnar allt þetta tímabil. Sveiflur á verði olíu og oftast upp á við eru því líklegar. Þess vegna má ætla að framleiðsla og notkun tilbúins eldsneytis verði æ álitlegri kostir jafnt á Íslandi sem annars staðar. Ærið margt bendir til að metanól muni víða verða fyrir valinu í stað olíuafurða sem eldsneyti fyrir alls kyns vélar, bæði stórar og smáar. Framboð á vélum fyrir fiskiskip og bíla sem brennt geta metanóli ætti því að verða nóg fyrir okkur Íslendinga. Metanól kemur þess vegna vel til greina sem eldsneyti á Íslandi í framtíðinni.

Ætli Íslendingar einhvern tíma að framleiða og nota metanól (eða annað tilbúið eldsneyti) í stórum stíl er nauðsynlegt að hafist verði handa nógu snemma til að undirbúningstíminn geti orðið langur. Við öðlumst ekki þá þekkingu og reynslu á einni nóttu sem þarf til að búa til nýtt eldsneyti snurðulaust. Vænlegast er að byrja í litlum mæli og auka hlut metanóls smám saman.

Líklegt er að fiskiskipaflotinn og bifreiðar landsmanna muni nota jafngildi 300.000 tonna af olíu á ári hverju það sem eftir lifir aldarinnar. Orkugildi 35.000 tonna af metanóli er helmingur orkugildis sama magns af olíu og nemur því um 5% ofangreindra 300.000 tonna. Það er einnig tiltölu-

lega lítið fyrirtæki að koma þessum 35.000 tonnum í lóg eins og sjá má af eftirfarandi tölum: Ársnotkun 10 togara svarar til u.þ.b. 20.000 tonna af metanóli og 3.000 bílar, sem er 20-30% af árlegum bílainnflutningi til landsins, nota jafngildi 7.000 tonna af metanóli á ári. Samtals eru þetta 27.000 tonn. Auðvitað var þessi fjöldi togara og bifreiða fundinn með því að reikna aftur á bak en draga má þá ályktun af öllu samanlögðu að 30-35.000 tonn sé heppileg byrjunarstærð íslenskrar metanóliðju.

ABSTRACT

It is shown that it is possible to produce 35,000 tonnes of methanol annually from MSW collected in Reykjavík and neighbouring townships. The investment cost of the methanol plant, which in addition to refuse uses electrolytic hydrogen and oxygen, is estimated to be $26.2 million (the figures do not include the electrolysis facility, which would cost another $7-8 million) and the production cost per tonne of methanol appears to be $280 (1980 prices).

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1 INTRODUCTION

In latter years energy self-sufficiency has become a goal nations throughout the world strive for, and Iceland is no exception. The stumbling blocks on the road towards energy independence have, however, proved difficult to overcome. It can be argued in many ways that the difficulties encountered in Iceland highlight the true nature of the energy crisis facing the industrialized countries. With vast resources of hydro power and geothermal energy, far in excess of present demand, the country is heavily dependent on imported oil to meet a large fraction of its energy needs. This situation is not likely to change very much in the immediate future for the energy forms most easily generated from indigeneous resources (electricity and heat) do not match the prevailing end-use pattern. For a long time to come large quantities of liquid fuels will be necessary to propel the fishing industry and the transportation sector.

Many have hoped that domestically produced synthetic fuels could ease the burden of an ever increasing oil import bill. But these hopes have been frustrated by the almost complete lack of suitable carbonaceous feedstocks. Among the solutions offered have been imported coal, indigeneous peat and carbon oxide extraction from industrial exhaust, shell sand, sea water and the atmosphere, but none appear particularly promising. A potential carbon source, which apparently has received little attention so far, is municipal solid waste (MSW). Although an Icelandic synthetic fuels industry designed to make a significant contribution to domestic fuel consumption would almost certainly require the import of huge amounts of coal it is worthwhile going through the exercise of estimating what sort of contribution MSW could make.

The liquid fuel that can most easily be produced from municipal refuse is methanol. Interest in methanol as a synthetic fuel option is growing worldwide for a variety of reasons, the main ones being:

1) Attractive fuel. Methanol burns efficiently and cleanly outweighing its relatively low heating value.
2) Production flexibility. Methanol can be produced from any carbonaceous feedstock, such as coal, biomass (wood, organic wastes), oil shale, etc.

3) Proven technology. Methanol manufacturing technology is well understood and commercially available.
4) Favourable economics. Compared to other synthetic fuel alternatives methanol manufacturing economics are quite attractive.

It appears increasingly likely that many nations will opt for methanol as a replacement fuel for refined petroleum products. The conversion to a new fuel system will be gradual and take a long time as difficulties in adjusting to methanol fuels will undoubtedly be encountered. Experience in the production of methanol from unconventional feedstocks and the general use of methanol will accumulate only slowly. Although it is impossible to predict whether or when a new oil crisis will strike with supply shortages and escalating prices, proven and probable petroleum resources will last only 30 years. Three decades should be sufficient time for a smooth transition to a new fuel system, but small scale production and experimentation in the use of methanol should be begun sooner than later to take full advantage of the available time.

It will be shown later in this report that approximately 35,000 tonnes/year of methanol can be manufactured from MSW collected in the Reykjavík area. To put this number into perspective it has been predicted that the demand for gasoline in Iceland will be close to 100,000 tonnes/year for the remainder of this century (Energy Forecasting Committee 1980, p 16). In the same period the total demand of the fishing fleet and the transportation sector for liquid fuels (gasoline, diesel oil and residual fuel oil) will amount to approximately 300,000 tonnes/year (Energy Forecasting Committee 1980, p 16). Since the heating value of methanol is only half that of gasoline 35,000 tonnes of methanol are equivalent to 17,500 tonnes of gasoline. Hence, a MSW-based methanol plant would make a modest contribution to Icelandic fuel supplies.

With adequate planning and foresight it should not pose any problems to find a market for these 35,000 tonnes/year of methanol. Automobile manufacturers on both sides of the Atlantic are already offering cars which run on 100% methanol. It has also been verified that gasoline-methanol blends containing up to 15-20% methanol (by volume) can be used in conventional spark ignited internal combustion engines with only minor modifications. Large diesel engines burning 100% methanol for use in ships should also be available soon. It should therefore be obvious that there are ample opportunities for experimenting with the use of methanol in Iceland.

2 AN ESTIMATE OF AN UPPER BOUND FOR THE AMOUNT OF METHANOL, WHICH CAN BE PRODUCED FROM MSW COLLECTED IN REYKJAVÍK AND NEIGHBOURING TOWNSHIPS

Before going into details it is advantageous to acquire a feeling for the order of magnitude involved. As limited information is available about the amount and in particular the composition of MSW generated in the Reykjavík area some assumptions will have to be made in order to complete the calculations.

In 1977 the total amount of solid refuse dumped in the city's landfill was 68,400 tonnes (Jón Erlendsson 1978, p 1). This figure includes industrial waste in addition to municipal waste (which is usually taken to mean household, institutional and commercial waste). On the other hand, there does not appear to be any overriding reason to expect a different organic fraction for the industrial waste (see Table p 6 in Jón Erlendsson 1978). Nor does the composition of the total refuse differ appreciably from the composition of the waste collected in a typical New Jersey community (compare Table 3 p 16 in Urban et al. 1979 and Table p 6 in Jón Erlendsson 1978). Whether the above amount of 68,400 tonnes includes all the refuse generated in the neighbouring townships is unclear. But it seems reasonable to assume that during 1987-1990 at least 75,000 tonnes/year of refuse will be available to a waste disposal facility such as a methanol plant.

The tremendous waste disposal problem afflicting the U.S. and a desire to recover some of the valuable ingredients in refuse have spurred the collection of considerable data on the amount of MSW generated in that country. It has been estimated that on average approximately 3 lb (1.4 kg) of MSW (does not include industrial waste) are generated per capital per day in the U.S. (Urban et al. 1979, p 25). Assuming the same figure for Reykjavík and its neighbouring townships, which have a combined population of 115,000, the amount of available MSW is 160 tonnes/day or 58,000 tonnes/year. If waste disposal patterns are similar in Iceland and the U.S. this indicates that a total amount of refuse of 75,000 tonnes/year is not unreasonable for the Reykjavík area.

Based on the results of oxygen gasification of MSW using the Purox process it appears that on average 1 tonne of MSW contains 0.27 tonnes of carbon (Union Carbide Corporation 1979, p 3-6; Ader et al. 1980, p 58). From 1 tonne of carbon and sufficient quantities of oxygen and hydrogen, 2.7 tonnes of methanol can be produced. Hence, an upper bound for the total amount of methanol, which can be manufactured from 75,000 tonnes of municipal waste, is 54,700 tonnes. This number is, of course, unrealistic as it is based on a carbon efficiency of 100%, which no actual process can match. A production potential of 35,000 tonnes/year appears more reasonable as will be demonstrated on later pages.

3 PRODUCTION OF METHANOL

The production of methanol on a commercial scale for use in the chemical industry is of long standing. The process of synthesizing methanol from a mixture of carbon monoxide and hydrogen ("synthesis gas") was developed in the early 1920's and by 1974 annual world production of methanol had reached 9 million tonnes (Hagen 1976). Early on coal gasification was a significant source of synthesis gas for methanol manufacture but the availability of inexpensive natural gas in recent decades made steam reforming methane a more economical source. The impending petroleum shortage has, however, led to a partial turnaround. The enormity of available reserves of gasification feedstocks, such as coal, wood and organic wastes, as compared to dwindling oil supplies has called for considerably increased research efforts into finding suitable ways of producing synthetic fuels. This search has been quite fruitful and the technical feasibility of various processes has been demonstrated. The economics are still uncertain but likely to improve markedly in the future as petroleum prices continue to rise. Methanol can be produced from almost any carbonaceous material making it one of the most attractive synthetic fuels. In the remainder of this section the production of methanol from solid feedstocks will be briefly described.

The production process can conveniently be broken up into four steps:

1) Preparation of feedstocks.
2) Gasification.
3) Gas cleaning and modification.
4) Methanol synthesis.

Figure 1 depicts the process schematically.

The chemical reaction producing methanol (CH_3OH) from synthesis gas is:

$$CO + 2H_2 \rightarrow CH_3OH$$

which is carried out at elevated pressures in the presence of a highly selective catalyst. The composition of the producer gas from the gasification step varies depending on the particular feedstock and the reactor specifications but will typically contain varying amounts of carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2), water vapor (H_2O), methane and higher hydrocarbons (CH_4, "C_3H_8"), and sulphur compounds (e.g. SO_2, H_2S). If air is used as the gasifying medium nitrogen (N_2) will also be present. In addition the gas stream will contain particulates and a fine mist of oil and tars. As the optimal composition of the synthesis gas is a nearly pure mixture of carbon monoxide and hydrogen in the molar ratio of 1 to 2, the gas will need extensive treatment before it can be allowed to enter the methanol synthesis loop. Undesirable compounds (most of the carbon dioxide and those containing sulphur) and particulates must be removed from the gas stream, both to minimize compression work requirements and protect the sensitive catalysts from contamination.

As the producer gas is usually deficient in hydrogen the carbon monoxide-hydrogen ratio can be adjusted according to the shift reaction:

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

unless an external source of hydrogen is available.

To boost the energy efficiency of the process steam reforming the hydrocarbons using the reactions:

$$C_nH_{2n+2} + \frac{n-1}{2} H_2O \rightarrow \frac{3n+1}{4} CH_4 + \frac{n-1}{4} CO_2$$

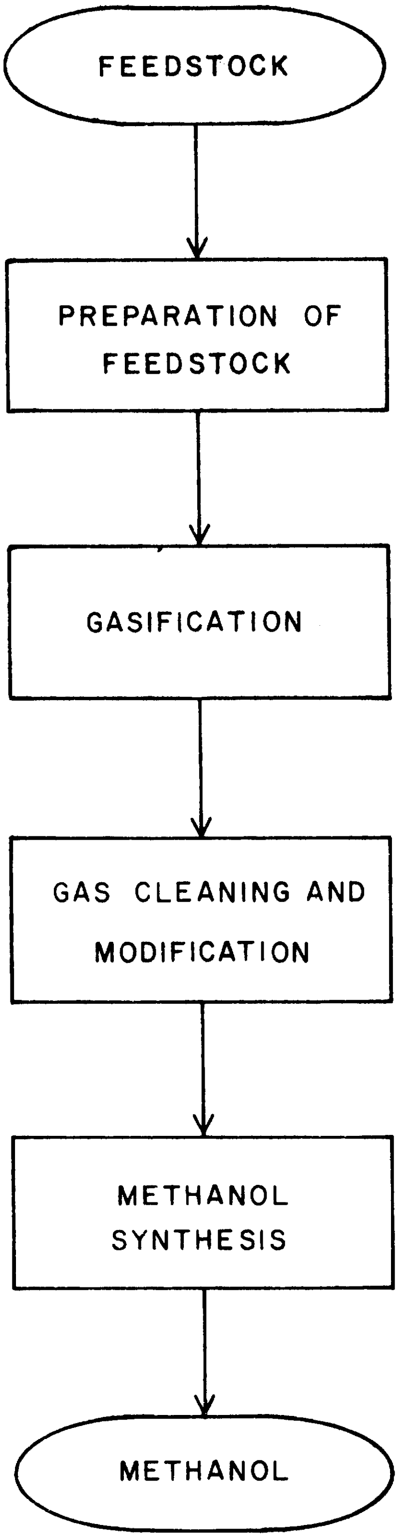
$$CH_4 + H_2O \rightarrow CO + 3H_2$$

will be necessary.

Having gone through a combination of the above treatment steps the gas must be compressed to 50-100 atmospheres before entering the synthesis reactor. The final product will be relatively clean methanol, which can be further purified by distillation.

This short description of methanol production will hopefully illuminate some of the following discussion.

Fig. I


FEEDSTOCK
PREPARATION OF FEEDSTOCK
GASIFICATION
GAS CLEANING AND MODIFICATION
METHANOL SYNTHESIS
METHANOL

4 A SELF-CONTAINED MSW-TO-METHANOL PLANT

Since 1974 Union Carbide Corporation has operated a commercial scale (180 tonnes/day) waste disposal facility at South Charleston, West Virginia (Union Carbide Corporation 1979; Ctvrtnicek et al. 1978). The Purox system, as it is called, is essentially an oxygen gasifier. Figure 2 is a schematic drawing of the basic features of the system (Union Carbide Corporation 1979, p 4). Having gone through a shredder and a magnetic separator the waste is fed into the vertical shaft furnace. Oxygen is injected at the bottom of the furnace where it reacts with carbon char residue producing hot gases which rise through the descending waste. The temperature generated in the combustion zone is sufficiently high to melt and fuse all noncombustible materials, which then continuously overflow into a water quench tank. In the middle portion of the furnace organic materials are pyrolized yielding a gaseous mixture high in carbon monoxide and hydrogen (see Table 1). As the hot gaseous products continue to flow upward they dry the entering refuse in the upper zone of the furnace. After cleaning and drying the resultant gas is a clean burning fuel, which can easily be turned into synthesis gas via the shift reaction, steam reforming and further gas cleaning, as described in the last section.

A plan for methanol manufacture based on the Purox gasification process is presented in Ader et al. 1980. Figure 3 (Ader et al. 1980, p 61) is a simplified flow diagram highlighting the most important aspects of the process. The production facility is self-contained insofar as it supplies its own oxygen and energy. Flue gas from the gas cleaning section is led to a steam generating boiler, which supplies the energy required in the oxygen plant and for pumping and compressing. This results in a significant drop in carbon efficiency since a considerable fraction of the carbon is lost as carbon dioxide from the boiler. Another cause of carbon inefficiencies can immediately be discerned from Table 1, where it can be seen that the carbon monoxide-hydrogen ratio is far from the optimal 1 to 2 ratio, requiring considerable use of the shift reaction. Steam reforming the hydrocarbons (CH_4, "C_3H_8") present in the gas also leads to some additional loss of carbon. As a result only 0.24 tonnes of methanol can be produced from 1 tonne of refuse, which is a small fraction of the 0.73 tonnes arrived at assuming 100% carbon efficiency. Some remedies to these problems will be presented in the next chapter.

The estimated production cost of methanol in such a plant as described above with an output of 250 tonnes/day is \$390/tonne (early 1980 prices) (Ader et al. 1980, p 66), which is unreasonably high for a positive cost is assigned to the feedstock while a negative one would appear to be more appropriate. This figure will not be comparable with the cost of production derived in the next section for a different method of assigning capital related costs will then be used.

TABLE 1

For the gasification of 1 tonne of refuse 0.2 tonnes of oxygen are required giving 0.7 tonnes of gas, 0.22 tonnes of char and slag and 0.28 tonnes of waste water. An analysis of the composition of the gas yields:

	Wt %	Wt (tonnes)	Mole %
CO	43.1	0.302	40
CO_2	42.3	0.296	25
H_2	1.8	0.013	24
CH_4	3.1	0.022	5
"C_3H_8"	8.5	0.060	5
N_2/Ar	1.2	0.008	1
Total	100.0	0.700	100

Fig. 2

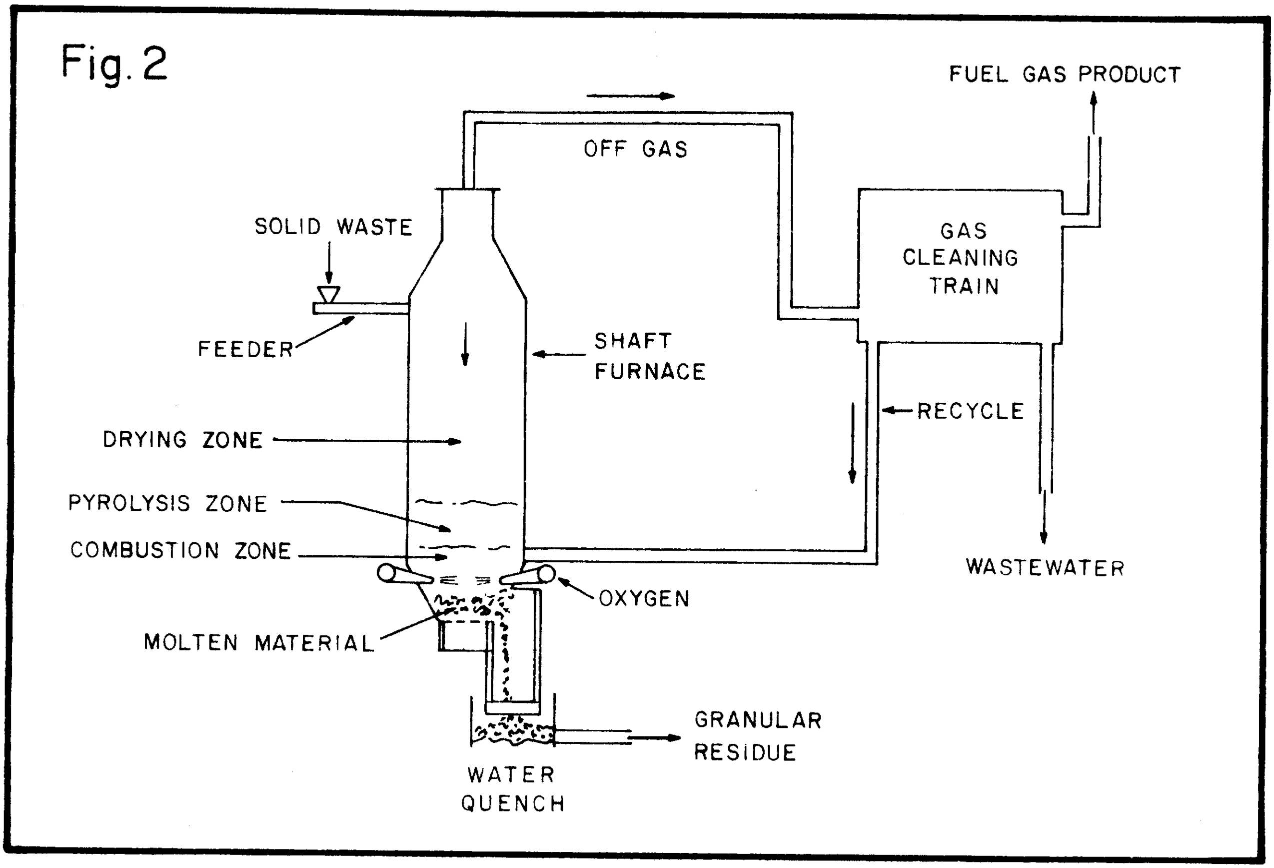


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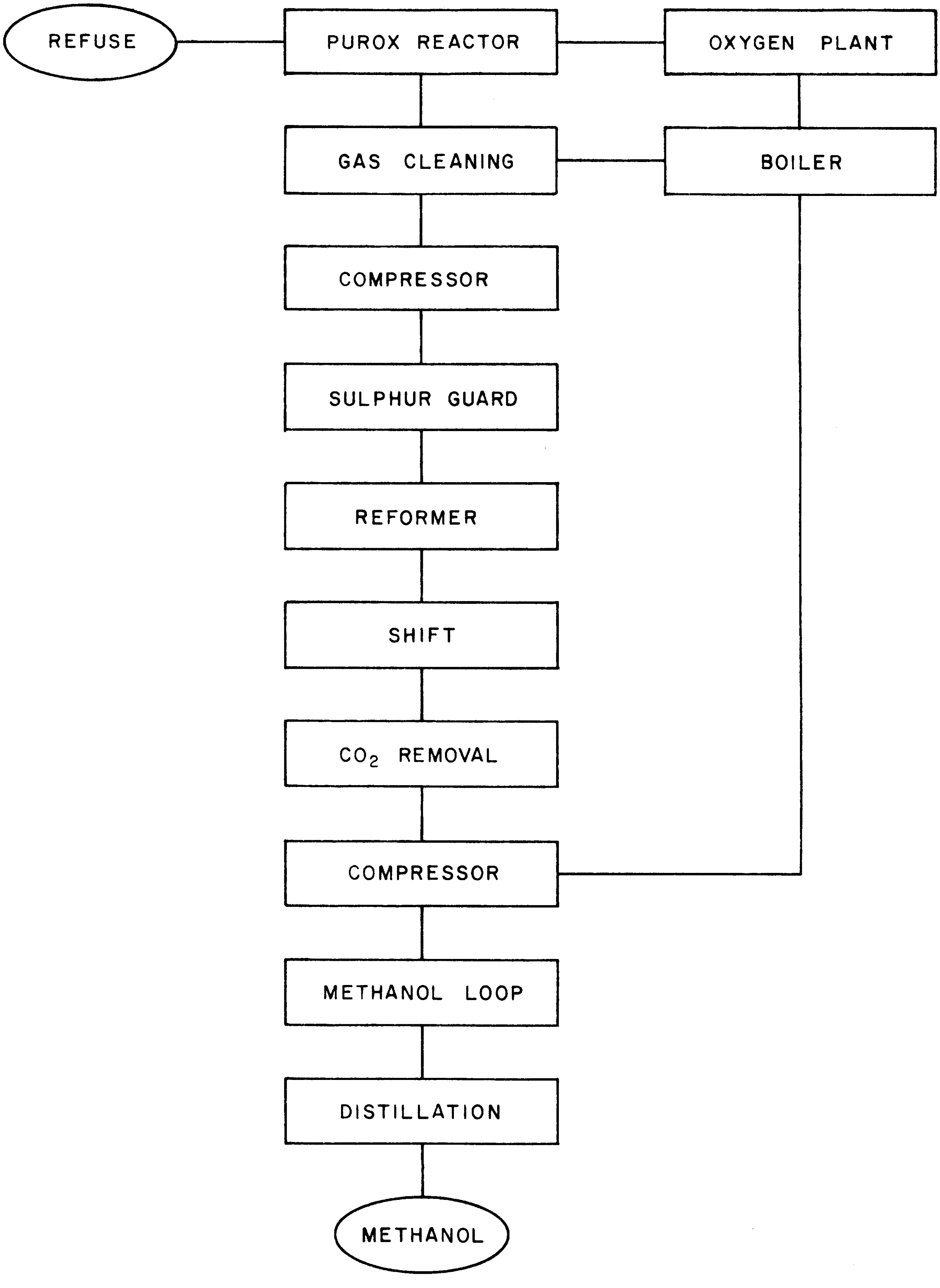
Fig. 3


REFUSE
PUROX REACTOR
OXYGEN PLANT
GAS CLEANING
BOILER
COMPRESSOR
SULPHUR GUARD
REFORMER
SHIFT
CO_2 REMOVAL
COMPRESSOR
METHANOL LOOP
DISTILLATION
METHANOL

5 A MSW-TO-METHANOL PLANT FOR REYKJAVÍK

As is evident from the discussion in the last section the main ways of improving the carbon efficiency of the conversion process are to:

1) Supply sufficient quantities of oxygen and hydrogen from external sources.
2) Use auxiliary energy to meet work requirements for pumping and compressing.

Since relatively inexpensive electricity should be available in Iceland both of the above ways seem feasible. Electrolysis of water, possibly in cooperation with the State Fertilizer Plant, could give the necessary quantities of hydrogen and oxygen and electric motors could be used to drive pumps and compressors. On the next few pages preliminary calculations for such a process are presented.

It has already been stated that 0.2 tonnes of oxygen are needed to gasify 1 tonne of refuse. To eliminate the shift reaction requirements, ignoring the small excess amount of hydrogen produced in steam reforming the hydrocarbons, 0.030 tonnes of additional hydrogen are needed for each tonne of MSW. The annual requirements for oxygen and hydrogen for the processing of 75,000 tonnes of MSW will then be respectively 15,000 tonnes and 2,250 tonnes. These numbers roughly represent the present production capacity of the 10 electrolyzers of the State Fertilizer Plant (Study Group on Hydrogen and Hydrogen Derived Compounds 1980, p 21). From the electrolysis reaction:

$$H_2O \rightarrow H_2 + \frac{1}{2} O_2$$

it can be seen that the weight ratio of oxygen to hydrogen produced via electrolysis is 8 to 1, which matches the specifications of the process. The electric power requirements of the electrolysis plant will be approximately 14 MW corresponding to 115 GWh electric/year.

The appropriate formula for calculating the work required for compression using a multistage compressor with perfect intercooling is:

$$E = n \cdot \frac{K}{\Sigma} \cdot \frac{\gamma}{\gamma - 1} \cdot R \cdot T \cdot [(\frac{P_2}{P_1})^{\frac{\gamma - 1}{K \gamma}} - 1]$$

where the following nomenclature is used:

n : number of moles
K : number of compression stages
Σ : efficiency of compressor (0.8)
γ : $\frac{C_p}{C_v}$, the ratio of the specific heat at constant pressure to that at constant volume (1.4)
R : the universal gas constant ($1.99 \cdot 10^{-3}$ kcal/mol·K)
T : ambient temperature (290 K)
P_1: initial pressure
P_2: final pressure

From Figure 4, which shows this process schematically, it can be seen that there are three compression steps. For each tonne of MSW the first step is the compression of 0.7 tonnes (45,000 moles) of producer gas from atmospheric pressure to 20 atmospheres. The electricity needed, assuming a 2-stage compressor, is:

E_1 = 140.9 kWh

The second step is the compression of 0.51 tonnes (35,000 moles) of synthesis gas from 20 atmospheres to 100 atmospheres requiring:

E_2 = 57.5 kWh

of electricity. The third step is the compression of 0.030 tonnes (15,000 moles) of hydrogen from 1 atmosphere to 100 atmospheres:

E_3 = 19.6 kWh

The total annual electrical energy demand is then 16.3 GWh (2.1 MW).

For each tonne of refuse the production of methanol will amount to almost 0.50 tonnes allowing for slight inefficiencies in the methanol loop. Total production on an annual basis then comes to a little more than 35,000 tonnes/year. Table 3 summarizes the main parameters of a methanol manufacturing plant in Reykjavík built on the preceding ideas.

Although reliable economic information is not available an approximate production cost for the methanol can be derived from cost figures given in reports on previous investigations (Study Group on Hydrogen and Hydrogen Derived Compounds 1980, p 23-31 and Ader et al. 1980, p 65-66). The issue of what cost should be assigned to the feedstock is not a settled one although the waste disposal service such a facility renders is of considerable value. In the following calculations the feedstock has been assigned a zero cost while a negative one could also be justified. The investment cost of the plant (excluding electrolysers, as it will be assumed the hydrogen and oxygen is bought from an outside supplier. The cost of a sufficiently large electrolysis plant would be in the range $7-8 million) can be estimated from information in the Ader report (Ader et al. 1980, p 65). The itemized investment cost can be found in Table 2. The total turns out to be $26.2 million. Assuming the cost of hydrogen and oxygen to be $1.800/tonne hydrogen (Study Group on Hydrogen and Hydrogen Derived Compounds 1980, p 23-31; assuming an electricity price of 16 millions/kWh) the total production cost of 35,000 tonnes of methanol is:

For oxygen and hydrogen:	$4.0 million
For electricity (16.3 GWh at 30 millions/kWh):	$0.5 million
Labor costs (25 men at $25,000/man):	$0.6 million
Maintenance (3% of investment cost):	$0.8 million
Capital related costs (15% of investment cost):	$3.9 million
Total:	$9.8 million

And the production cost per tonne of methanol is $280.

TABLE 2

Investment Cost of Methanol Plant

Purox gasifier and refuse handling	$ 4.0 million
Gas cleaning	$ 1.8 million
Reformer	$ 3.7 million
Compressors	$11.5 million
Methanol synthesis and distillation	$ 5.2 million
Total	$26.2 million

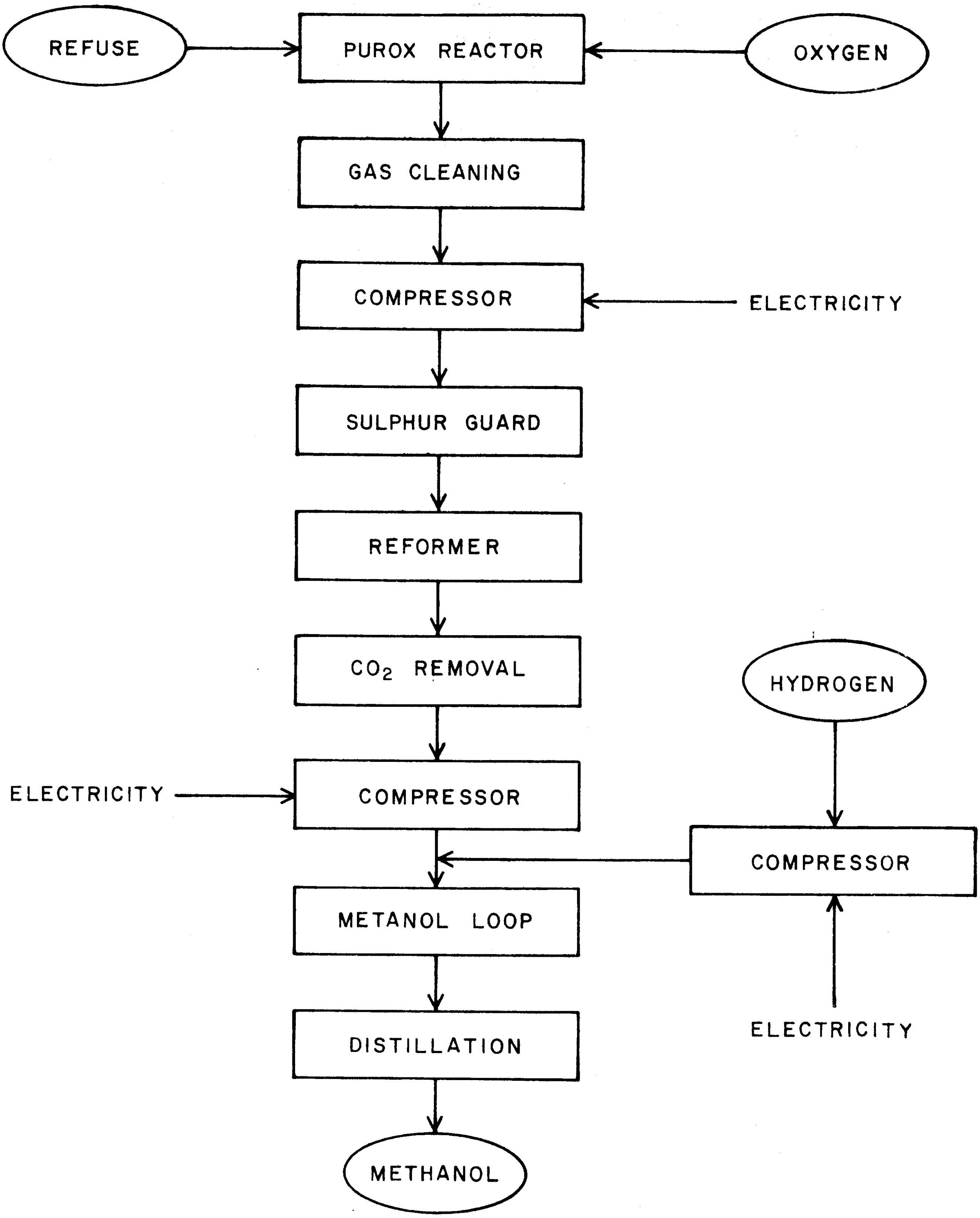
TABLE 3

Main Parameters of MSW-to-Methanol Plant

Amount of refuse processed annually	75,000 tonnes
Annual production of methanol	35,000 tonnes
Power requirements	2.1 MW
Electrical energy required	16.3 GWh/year
Investment cost	$ 26.2 million
Total annual production cost	$ 7.9 million
Production cost per tonne methanol	$280

In addition sufficient quantities of hydrogen and oxygen (2,250 tonnes hydrogen and 15,000 tonnes oxygen) can be supplied from an electrolysis plant at a cost of $1800/tonne of hydrogen produced. This plant will require 14 MW of electric power and use 115 GWh/year.

Fig. 4


REFUSE
PUROX REACTOR
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ELECTRICITY
SULPHUR GUARD
REFORMER
CO_2 REMOVAL
HYDROGEN
ELECTRICITY
COMPRESSOR
COMPRESSOR
METANOL LOOP
ELECTRICITY
DISTILLATION
METHANOL

6 CONCLUSION

A production cost of \$280/tonne of methanol is relatively low, especially in such a small facility, and can be compared to the \$390/tonne referred to in section 4. There are three main reasons for this difference:

1) The latter cost figure is based on a positive feedstock cost, which is difficult to justify.
2) Different methods of assigning capital related costs are used.
3) Electrolytic hydrogen ceases to be exorbitantly expensive when the "by-product" oxygen can also demand a high price. Oxygen gasification and the use of hydrogen to boost the carbon efficiency of solid fuel conversion appear to be a very attractive combination when inexpensive electricity is available.

The above cost of \$280/tonne methanol (\$0.86/gal) compares favourably with the present \$380-400/tonne (\$1.20-1.25/gal) import price of gasoline. Although the heating value of methanol is only half that of gasoline it is known to burn up to 30% more efficiently in internal combustion engines for it permits the use of a higher compression ratio and a leaner air/fuel mixture. Hence, each BTU (or GJ, gigajoule) in methanol can cost up to 30% more than each BTU in gasoline. Assuming a price of \$400/tonne for gasoline it then follows that methanol can cost \$260/tonne and still be competitive. If gasoline prices increase another 10-15%, to \$430-450/tonne, methanol at \$280/tonne will be just as economical.

The preliminary results derived in this report appear encouraging enough to warrant further work either to refute or establish the validity of these calculations.

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