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Wood gas generators for small power (~ 5 hp) requirements

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Abstract. This paper reports experimental and developmental studies on wood gas generators meant for running 5 hp diesel engines in irrigation water pumping. Critical inputs for the design of small reactors are presented. A prototype of the gas generator based on these inputs has been built and tested along with a diesel engine pumpset. The results of various tests on the system are described along with some critical operational features. The lowest amount of diesel at which the engine could be run with a mixture of diesel and gas is about 15% of the consumption with diesel alone. However, to obtain the same energy, that is the same amount of water at a given height, the best replacement of diesel obtained is about 75%. The paper also comments on the economics of such systems.

Keywords. Wood gas; gasifier design; diesel pumps; diesel replacement; alternate energy sources.

1. Introduction

Though producer gas as fuel has been known since 1785, gas generators for use with engines were evolved only around 1920. In the years that followed, quite a few of designs went into commercial production; the one by Imbert was most successful and extensively used. There were also several others in use between 1940 and 1950. The shortage of petroleum fuels in Europe during the Second World War created a new demand for gas generators in several countries; for example, Sweden converted 40% of its entire motor vehicle fleet into those running entirely on producer gas in that period. An essential feature of all those reactors was that they were developed for engines of 20–200 hp, used in automobiles and other transport vehicles; smaller reactors were not built. The SERI Report (1979) summarises excellently the Swedish experience with gas generators during the above period. The report also mentions that design and operation of gas generators for smaller power ratings pose problems, but does not elaborate on it.

The problem of using renewable sources of energy for generation of motive power has in recent years assumed significant magnitude the world over and is a subject of discussion of both the elite and the non-elite. In India, the position as regards petroleum fuels is not by any means rosy; indigenous supplies meet only a part of the demand, though the situation is slowly improving. Secondly, the country's ability to make such fuels available to all needy areas is not very satisfactory. Furthermore, the buying power of rural users for obtaining fuel oils at inflated costs is extremely limited. Lastly, the use of electricity for motive power is quite unsatisfactory because of the inability of the public distribution systems to reach users located far away from urban centres. In the light of these factors, the development of 'gas generator-based power supplies' for small ranges of power appears desirable.

When the work reported in this paper started, the task of development did not appear particularly promising. This is due to the difficulties anticipated by earlier workers (SERI Report 1979; Anon 1981) with small-sized reactors. However, these difficulties have been overcome and the experience thus obtained is reported in the following sections.

2. Gas generators—How do they work?

A brief description of the elements of a gas generator and the 'happenings' inside it is perhaps desirable. Figure 1 shows the various features of a typical gas generator. Wood chips move downward and get converted to useful gas (and ash) as shown in the figure. Heat transmitted from the combustion zone chars the wood chips as they approach the air inlet. In the process, they lose most of their moisture content and some volatiles, which is known as pyrolysis and takes place at the bottom of the hopper zone P (figure 1), where the temperature is about 200°C or more. The partially charred wood and the gases meet the oxygen from the air near the inlet nozzles and combust fiercely. The typical temperature during combustion is about 1200°C and the pieces of charred wood get reduced in size (see §6.8) as they move downward to the reduction zone.

The gases produced in the combustion zone are typically CO_2 and H_2O. As they proceed further, these gases along with N_2 from the incoming air meet a hot zone of charcoal. There CO_2 gets reduced to CO with H_2O participating in two reactions as

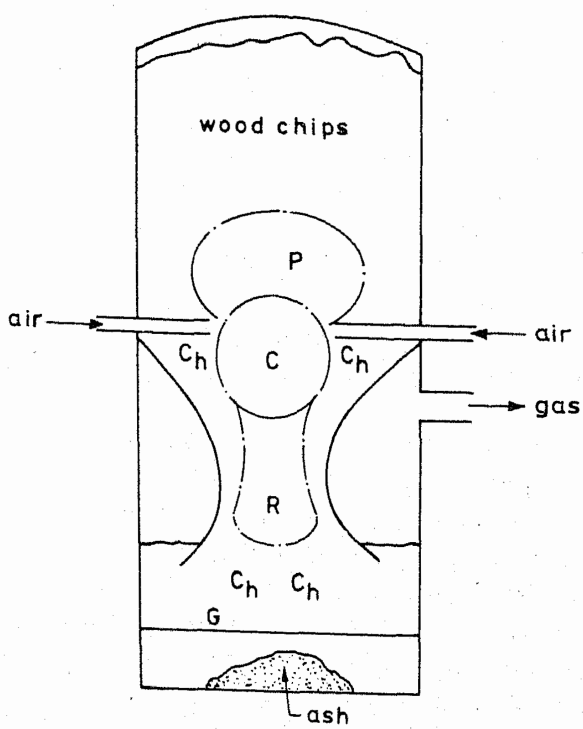

Figure 1. Typical gas generator. C_h: char; G: grate; P, pyrolysis; C, combustion; R, reduction.

shown below:

$$C+CO_2 \rightarrow 2CO,$$
$$C+H_2O \rightarrow CO+H_2,$$
$$CO_2+H_2 \rightarrow CO+H_2O.$$

The first two are heterogeneous phase reactions and the last gas phase reaction is the well-known water-gas reaction. An examination of the equilibrium relations between the various species participating in the reactions suggests that the conversion of CO_2 to CO is nearly complete beyond 1000°C but falls steeply to 30% at 600°C. A typical composition of wood gas is CO (20–25%), H_2 (16–18%), CO_2 (8–10%), and N_2 (45–50%) with traces of other combustible gases like methane and higher hydrocarbons. Its heating value is 1100–1250 kcal/kg. This would mean (after some calculations) that to produce shaft power output equivalent to that of 1 litre of gasoline, 3 kg of wood (or 1·7 kg of charcoal) is required in practical operations.

In actual practice with generators, the reactions mentioned earlier do not attain equilibrium because they have finite reaction velocities. Therefore, the system design must consider the velocities of the various reactions. Amongst the three mentioned earlier, the water-gas reaction is the fastest and as such, attains equilibrium in most cases. The extent to which the other two reactions proceed depends on the accessibility of active surface sites and hence, is dependent in a rather complex way on the geometric features of the medium.

3. A few designs

There are essentially three different reactor configurations depending on the directions in which fuel and gas flow in the hearth. They are the up-draft, the down-draft and the cross-draft types as shown in figure 2.

Of the three, the up-draft (also called the counter current) type is essentially a bed of charcoal from the base of which air enters. Along the path of the air both combustion and reduction take place sequentially and the gases move upwards heating the contents of the hopper. The reactor could be used only with fuels free of tar because the gases carry the tar with them as they move up the hopper.

In the down-draft (co-current) type the fuel and the gases move in the same direction inside the hearth. It has a constriction in the passage (below the air inlets) through which all the hot gases have to pass. The tar and the other volatiles produced during pyrolysis get cracked significantly in this zone, thereby delivering a relatively clean gas when the hearth parameters are optimized.

The cross-draft type has an air inlet and a gas outlet diametrically opposite at the bottom of the reactor with the fuel bed moving perpendicular to the gas flow. This configuration is again known to be useful only for non-tar emitting fuels; it also causes large pressure drops across the hearth.

Figures 3a to 3d show four of the several designs which went into commercial production. These are the Imbert design, the Brandt design, the Kalle design and the Zeuch design. The figures are self-explanatory in showing the various zones, namely, pyrolysis, combustion, and reduction. A few characteristic features are listed in table 1, some of which have been incorporated into a new design described in the next section.

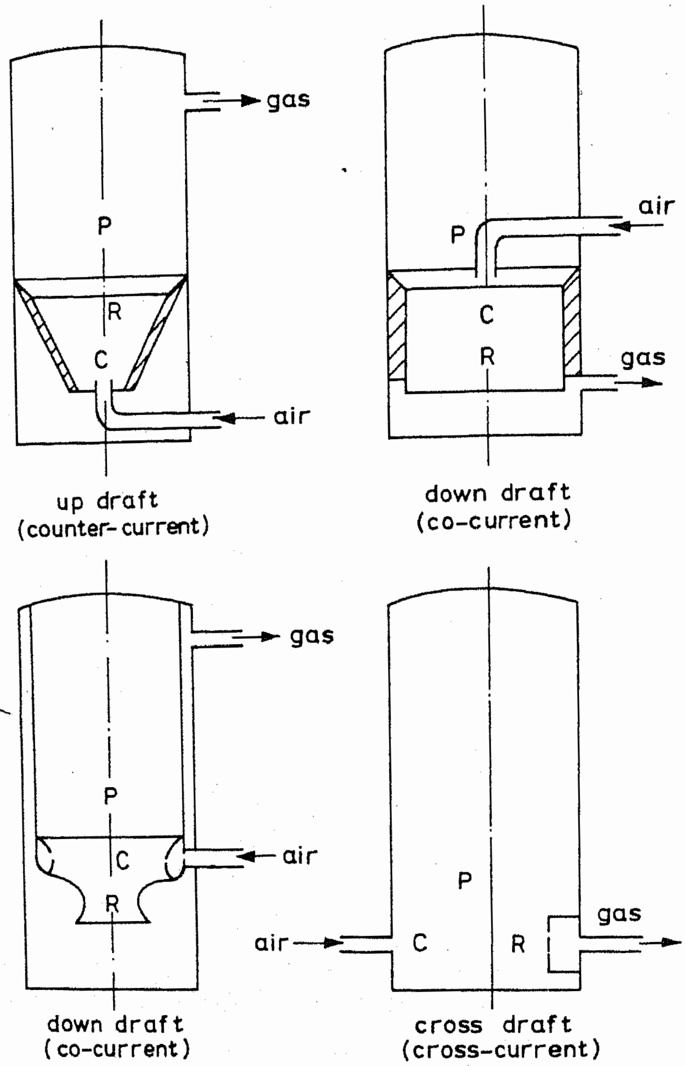

Figure 2. Reactor configurations.

4. Present design

4.1 *Rating*

The present design is meant for supplying enough wood gas to drive a 5 hp engine coupled to a pump. Since it is reasonably well known that the amount of diesel that can be replaced is about 70–80 %, the amount of power for which the gas generator is to be designed is about 3·5 to 4 hp.

4.2 *Reactor configuration*

As discussed earlier, the down-draft configuration is the only choice available to cater to tar-emitting fuels. Hence it has been adopted here, and the various dimensions that need to be specified for it are: (i) the throat diameter, d_h; (ii) the nozzle ring diameter, d_r; (iii) the nozzle opening circle diameter, d_{r1}; (iv) the reduction cone bottom diameter, d_{h1}; (v) the distances h, h_1, h_2 and h_3 between the planes corresponding to the nozzles,

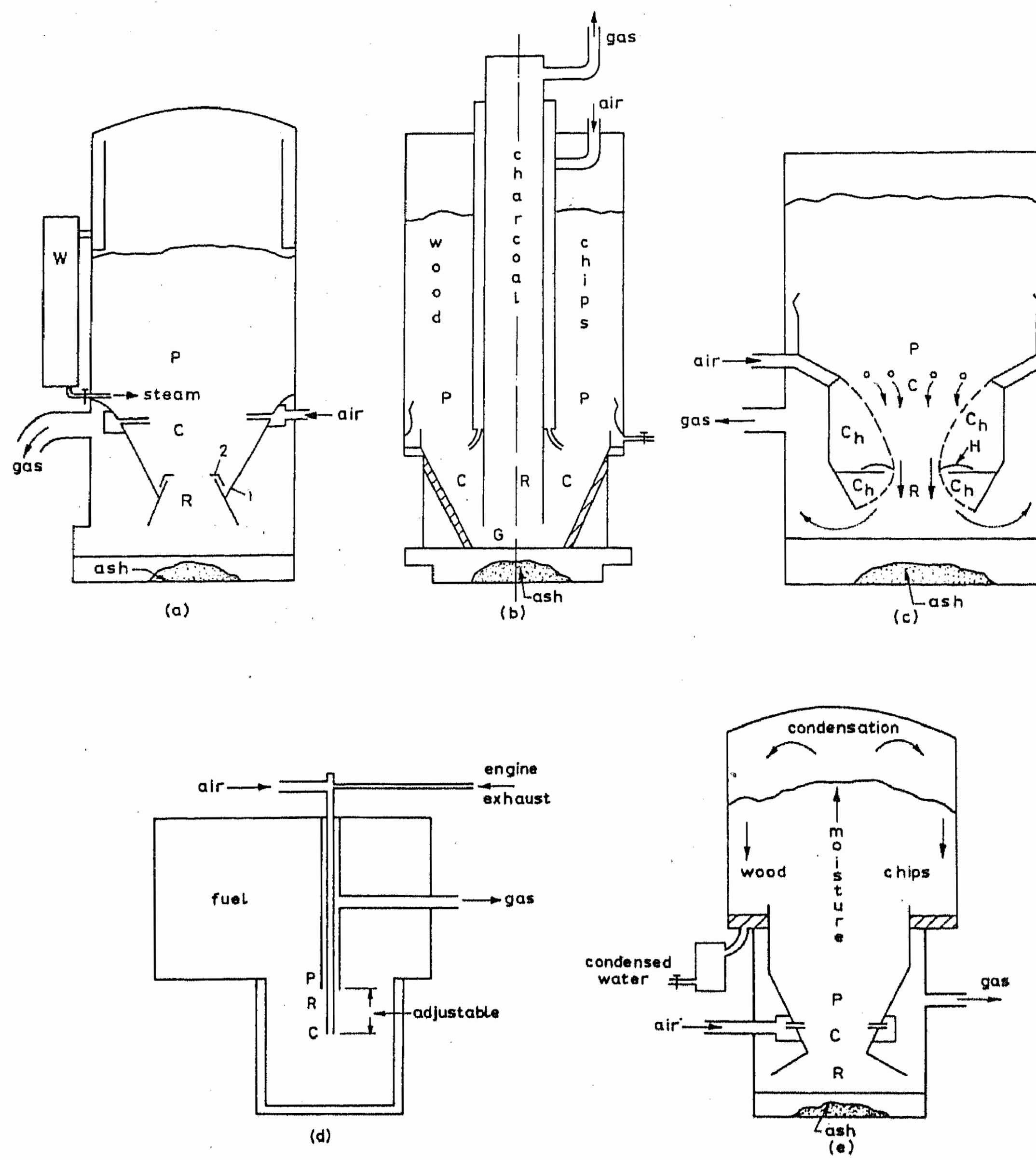

Figure 3. **a.** Wood gas generator—Imbert design, 1, ash keeping; V, hearth; 2, removable hearth ring; W, condensation water collection. **b.** Brandt reactor. **c.** Zeuch design, H, replaceable hearth ring with hearth constriction; C_h, insulating char envelope. **d.** Kalle reactor. **e.** Monorator.

throat, end of reduction cone, grate and the bottom of the reactor respectively. These are shown in figure 4.

4.3 *Hearth loading*

The concept of hearth load is used in obtaining the dimensions of the throat (the hearth-constriction); the hearth load is defined as B_h(Nm^3/cm^2-hr) which equals the quantity of prepared producer gas in (Nm^3/hr)/smallest passage (throat) area in cm^2. (Nm^3 refers to normal m^3 which is 1 m^3 at 0°C and at a pressure of 1 atm.)

The hearth load varies between an upper limit, $B_{h\,max}$, above which the gas quality is poor because of charcoal dusting in the combustion zone and a lower limit, $B_{h\,min}$,

Table 1. Characteristic features of a few reactors

	Imbert	Zeuch	Brandt	Kalle	Reactors with monorators
Fuel	Wood chips	Wood chips	Wood chips + charcoal	Crushed charcoal	Wood or charcoal
Special features	Ash holding V-hearth to reduce heat losses from the hearth. Replaceable hearth rings for easy maintenance. Preliminary cooling of the hot gases takes place at the hopper. Pre-heating of the incoming air using the hearth gases. Very sensitive to moisture.	Both the combustion and the reduction zones are insulated using charred material. Has easily replaceable hearth rings. The hearth uses a simple geometry which is easier to fabricate. Has an arrangement for extracting moisture from the fuel.	Hearth has two separate compartments. One for wood chips or agricultural wastes and the other for charcoal pieces which form the reduction zone. Has arrangements for extracting moisture from the fuel. Has simple geometry (Ref. 3)	Has provision for continuously varying the depth of the reaction zone. To keep the hearth temperature under control, a portion of the engine exhaust is mixed with the inlet air. Is very sensitive to moisture and tar contents of the fuel	Monorator is an arrangement for extracting moisture from the fuel in the hopper itself. Reactors with these devices can tolerate large variations in the moisture content of the fuel.

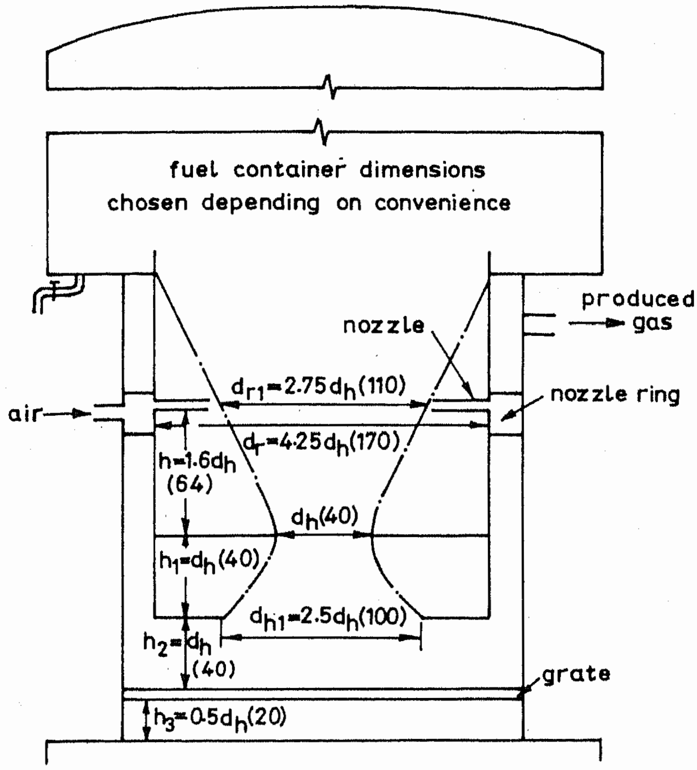

Figure 4. Critical reactor parameters. (Figures in parenthesis are prototype dimensions in mm)

below which due to too low a temperature in the hearth, the gas will contain unacceptably large quantities of tar.

In Imbert wood gas generators and other similar reactors, $B_{h\,max}$ reaches about 0·9 in continuous operation and $B_{h\,min}$ is about 0·3 to 0·35. For the design here, $B_{h\,max}$ has been assumed to be 0·9 and the rated power of 3·5 hp is assumed to be obtainable at a $B_{h\,rated}$ of 0·8 Nm^3/cm^2-hr.

4.4 *Specific fuel consumption*

This is computed from the formula:

$$\text{Specific consumption, } b(\text{kg/hp-hr}) = 632/\eta_{gen}\cdot\eta_{mot}\cdot H_i,$$

where, η_{gen} is generator efficiency, η_{mot} is engine efficiency and H_i is the effective heating value of wood. The following values have been assumed.

$\eta_{gen} = 0{\cdot}7$ (this value corresponds to the case where the gas coming out of the generator has to be cooled to room temperature and where no provision has been made for heat recovery),

$\eta_{mot} = 0{\cdot}22$,

$H_i = 3500$ kcal/kg (for wood with 20% moisture)

Then, $b = 1{\cdot}3$ kg/hp-hr.

4.5 *Fuel consumption*

Since it has been assumed that 3·5 hp will be delivered at $B_{h\,\mathrm{rated}} = 0{\cdot}8\ \mathrm{Nm^3/cm^2\text{-}hr}$, the power that can be delivered at $B_{h\,\max}$ is 4 hp. Therefore, nominal fuel consumption (at 3·5 hp) = 4 kg/hr and maximum fuel consumption (at 4 hp) = 5·2 kg/hr.

4.6 *Throat diameter* d_h

This is obtained from the maximum fuel consumption and $B_{h\,\max}$. From SERI Report (1979) the quantity of gas generated is about 2·2 Nm^3 for every kg of wood with 20% moisture content. Therefore, the maximum gas generation = 11·5 Nm^3/hr. Hence the throat area = 11·5/0·9 cm^2 = 12·8 cm^2 or d_h (throat diameter) = 4 cm.

4.7 *Other hearth dimensions*

SERI (1979) presents graphs and recommendations for a number of other hearth parameters. They have been obtained from the values taken from a range of successful generators. Using these data and extrapolating them whenever necessary (as shown by dotted lines) the following parameters have been fixed.

(a) nozzle ring diameter, d_r ($= 4{\cdot}25\,d_h$) = 170 mm (figure 5a),
(b) nozzle opening circle diameter, d_{r1} ($= 2{\cdot}75\,d_h$) = 110 mm (figure 5a),
(c) height of the nozzle plane above the hearth constriction, h ($= 1{\cdot}6\,d_h$) = 64 mm (figure 5b),
(d) height of the reduction cone, h_1 ($= d_h$) = 40 mm,
(e) diameter of the lower opening of the reduction cone, d_{h1} ($= 2{\cdot}5\,d_h$) = 100 mm.

4.8 *Nozzle dimensions*

The ratio between the total nozzle area A_m and the smallest passage area of the hearth, A_h varies in generators with good operational properties within very wide limits—between 3% and 14%. Figure 5c shows the Hasselman recommendation for different values of d_h. These curves were extrapolated (as shown by dotted lines) and a value of 12% was used for the ratio A_m/A_h. Based on the recommendations given in table 2, the number of nozzles chosen was 3 leading to a nozzle diameter of 8 mm for each nozzle.

4.9 *Other features*

Since the proposed reactor is of small capacity, to maximise its chances of success, a number of features from available successful generators described in §3 were

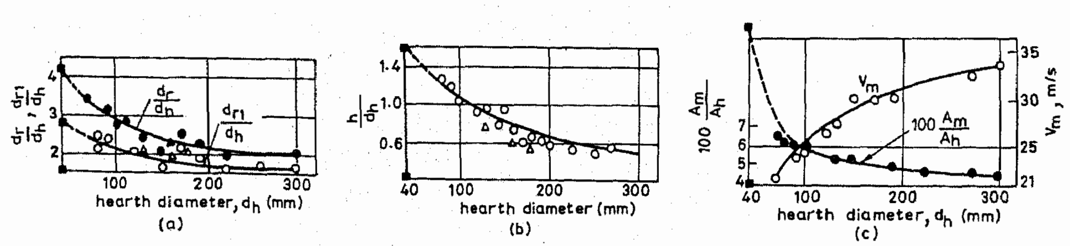

Figure 5. **a.** Recommended values of nozzle ring dia d_r and nozzle opening circle dia d_{r1}. The solid square ring refers to prototype parameters. **b.** Recommended values of h, height of the nozzle plane above hearth constriction. **c.** Hesselman recommendation for total nozzle area A_m.

Table 2. Suitable nozzles for wood gas generators for four cycle engines

d_h mm	d_{nozzle} mm	Number of nozzles	$100 \times A_{nozzle}/A_h$
70	10·5(10)	3(5)	6·7(10·2)
80	9 (11)	5	6·3(9·5)
90	10 (12)	5	6·2(8·9)
100	11 (13)	5	6·05(8·5)
120	12·7(15)	5	5·6(7·8)
130	13·5(16)	5	5·4(7·6)
150	15 (18)	5	5·0(7·2)

Figures in parentheses indicate values for operating slow two-cycle engines

incorporated in it. They are: (i) A monorator for the hopper, a feature shown in figure 3e. By extracting a portion of the moisture from the wood chips, this hopper improves the dryness of the wood chips as they enter the charring zone. (ii) The concept of a V-hearth to reduce heat losses from the reduction zone. (iii) The method used in the Zeuch design, namely, to provide an insulating char envelope to the reaction zone; this arrangement also introduces significant simplicity in the fabrication of the hearth (see figure 3c). (iv) Air injection from the sides (as shown in figure 4) to minimize heat removal by the nozzles from the reaction zone and to cause minimum interference to the flow of wood chips.

4.10 *The complete configuration*

The complete arrangement is shown in figure 6 which includes the reactor and the scrubber cleaner. The hopper dimensions are chosen to hold about 8 hr supply of wood chips (since weight is not a consideration for a stationary reactor). If refeeding is done once in 4 hr, there will always be an adequate quantity of dried wood chips while starting the reactor.

The design for the scrubber cleaner adapted here, provides cooling of the hot gases to room temperature, and has been successfully used for both stationary engines and

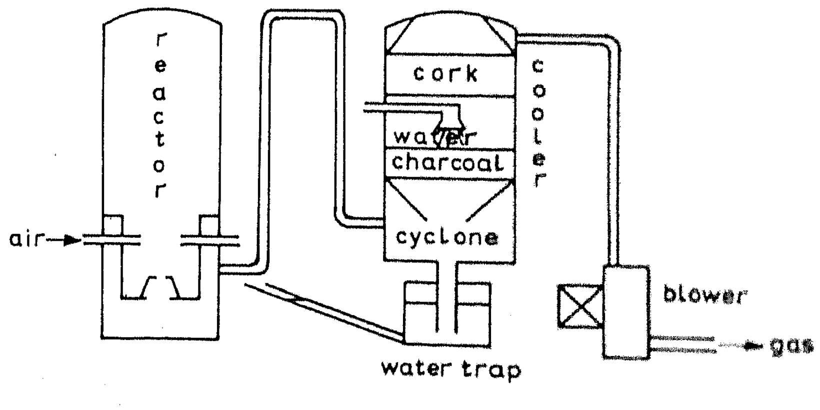

Figure 6. Reactor-cooler system

marine engines. It consists of a cyclone, a wet bed of charcoal being continuously washed with water, and a bed of cork pieces for drying the gas, placed sequentially in the path of the gas. The overall dimensions of the cooler (figure 6) have been chosen to be the same as that of the gas generator based on the photographs of various working units given in SERI Report (1979) (as there are no critical considerations for the choice of these dimensions).

5. Test plan

5.1 The test set up consisted of a 3 hp blower, the reactor, the scrubber cooler, a burner with a chimney and a 5 hp diesel engine-pump set. The two preliminary operations involved in starting the reactor were:

(i) Charging of the reactor: This was done by filling the reactor up to the hearth level with charcoal and then filling the hopper with the required fuel.
(ii) Ignition of wood chips: This was effected by pushing a few burning cinders through the ignition port and then blowing through the ash port with the ignition port closed such that air and the hot gases pass through the hearth and come out of the air nozzles. Blowing for about 5 minutes with a hand blower could raise the hearth temperature sufficiently such that the moment the reactor was connected in the test mode, it would start functioning.

5.2 The reactor was tested in five modes in the sequence indicated in table 3. The following measurements were made: (i) temperature at the throat, (ii) temperature at the end of the reduction cone, (iii) pressure drops across the reactor and the cooler, (iv) when using the engine, its rpm, the pumping head and the fuel consumption.

5.3 The load on the engine was varied by changing the pumping head with a throttle valve in the pump delivery line. The modifications made on the diesel engine for running on gas were: (i) the filter at the air intake was removed and an additional manifold for mixing the air with the gas from the reactor was fixed in its place. This

Table 3. The test scheme.

Blower Mode	Fuel	Set up	Comments
Blowing mode	Charcoal	Blower-reactor-scrubber-burner	The generated gas was flared in the burner
Blowing mode	Wood chips	-do-	-do-
Suction mode	Charcoal	Reactor-scrubber-blower-burner	-do-
Suction mode	Wood chips	-do-	-do-
Suction mode	Wood chips	Reactor-scrubber-engine	The gas generated was burnt in the engine

mixture was directly inducted into the cylinder using engine suction. (ii) The governer link available outside the engine for shutting off the fuel supply was modified to facilitate its locking at suitable positions for controlling diesel injection.

6. Test results and experience

(a) In the blower mode with charcoal, the gas when flared burnt with a bright yellow flame in the burner. The temperature at the throat varied from 1100–1250°C. The flow rate was varied using a throttle valve. Ignitable gas was obtained for throttle settings betweel full open to about 1/4 turn open on an 8 turn throttle valve; only the last two turns were effective (see figure 7). The pressure drop across the reactor and the cooler put together was 150 mm of water at a flow rate of 3 *l*/s before firing. The charcoal consumption averaged over 4·5 hr was 2·1 kg/hr.

(b) The blower mode with wood also gave ignitable gas as before. The flame for various throttle settings appeared to be healthier. The throat temperature varied from 900 to 1150°C. Fuel consumption was found to be 5·6 kg/hr (an average of 8 hr) corresponding to a hearth loading of 0·97 Nm^3/cm^2-hr at nominal gas production (2·2 Nm^3/kg).

(c) For easy trouble shooting, the set-up was run in the suction mode first with charcoal and its ability to run satisfactorily was ascertained. The maximum pressure drop recorded across the reactor and the cooler was 180 mm of water.

(d) Lastly the set-up was put into the suction mode with wood chips as fuel. The gas generated could be satisfactorily flared. The reactor was run continuously for 8 hr without any significant change in the flame. The throat temperature remained between 925 and 1125°C. The highest pressure drop recorded across the reactor was 25 mm of water and that across the cooler was 100 mm of water. The gas composition was measured using an Orsat apparatus. The results of the measurements are shown in table 4. The results indicate the proportions of CO and CO_2 to be roughly the same as

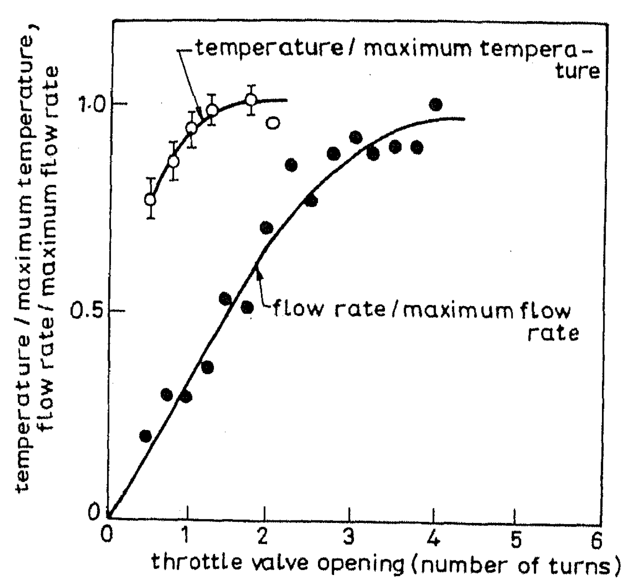

Figure 7. Reactor temperature and air flow rate

Table 4. Composition of the wood gas (volumetric %)

Temperature at the throat of the hearth	Measured		Estimated	
	CO	CO_2	H_2	N_2
1050°C	18·8 to 19·6	6 to 4	19	57

those obtained in other reactors which indicates that the reactor seems to work satisfactorily.

After the gas composition and the flow rate were ensured to be satisfactory, the system was coupled to the engine pumpset. In the engine mode, the gas could be satisfactorily generated using only engine suction which was 265 mm of water as measured at the generator outlet. The value of suction was more than the pressure drop observed across the gas generator and cooler. The various test results are discussed in a later paragraph in this section.

(e) The engine governer appeared to be sluggish and could not cut down injection of diesel when gas was introduced. In fact as gas was being sucked in, the rpm dropped slightly and the governer tended to pump more fuel and spoil the combustion in the engine. This was indicated by an increase in fuel consumption and the exhaust getting more and more fouled up with the appearance of blue fumes. At this point, the governer control was used to manually cut down fuel injection and the gas throttle was progressively opened. The control lever was then locked at the lowest possible fuel injection position at which the engine could run on its own. In this mode, it was found that the combination of the reactor and the engine with load could run smoothly without requiring any one to attend to it.

(f) After introducing manual control of diesel injection, there was no significant rise in the engine exhaust temperature or the cooling water outlet temperature. The exhaust gases appeared clean and almost invisible. After a few hours of operation there was no sign of fouling up of the engine gas intake with tar.

(g) The size of the fuel chips appeared to be crucial for the reactor. The chips used in the beginning contained a few large pieces of more than 50 mm. Even after the reduction in size at the nozzle zone and below, the chars of these large pieces were not small enough to go through the throat. (The reduction in size taking place in the combustion zone was in fact measured; the average surface area of char samples decreased from 1620 to 634 mm^2 (as indicated in table 5) in a distance of 17 mm from the nozzle plane). As a result, the throat got blocked, the reactor temperature shot above 1450°C (which was indicated by the thermocouple before it broke down) and the gas would not ignite. A similar situation arose again while using charcoal; this time a lump of soil in the charcoal had vitrified and partially blocked the throat. In normal operation, the hearth above the throat goes on feeding the reduction zone with small pieces of char. This could not take place with the throat blocked and the reduction zone was empty of any char and hence ineffective; no CO was produced.

(h) The monorator was able to extract moisture from the wood and give out the condensate in the blower mode. However, in the suction mode no condensate could be obtained.

Table 5. Size distribution of fuel char in the combustion zone

: below the ›lane mm†	Average surface area s (mm^2)‡	Number of sample of char pieces, n	Standard Deviation σ_{n-1} (mm)	$\sigma_{n-1}/\bar{s}$
(0)	1620 (100%)	24	710	44%
(27%)	634 (39%)	16	500	79%
(73%)	461 (28%)*	13	260	57%

.ds to a change in diameter of an equivalent sphere of same surface area by 53%.
paranthesis give ratio of the distance between nozzle and constriction
paranthesis give s/s_{max} value of the pieces

ıttempt was made to pre-heat the incoming air using the heat radiated from ı's outer jacket. This resulted in a lower temperature at the end of the zone. The gas quality turned out to be poor. In addition, for effective pre- ıe insulation on the outside of the hearth was removed. This caused larger n the hearth during starting. As a result there were enormous difficulties in e reactor at the end of blowing, probably because the hearth was losing heat at er than it was generating. After replacing the insulation the reactor could be hout difficulty. Therefore, an attempt was made to pre-heat the air using the the reactor outlet; in this mode the reactor operations appeared normal. An : hearth insulation can be obtained from the following:

Temperature at the hearth centre: 1200 to 1300°C,
Temperature at the outer hearth wall: 100 to 150°C,
Ambient temperature: 30°C
$\Delta T_{\text{centre to the wall}}/\Delta T_{\text{wall to the ambient}} = 10$ to 15,

ıite satisfactory by normal engineering standards. This could be further n another observation in which 35 minutes after the reactor was switched oat temperature was found reduced from 1042 to 465°C, still within the ıich the reactor would restart without requiring new cinders.
ıearth temperature was found to be fluctuating. The data of the tempera- throat of the hearth as well as downstream (end of the reduction zone) are ı figure 8. These indicate that the hearth temperature fluctuates about a)0°C (standard deviation $\simeq$ 90°C) and the downstream temperature with a)°C (standard deviation ~ 45°C). The mean period of fluctuations is about ely that these fluctuations are related to the movement of the hot charcoal ı the hopper through the respective zones. The precise fundamental ; of these fluctuations are yet to be understood.
modes where the engine was not used, the best performance, as judged by uality of flame, was obtained at the highest measured flow rate. Figure 7 ariation of temperature at the throat with gas flow rate; the temperature th decrease in flow rate. While running the engine, the hearth temperature '5°C as compared to 925 to 1125°C obtained with the blower in the suction ıre 7, this corresponds to 80–90% of the temperature with the maximum about 50–80% of the maximum flow rate. This suggests the choice of a

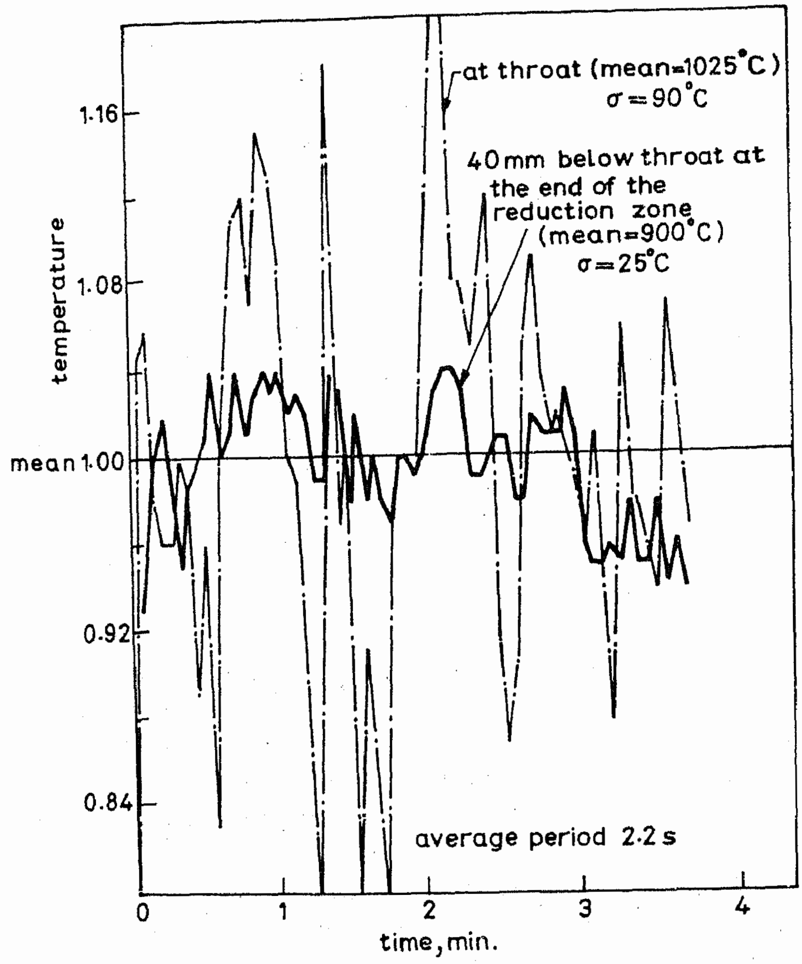

Figure 8. Hearth temperature fluctuations

smaller hearth diameter for the range of parameters for which the engine-pump combination has been tested. It has been observed earlier that the pressure drop across the reactor is small as compared to the engine suction. In view of this, lowering of the throat diameter is not expected to cause any significant loss in the engine efficiency.

(l) Other workers (Damour & Sabine 1982) while trying to design reactors for the same 5 hp engine used a throat diameter of 60 mm and a number of larger diameter nozzles. This could not give ignitable gas and produced unmanageable quantities of tar confirming the observations made in this section that for a 5 hp engine one should use a $d_h \leqslant 40$ mm.

(m) Constructional details of the reduction zone of the hearth also appear to be critical for satisfactory working of the reactor. For example, when the existing shell for the reduction cone (see figure 9) was replaced by a constriction plate as in the Zeuch reactor (shown in figure 3c), no ignitable gas could be obtained either with wood chips or charcoal. However, the reactor worked satisfactorily immediately after replacing the new constriction plate with the old shell. It is likely that the shell absorbs heat from the combustion zone and conducts it downward along the shell wall, thereby reducing the heat loss from the reduction zone.

(n) The data of tests on the engine-reactor configurations are presented in table 6. They contain the rpm, the fuel consumption and the reactor temperature at different

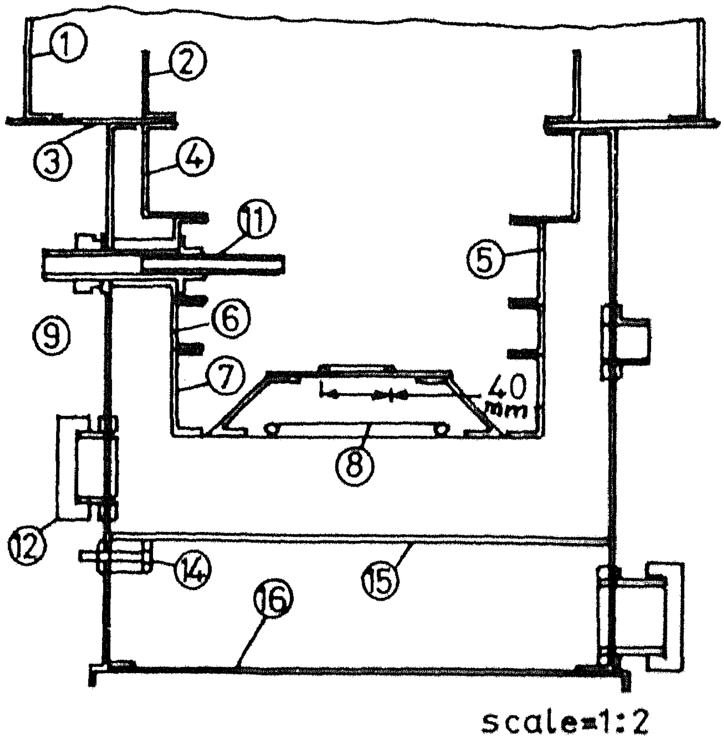

Figure 9. Reactor prototype. The numbers in the figure represent part numbers.

pumping heads ranging from 0·9 kg/cm^2 to 1·7 kg/cm^2. At 1 kg/cm^2 the fuel consumption is obtained for different engine rpms corresponding to different quantities of diesel injection. From the computed value of 'fuel consumption/maximum observed fuel consumption', water pumped per litre of diesel injected, and the extent of diesel substitution, also presented in table 6, one can draw the following conclusions:

(i) The engine while pumping water with a delivery pressure of 1 kg/cm^2 could be operated using wood gas with as little as 15 to 20% of the fuel required for the 'diesel

Table 6. Test results

Delivery head (kg/cm^2)	Engine (rpm)	Fuel consumption (litre/hr) (F_c)	Reactor temperature at the throat (°C)	$F_c/F_{c\,max}$ (%)	Water pumped m^3/litre of diesel	Extent of diesel substitution for unit water pumped
1	2850	1·62*	—	100	31	—
1	2200	0·36	850	22	88	65
1	2200	0·32	850	20	98	68
1	2200	0·22	875	14	143	78
1	2250	0·23	—	14	137	77
1·2	2450	0·36*	950	22	—	—
1·7	2900	1·21*	—	75	—	—
1·6	2700	0·84*	—	52	—	—
0·9	2100	0·16*	—	10	—	—

*diesel alone

only' mode. The exact point of operation will depend on the ability of an operator to 'fine tune' diesel injection. Certain skill is required here because the fuel injection system on the engine is not designed for operation in the above range of injection.
(ii) As the head varies, the engine-pump characteristic *i.e.* the rpm *vs* quantity of water pumped (figure 10 shows one such characteristic) is likely to vary and also, therefore, the ratio of water pumped in unit time Q_w to the diesel consumption F_c) in the same time, in the 'diesel alone' mode. This will play an important role in determining the Q_w/F_c ratio for the co-generation mode. The ratio of the diesel consumption per unit water pumped is about 25 % (varies between 22 and 28 %) for a head corresponding to 1 kg/cm^2 of delivery pressure. This ratio is likely to be different for different pumping heads and therefore the values of the extent of diesel substitution are expected to be

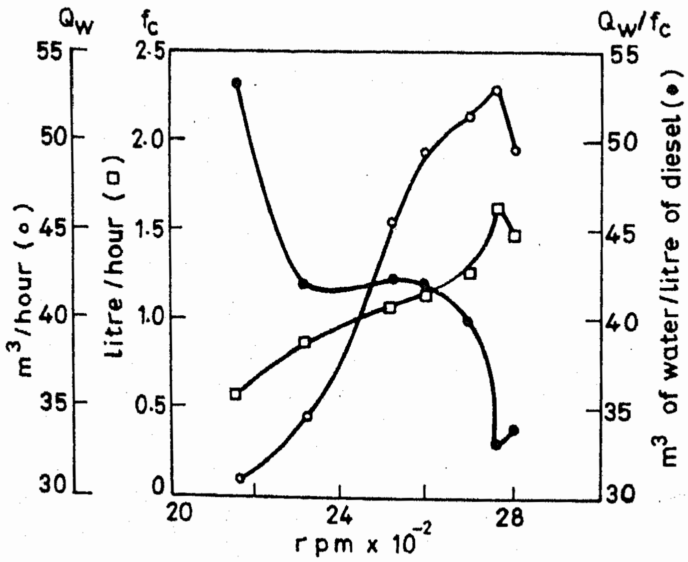

Figure 10. Diesel engine pumpset characteristics at a delivery pressure of 1 kg/cm^2. Q_w, water delivery; F_c, diesel consumption

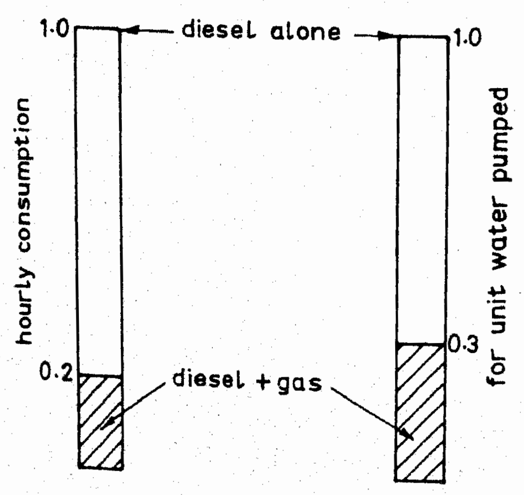

Figure 11. Diesel requirement

between 70 and 80% (shown in figure 11) which means that with a given quantity of diesel one could pump 3 to 5 times more water as compared to the 'diesel only' mode. The quantity of water pumped in the diesel only mode is also indicated in table 6.

(o) Attention of the authors has been drawn by one of the referees to the possibility of tar formation. In the present experiments no direct measurement of tar content was made. It was hypothesised from an examination of basic information on the decomposition of tars, that if the throat temperature was beyond 850°C–900°C, there would be no significant tar remaining in the gas from the reactor. Even if there were some, the cyclone and the cooler would absorb them letting a tar-free gas into the engine. This hypothesis was verified by examining the engine inlet manifold after a run of several hours, each time it was run. The engine manifold had very little deposition of tar except when the throat temperature went below 750–800°C. As such the present judgement is that if the temperature of the gases at the throat is higher than ~ 850°C, there will not be any significant tar in the gases entering the engine. During the most operational regime of the engine the throat temperature is beyond 850°C. As such it may be concluded that the problem of tar formation is not significant for the operation of the engine.

(p) On the whole, the feasibility of running a diesel engine pumpset on a wood gas–diesel mixture with diesel replacement being about 75% has been demonstrated. While further optimisation of some parameters may be possible, the present performance compares favourably with those reported in SERI Report (1979) for larger reactor-diesel engine systems.

7. Potential of the present technology and its economics

The technical feasibility of a wood gas generator running a diesel engine pump set has been demonstrated. The primary reason for concentrating on this device is the promise of large scale use it holds in the country at present. There are over 17 lakh diesel engine pumpsets in India, all of them together consuming approximately $2{\cdot}5 \times 10^6$ kl of diesel oil (Reddy 1981). This constitutes about 74% of the diesel actually used in agricultural operations (Prasad 1981). Thus, any reduction in its utilisation has a direct impact on the total consumption of diesel in the country.

The other areas where a significant contribution can be made by the use of wood gas generators are: (i) agricultural operations including processing of the raw materials and produce, providing local transport and the running of cottage and small scale industries by generating if necessary electrical power. (ii) The operation of the gas generator need not be restricted to wood. One could use compacted and preprocessed biomass, lignite, coal, coke etc. While the present study has evaluated wood chips only, it appears worthwhile to attempt to run the system with the above mentioned other raw materials, as by doing so the technology can become locally adaptable; there are areas in our country which are rich in one or several of these raw materials.

As far as the cost of the system is concerned, one must consider the gas generator as well as the power generation/utilisation device together. In the present context, the diesel engine pumpset is the commercially available one, costing about Rs. 6000. The first-generation experimental gas generator costs about Rs. 3500. There are possibilities of reducing the cost to about Rs. 1500 or Rs. 2000 through alterations in the design (size) and the fabrication scheme.

The next phase of the work on the gas generator concerns the evolution of a model which has design features for convenient operation and is also economical in terms of production. One of the other features it will be designed for is that it should be capable of being operated by non-technical personnel. Subsequently, it will be field-tested for about six months before it is qualified for production. There are questions regarding the scheme for the supply of wood chips and maintenance of the system which at the present moment remain unexplored in detail. While solutions are being worked out, the present discussion does not include these details.

8. Conclusion

This paper describes the development of a small gas generator for running diesel engine pumpsets carried out during August 1981 to October 82. The key features of the gas generator, namely, the hearth diameter, the air entry zone and the construction of the reduction zone have been identified and the non-optimal performance due to the wrong choice of these parameters has been brought out.

Consequent upon the tests conducted on the gas generator diesel engine pumpset, it appears that the system can be used with as little as about 15% of the normal diesel consumption.

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References

Damour V, Sabine M 1982 Private Communication

French Engineers 1981 Private Communication

Goldman B, Jones N C 1939 *J. Inst. Fuel* **12** 63

Prasad C R 1981 IC engines and alternate liquid fuels, Lecture No. 3, 4, 7. Rural Technology, ASTRA, Indian Institute of Science, Bangalore

Reddy A K N 1981 *Curr. Sci.* **50** 50

SERI 1979 Generator gas—The Swedish experience from 1939–45 (translation) Solar Energy Research Institute (1536 Cole Boule Varch, Golden, Colorado 80401, USA); reproduced by US Department of Commerce, NTIS, SERI/SP-33-140