מדינת ישראל

משרד האנרגיה והתשתית

אגף מחקר ופיתוח

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צינור חום כימי סולרי

מעגל ריפורמר/מתנטור בהספק של 20 קילוואט בתנור השמש

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מכון ויצמן למדע, רחובות

לפי חוזה מס' 87-1-85-LC

שבט התשמ"ט, ינואר 1989

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תוכן העניינים

ת ק צ י ר

ריאקטורים קטליטיים צינוריים בתוך קולט אנכי הופעלו בתנור השמש על שם שפר. הריאקטורים שימשו לחימום CO_2 ולריאקצית ה-Reforming האנדותרמית. 3.8 קילווט נקלטו על יד ה-CO_2. האנרגיה המכסימלית שנקלטה על ידי הריאקציה היתה 6.9 קילווט, עם הפיכה (קונברסיה) של מתן של 38%. הפיכה של 84% התקבלה בזרימה נמוכה של מגיבים. קורלציה למעבר חום עבור הריאקטורים חושבה מתוך התוצאות הנסיוניות. הותאמו תנאי הפעלת הריפורמר, בהם הרכב גזי התוצרת מתאים להזנה ישירה למתנטור.

סיכום מפורט של העבודה מצורף בזה.

ABSTRACT

Tubular catalytic reactors were tested in a vertical receiver in the Schaeffer Solar Furnace. The reactors were used for heating CO_2 and for the endothermal reforming reaction. 3.8 KW were absorbed by the CO_2 The maximum energy absorbed by the reforming reaction was 6.9 KW, with methane conversion of 38%. Conversion of 84% was obtained with low reactant flow rates.

The heat transfer correlation for the reactors was calculated from the experimental data.

Reformer operating conditions in which the product gas can be fed directly to a methanator, were found.

The complete report is hereby submitted.

The Weizmann Institute of Science

Department of Materials Research

Tubular Reformers in the Vertical Solar Receiver

Report No. 3

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Reactor UV - U shaped, 93 cm length, 12.7 mm ID

The vertical receiver was expected to be much more efficient in using the energy supplied by the solar furnace, compared with the horizontal tubular receiver previously used. This should be achieved by better energy distribution inside the receiver and by smaller heat loss.

Heat was absorbed by heating CO_2 and by the endothermic reforming reaction (CH_4+CO_2)

The flow of CO_2 was in the range of 800 to 8400 l/hour (Re=300 to 1800), and the maximal energy input to the gas was 3.8 KW.

The flow of the reaction mixture (CH_4+CO_2) was in the range of 1000 to 11000 l/hour (Re=200-1600) and the maximum energy absorbed was 6.9 Kw, in the Reactor 2V, with methane conversion of 38%. Maximum methane conversion of 84% was obtained with low Re numbers. Heat flux reached 110 Kw/m^2. The operation of the reformers was limited by two restrictions:

(a) The reactor wall temperature can not exceed 950° (safe limit for the Inconel 600).

(b) The flow of reactants is limited by the size of the flow controllers used at that time.

The heat transfer correlation was obtained from 328 runs in the three reactors, including both reforming and CO_2 heating. The equation is

$$Nu = 0.534\ Re^{0,5}\ Pr^{0,7}$$

1.2 Preliminary calculation were made for the design of a Reformer of 50-100 Kw, to be constructed and operated in the Solar Tower.

2. Introduction

The principle of the chemical heat pipe was previously described (1,2) (see Figure 1).

The work presented in this report was aimed at two main points:

a) Evaluation of the performance of directly heated solar reformers/receivers.
b) Obtaining data for the chemical reaction and heat transfer in different reactors in a vertical receiver.

Results obtained in this work will be used for the design of a 80 Kw Reformer planned to be operated in the Solar Tower.

The reaction system was similar to the one previously described for the Sodium Receiver (2). The mode of data flow (acquisition, storage and transformation) is shown in Figure E.

3. The Vertical receiver and reactors

Figures A and B show the reactors 2V and UV in the vertical receiver. The reactor 1V is made of the same tube as 2V, but is only 60 cm long and the exit of the product gas is at the lower end of the receiver.

All the reactors are made of Inconel 600; the dimensions are given below:

Reactor	OD, mm	ID, mm	Catalyst bed length, cm
1V	24	20	60
2V	24	20	115
UV	16	12.7	93

The temperatures of the reactor wall are measured by Thermocouples inserted into wells, made of 3 mm inconel tubing and welded to the reactor wall. Measurements are taken on the front and back walls, at points 15 cm apart.

The gas temperatures are measured at intervals of 15 cm, by a multipoint thermocouple and additional single thermocouples.

The catalyst is 0.5% Rh on 1/8" Alumina pellets (same as previously used).

The receiver is an aluminum box, with all the walls insulated by a 5 cm thick Fiberfrax Durablanket alumina blanket. The inside dimensions are: 30 x 30 x 60 cm. The opening on the front wall, facing the concentrator, is of 10 cm diameter.

The first experiments in the Solar Furnace were done with a horizontal receiver reformer (3), the reactor being a U tube with gas inlet and outlet at the back of the receiver. In this configuration very ununiform heating of the reactor was obtained; overheating was observed at the front of the receiver, were the middle of the reactor was directly irradiated, and toward the exit of the reactor the gas cooled down, leading to a back reaction. As the wall temperature must be limitted at 950-970°, parts of the reactor wall could not be heated enough to allow the necessary heat transfer to the reacting gas, thus limiting the total energy input possible.

We built the vertical receiver in order to overcome these difficulties, mainly planning to get uniform heating of the reactor walls. The vertical receiver/reformer should also serve as a model for the larger scale reactor to be used in the Solar Tower, where a vertical secondary concentrator will probably be added to the receiver.

The receiver was placed with the opening in the focal plane, and the reactor was fit into the receiver at a distance of 18 cm from the opening. In this position, the whole length of the reactor is "illuminated", but the central part of the reactor, facing the opening, gets more concentrated radiation. Therefore, we get 2 "peaks" on the temperature profiles of the front reactor wall (see Figures P1-P4), at about 30 and 100 cm of the reactor length. At these points, especially at 30 cm, we got the highest temperature difference between the front and back reactor wall (about 100°, compared to 20-30° at the other points).

As in the horizontal receiver, the peak wall temperatures limited the possibility of heating the whole reactor to a high enough temperature. In order to prevent this overheating of the front wall, we put in the receiver two vertical ceramic tubes of 15.5 mm OD, located between the opening and the reactor in order to protect the reactor wall from direct radiation. The tubes were at 80 mm distance from the opening and 110 mm from the reactor.

With this configuration, the temperature differences between front and back reactor wall decreased to 0-30° but the hot peaks did not totally disappear.

In the heat transfer calculations, the wall temperatures (TWa) were taken as average between front and back wall temperatures.

4. Heating CO_2 (Figures C1-C7)

4.1 Purpose

By heating CO_2 gas at various flow rates and energy inputs we obtained useful information about the thermal performance of the receiver and the various reactors used. Temperature profiles are presented, heat fluxes along the reactor are calculated, and energy input data are combined with data from the reformer for the construction of the heat transfer correlation.

Part of the data are presented in Tables 1-CO_2 to 5-CO_2. All the other data are available on computer disks.

4.2 Temperature profiles

In Figure C1 the wall and gas temperatures along the reactor are shown. 3 runs where chosen, in which the wall temperatures at the end of the reactor - 100 and 115 cm - were similar and high: ~900°, and the Re numbers were different, as shown. (The wall temperatures depicted are the averages between front and back wall). At 15 cm reactor length, the wall temperature was already 730, and rised monotoneously to 900 at 115 cm.

The gas temperature profiles for the 3 runs are very similar in trend. The gas always reached the wall temperature, and, as expected, this temperature was reached earliest at the lowest Re (line 1, at 70 cm). In the last part of the reactor, the temperature differences between wall and gas is only 40-60°, and practically no heat transfer occurs. Even at the highest Re (line 3), most of the heat is absorbed in about 75% of the reactor length.

The total amount of heat absorbed was limited by the gas flow rate, which reached the maximum allowed by the Flow Controllers used.

The wall temperature profile for reactor 1V (60 cm) is shown for comparison. The trend in the temperature rise is very similar. The reactor 1V is somewhat hotter than reactor 2V, possibly because of its position in the middle of the receiver. Figure C2 shows, for reactor UV, temperature behaviour very similar to that described for reactor 2V.

4.3 Energy input

Figures C3 and C4 show the energy input along the reactor, for the three reactors used. The expected dependency of heat transfer on Re is clearly observed, for all the reactors.

In Figure C4, the effect of the wall temperature on energy input is observed by comparing line 1 (wall temperature = 911) to lines 2-4.

Line 1 also shows that in the first half of the reactor 1.9 Kw were absorbed, whereas in the rest of the reactor - only 0.7 Kw. In the case of low Re - line 4 - at half of the reactor the CO_2 practically reached the wall temperature and no more energy input occurs.

4.4 Heat flux

Figures C5 and C6 show the heat fluxes along the reactor, again comparing the three reactors used.

Each point on the graph is the average heat flux on the relevant segment, and is located at the point on the "reactor length" axis which is the middle of the segment.

The division into segments for the 3 reactors is as follows:

Segment No.	cm		
	1V	2V	UV
1	0-15	0-60	0-23
2	15-30	60-85	23-57
3	30-45	85-100	57-79
4	45-60	100-115	79-93

The highest fluxes are always observed at 30-40 cm reactor length; this is the region where the wall temperature increases sharply whereas the gas temperature is still low. The trend is similar for all the reactors and different Re numbers. Fluxes are markedly increased as Re increase, the limit being, as previously mentioned, the maximal flow possible in our flow control system. The highest heat fluxes we obtained in our system, for CO_2

heating, were 60-70 Kw/m^2 (Fig. C5). This maximum, obtained at wall temperature of 911°, can be increased by heating the wall to 950-960 or by increasing gas flow rate. Figure C7 shows the dependence of the heat flux on Re for reactor UV, at four points along the reactor. The relation is linear in the range of temperatures and Re measured. Fluxes are very low at Re under 800, and drop to <10 Kw/m^2 in the last part of the reactor.

5. Reforming (Figures F, G, P1-P4, 2-15)

The reforming reaction was conducted at various flow rates and energy inputs into the receiver. We controlled the input by the size of the door opening, limitations being, of course, the direct solar radiation and the reflectivity of the Heliostat and the concentrator.

The obtained temperature profiles on the reactor wall and in the gas are presented below. The methane conversions, average fluxes, energy inputs as chemical enthalpy and sensible heat, as well as a general heat transfer correlation were computed.

The range of the reaction parameters and results for the three reactors tested is given below.* Figures F and G show the conditions for one day of Reforming: solar radiation, flow rates and temperatures.

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*Additional detailed results for Reactor 1V will be summarized separately.

Reaction Parameters

Wall temperature, at the hottest point: 960°.

Reaction temperature (product gas temperature): 580-840°.

System pressure: 4 atm.

Feed flow: 1000-11000 l/hour.

Reynolds Number: 200-1600.

GHSV 8000-50000 hr^{-1}.

Results (maximum values)

CH_4 conversion: 84%

Reaction rate: 12.5 l CH_4/ml catalyst·hour

Total energy input: 6.8 Kw

Average heat flux: 100 Kw/m^2.

Part of the data are presented in tables 1-2V to 5-2V and 1-UV to 4UV. All the other data are available on computer disks.

As previously mentioned, the maximal energy input into the reactor was limited by two factors:

(a) The reactor wall temperature could not exceed 950-960°C (material constraint, the limit for Inconel 600 is 1050°).

(b) The throughput of our flow controllers was limited at 100 l/min.

In the range of flows available, we could still increase the Reynolds number and thus increase total energy input; but at high flow rates the gas temperature decreases, the pressure increases, causing a drop in the equilibrium conversion; thus most of the energy absorbed will be converted into sensible heat and not into chemical energy, making the high flow rates nonpractical in our system.

5.1 Temperature profiles

Figures P1 and P2 show the temperature profiles for two runs in reactor 2V. In spite of the inhomogeneous increase in the wall temperature (discussed previously in section 3), we note a homogeneous increase in the gas temperature, at high and low Re number as well.

The wall temperature profiles shown here are markedly different than those in Figures C1 and C2, where no reaction takes place and CO_2 is only heated: two maxima are clearly seen in Figures P1 and P2 at the position on the reactor facing the opening in the receiver. In both Figures the temperature difference between wall and gas at the reactor exit is quite high (100-140°), indicating that the whole reactor surface is used efficiently for heat transfer. Thus, the drop in wall temperature in the range which is not directly heated (60 to 80 cm) cannot be compensated entirely by reradiation from the receiver wall.

Another significant observation is the wall temperature at 15-20 cm reactor length: even at the higher gas flow rates (Re=863, Figure P1), the wall at 20 cm has already 700°, which is only about 100° less than the hottest point on the wall. Thus, we have a quite uniform temperature on most of the reactor wall, resembling the configuration of the indirect heated receiver, e.g. through sodium. At the low flow rates (Figure P2), the reactor wall temperature is almost uniform from 15 to 115 cm length.

Figure P3 shows that for reactor UV, the trend of gas and wall temperatures is similar to that in reactor 2V. At about 20 cm reactor length, the wall already reaches almost its final temperature, the difference between TWa 92 and TWa 20 being only about 30°.

However, as expected, the temperature difference between wall and gas is generally smaller in reactor UV than in the bigger reactor 2V.

Figure P4 shows two runs for which the gas temperature profiles are very similar. As the gas flow rates are different, it is clearly seen that at the high Re (line b), the wall temperature must be kept about 120° higher than for the low Re (line a) in order to obtain similar gas temperatures in both runs.

5.2 Product gas temperatures

In Figure 2 we present the product gas temperature related to Re, for various wall temperatures in reactor 2V.

For the whole range of Re, the product gas temperature depends strongly on the reactor wall temperature (TW100 is the wall temperature at the hottest point of the reactor, i.e. at 100 cm length of catalyst bed). At Re=800 the highest amount of energy was absorbed (6.8Kw), when the wall temperature was 940-960°, whereas at 720-760°, the product gas temperature drops to 540°, and very low conversions of CH_4 could be obtained.

The slope of the gas temperature vs. Re line decreases with increasing Re; this results from the fractional exponent of Re in the relation of the heat transfer coefficient to Re:

$$Nu \propto Re^{0,5}$$

The extrapolations (broken lines), show the approach of the gas temperatures to the range of the wall temperatures at lower to zero flow.

Figure 3 shows the near to linear relation between the product gas temperature and the highest wall temperature, for all the three ranges of Re.

The lines are for reactor UV, and additional points are given, for comparison, for reactor 2V at similar ranges of Re. As similar Re for both reactors mean a much higher flow rate in the big reactor (2V), it is obvious that the temperatures reached in reactor 2V are considerable lower. (Note that when we compare the two reactors at the same Re, the increase in heat transfer surface from UV to 2V is smaller than the increase in mass flow rates of the gas).

5.3 Energy input (Figures 4,5,6,7,14 and 15)

As expected, the highest values for energy absorption were obtained at highest Re numbers (best heat transfer) and at the highest wall and gas temperatures. This holds for both reactors 2V and UV, and is shown in figures 4,5 (2V) and 6,7 (UV).

Since TW 100 of 940-960° is the highest temperature allowed (from material consideration), the line at this temperature (black points in Figure 2) is the line of highest energy absorption in the range of Re investigated.

As seen from the graphs, energy absorption might be increased even more by increasing the feed flow rates.

As the main purpose of the Reforming system is the conversion of solar energy into chemical energy (through the endothermic reaction), we are not interested in absorption of energy in the form of sensible heat alone. As previously seen, above a certain value of feed flow rates, the product gas temperature drops to such a value where equilibrium conversion is very low. By increasing the length of the reactor this difficulty could be overcome. In runs where Re is high, we observe that there is a considerable difference between wall and product gas temperature: in this case we could increase the catalyst bed length by adding catalyst up to 130 cm, and this would lead to increase in product gas temperature and methane conversion.

Figure 14 shows the sharp increase in the ratio of Q_{heat} to Q_{react} with increase of Re over 900. This point should indeed be the practical limit of flow rates in our system.

The chemical enthalpy and the sensible heat are equal at Re=1100 (Tw 79 = 800-830), and at Re=1300 (when the wall temperature is at its maximum 900-940°). Evidently this equality is obtained at lower Re numbers in reactor 2V (2 points shown in Figure 14). From the data in Figure 15, we can find the methane conversion for any ratio of Q_{react}/Q_{heat} that we choose to maintain in the system (f.i. at around 80% conversion about two thirds of the energy absorbed is converted into chemical energy).

5.4 Reaction rates and methane conversion (Figures 8-13)

Figures 8 and 10 show the dependence of reaction rate (liter CH_4 reacted per ml catalyst per hour) on the product gas temperatures, for reactors 2V and UV, at different groups of Re numbers.

The reaction rate increases with the product gas temeprature and Re.

Figure 9 was constructed from the data of Figure 8, using the average Re for each group. As seen, the gas temperature of 800° could be obtained in reactor 2V only at Re up to 300, and 700° - up to 550. At higher Re, the product gas temperature does not rise to 700°, even when the wall temperature was at its maximum (950°). As previously mentioned, we did not increase the feed flow over the values that gave about 650° in the product gas, which is the limit for reasonable methane conversions and not too low reaction rates (about 2.5 l CH_4/ml cat.hour, for reactor 2V, see Figure 9).

Similar reaction rates were obtained in both reactors, when compared for the same temperatures and the same range of Re. For instance, line 1 in

Figure 8 can be compared with line 2 in Figure 10, for the range of Re=715-865.

Data for Re=400-450 (not shown in the graph for 2V) also indicate similarity of reaction rates in both reactors. At this range of Re, the methane conversion approaches nearly the equilibrium conversion in both reactors, as shown in Figures 11 and 12.

Comparing Figure 11 with 12, we observe a clear dependence of methane conversion on Re for reactor UV, whereas in reactor 2V the data are scattered near the equilibrium conversion line, not showing a dependency on Re in the range of Re measured.

In reactor UV it was possible to work with Re numbers up to 1480, without decreasing too much the product gas temperatures (line 1 in Figure 10). Reaction rates of up to 12.5 liters methane reacted per hour per ml catalyst could be obtained, but conversions were markedly lower than the equilibrium ones (line 4 in Figure 12). Perhaps at high flow rates the reaction rate becomes the limiting factor for the process. In general, it can be expected that reaction rates, at high flows, might be lower in reactor UV, because of "channeling" effect of the gas in the vicinity of the wall, which is much more expressed in narrow tubes.

As previously mentioned, in the chemical heat pipe it is important to convert most of the solar energy into chemical enthalpy. Thus, not less than 70-80% conversion of methane are required. For this level of conversions, even when equilibrium conversion is reached, the temperature of the exit gas must be over 750°, and the wall temperature must be kept $\geq$900°, in order to supply sufficient heat fluxes.

In reactor 2V we obtained these conditions only at Re $\leq$ 300, whereas in reactor UV, temperature of 800° in the product gas was obtained even at Re=1200. This indicates that for a tube in the size of reactor 2V, the catalyst bed length should be increased. This will be discussed in detail in section 7 below.

6. The Heat Transfer Correlation (Figures 16 and 17)

An important topic in the evaluation of the directly heated reformers is to derive the heat transfer correlation, which relates the heat transfer capability of the system to the flow properties of the feed and to its physical properties at the reaction temperatures.

The general form of the correlation is:

$$Nu = a\, Re^{m}\, Pr^{n}$$

The dimensionless terms being defined as:

$$Nu = \frac{\alpha\, Dp}{\lambda} \quad ; \quad Re = \frac{G \cdot Dp}{\mu} \quad ; \quad Pr = \frac{Cp \cdot \mu}{\lambda}$$

We obtain the experimental Nu numbers from the heat transfer coefficient α, which is calculated directly from the total energy input into the reactor and the average temperature difference between wall and gas.

Data are taken from all the three reactors, for CO_2 heating and for the reforming reaction. α values for CO_2 heating were calculated for the whole reactor and also for segments of 15 cm length along the catalyst bed in reactor 2V and segments of 23, 24, 22 and 13 cm along the reactor UV.

The values of m and n are found analitically from the experimental values. The value of a is found by linear regression, using 328 experimental points.

The equation obtained is:

$$Nu = 0.534\ Re^{0,5}\ Pr^{0,7}$$

with a scatter of ±14% (R^2 = 0.72). The experimental data with the correlation line are shown in Figure 16.

The experimental Nu numbers vs. the estimated values (calculated from the equation) are shown in Figure 17, where the scatter around the "y=x" line is observed.

7. Reformer scale up considerations

From the results presented in the previous sections, it is evident that the heat transfer to the catalyst bed is the main limiting factor in the reforming process, when the directly heated reactor is used. This factor becomes more significant with the increase of the reactor diameter. In our reactor 2V, the product gas temperatures and, correspondingly, methane conversions, were low: thus, at the highest allowed wall temperature (950°), at flow rates giving Re>700, the product gas temperature was about 670° and the methane conversion - not more than 24%. To increase these values, the length of the reactor must be increased. Note that the efficiency of the existing reactor 2V (20 mm inside diameter) might be increased by adding catalyst to a length of 130 cm, the wall temperature at 130 cm being high enough (related to the product gas temeperature) to enable more heat input at high Re numbers. Replacing the reactor material by a higher grade alloy (f.i. Inconel 800) might also be considered, in order to allow for higher reactor wall temperatures.

Using the heat transfer correlation derived from the experimental data, and the wall temperature profiles measured, it is possible to calculate the reactor length and the process parameters for any desired tube size and flow rate, using a computer model. Work on this subject is in progress.

In this chapter we present some simple calculations, giving general data related to the design of the 50-100 Kw reformer to be operated in the Solar Tower.

The configuration of the reaction site in the Solar Tower allows for a vertical receiver of 2-2.2 m height. Thus, a reactor of 2 m length can be directly irradiated. If a U shape will be used, 4 m reactor length will be available. The use of a vertical-two-dimensional secondary concentrator is considered.

7.1 Calculation

For any given combination of flow condition (Re number) and wall temperatures, we can use the experimental data in order to calculate the length of a bigger reactor, which will give the same results (product temperature and methane conversion). The relationship to be used is (3):

$$L = \frac{D_i^2 \cdot l \cdot d_{av}}{D_{av} \cdot d_i}$$

l, d_i, d_{av} - length, inside diameter and average diameter of the reactor in which the experimental data were obtained.

L, D_i, D_{av} - the respective values for the calculated reactor.

Thus, in order to obtain in a 2" tube the same results as in 1" tube of 115 cm length, a reactor of 2.4 m length is needed. The real diameters of the tubes mentioned are: "1 inch" - OD=24 mm; ID=20 mm. "2 inch" - OD=44mm; ID=40 mm.

One example is run 71605, in reactor 2V, where the energy absorbed was 6.8 Kw at methane conversion of 37%. If this run would be conducted in a 2" reactor of 2.4 m length, the energy obtained will be:

$$6.8 \times 4 = 27.2 \text{ Kw}$$

(For equal Re, in a tube with twice the diameter, the mass flow rate is 4 times bigger).

In a reactor of 4 m length, increase of conversion to about 65-70% might be expected, taking in account the decrease in heat fluxes when product gas temperature is higher (lower ΔT between wall and gas). Thus, the energy absorbed will be about 40 Kw.

A second example taken was run 101321, in reactor UV (where 3.5 Kw were absorbed at 64% conversion). To conduct this experiment in a 2" tube, 2.9 m length are required in order to obtain the same conversion of 64% at Re=718. Since the increase in mass flow rate is $0.04^2/0.0128^2 = 9.8$, the energy absorbed in the 2.9 m will be:

$$3.5 \times 9.8 = 34.2 \text{ Kw}$$

If 4 m length will be used, the conversion will increase in the last 1.1 m, and it might be estimated that about 40 Kw will be absorbed.

A similar calculation for this run was done for a long reactor of 1" tube. The length of catalyst bed required is 1.5 m. The increase in energy from run 101321 to this reactor is:

$$0.02^2/0.0128^2 = 2.44 \text{ times,}$$

and the energy absorbed will be:

$$3.5 \times 2.44 = 8.5 \text{ Kw.}$$

Considering increase in conversion, on 2 m reactor length 10-11 Kw might be expected. Thus, 4 tubes of 2 meter are required for 40 Kw

The use of 4 m length of a 1" tube is not practical, because the temperature of 800° in the product gas can be reached in a shorter reactor. In addition, increase in Re number might lead to a high pressure drop on the catalyst bed.

In a 2" reactor, the problem of pressure drop, if occuring, might be solved by using a larger size of catalyst pellets (6 mm, instead of 3 mm used in the small reactors).

7.2 Results and conclusions

In the following table we summarize the results of the preliminary calculations described.

Reactor Scale-up

Run no.	Reference experiment: Reactor d_i mm	Reactor length m	Re	CH_4 conv. %	Energy abs. Kw	Scale-up values: Reactor D_i mm	Length m	Re	CH_4 conv. %	Energy abs. Kw	Number of tubes for 80 Kw
71605	20	115	729	37	6.8	40	2.3	729	37	27.2	
						40	4.0	729	65-70	~40	2
101321	12.8	93	718	64	3.5	40	2.9	718	64	34.2	
						40	4.0	718	≥64	~40	2
						20	1.5	718	64	8.5	
						20	2.0	718	≥64	10-11	8
101316	12.8	93	1300	43	4.7	20	1.5	1300	43	11.5	
						20	2.0	1300	≥43	14-15	6

$$L = \frac{D_i^2 \times l \times d_{av}}{D_{av} \times d_i^2}$$

The optimal combination seems to be the use of 2 U shaped tubes, 4 m length each. Absorption of about 80 Kw is estimated, at Re=~730. However, the availability of 80 Kw from the Heliostat field, at the reaction site located at the 20 m level in the solar tower, depends on several factors:

a) The number of Heliostats useful for the 20 m level.

b) The type and size of the secondary concentrator that will be used.

c) The season of the year.

The combined effect of these factors is being evaluated, using the MIRVAL computer program (4) and data on secondary concentrators.

8. Acknowledgement

Itshak Levy did the mechanical design of the vertical Receiver. He is also responsible for the proper functioning of the mechanical systems in the Solar Furnace.

Oshia Mirel assisted in the construction and assembly of the reaction systems.

Their participation in the project is much appreciated.

Nomenclature and Units

C_p – Fluid heat capacity, Kj/Kg·°C

d_p – Equivalent diameter of the catalyst particle, m.

D_i, d_i – Reactor tube inner diameter, m.

D_{av}, d_{av} – Reactor tube average diameter, m.

F – Average heat flux from the reactor wall to the fluid, Kw/m^2*

G – Mass flow rate, based on the cross section area of the empty reactor: $Kg/m^2 \cdot sec$.

L, l – Length of the packed (catalyst) bed in the reactor – m.

Nu – Nusselt number, $\alpha d_p/\lambda$, dimensionless.

Pr – Prandtel number, $C_p \mu/\lambda$, dimensionless.

Q_h* – Sensible heat, absorbed for heating the fluid, Watt.

Q_{react} – Energy absorbed for the endothermal reaction, Watt.

Q_t – The total energy absorbed by the fluid per hour, Watt.

r – Reaction rate, liter CH_4/ml catalyst · hour.

Re – Reynolds number, Gd_p/μ, dimensionless.

Tg – Fluid temperature**

Tw – Reactor front wall temperature.

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* All the energies are calculated for 1 hour.
** All the temperatures are in °C.

T_{wb} - Reactor back wall temperature.

T_r - Receiver wall temperature.

α - Heat transfer coefficient from reactor wall to the fluid, watt/$m^2 \cdot °C$.

λ - Heat conductivity of the fluid, watt/$m \cdot °C$

μ - Dynamic viscosity of the fluid, Kg/m·sec.

References

1. D. Fraenkel, R. Levitan and M. Levy. International J. Hydrogen Energy, 11, 267 (1986).
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TABLE 1 - CO2

FLOW RATES AND GAS TEMPERATURES

7-5,6,10,11-1988 REACTOR 2V HEATING CO2

RUN No.	Time	CO2 l/h	P,atg.	GHSV h-1	Re	Radiation watt/m2	Door n.	Gas Temperatures TG0	TG60	TG70	TG85	TG100	TG115
7504	09:09:00	3392	3.6	9285	392	646	2	346	531	565	590	601	614
7603	11:43:00	5820	3.9	15520	722	806	4	51	668	754	809	848	857
7604	12:03:00	8454	5.3	22544	1042	838	4	48	622	719	788	839	875
71037	16:08:00	7437	0.3	20296	946	606	3	137	521	552	608	651	683
71102	13:16:00	5676	2.4	15138	744	731	4	43	598	670	705	734	750
71103	13:20:00	6516	3.0	17378	831	768	4	46	585	672	727	776	803
71104	13:26:00	7429	2.5	19813	927	709	4	51	620	709	766	814	844
71105	13:33:00	7880	2.6	21016	970	741	4	56	621	720	780	831	863
71106	13:38:00	7842	2.1	20914	990	706	4	59	563	654	715	770	802
71107	13:45:00	7878	2.6	21010	1005	698	3	59	548	638	697	747	781
71108	13:48:00	7974	3.0	21266	1045	713	3	59	479	566	628	676	724
71109	13:55:00	8236	3.5	21964	1111	694	3	57	443	525	583	632	669
71110	14:05:00	8662	2.6	23100	1319	715	2	51	272	350	397	436	472
71111	14:10:00	9000	2.6	24002	1532	653	2	48	175	221	259	291	326
71115	14:39:00	6339	2.0	16906	969	663	2	47	295	356	401	435	472
71116	14:42:00	6246	2.8	16658	901	669	3	48	382	447	490	526	563
71117	14:47:00	6128	3.0	16343	846	668	4	50	435	508	559	598	636
71118	14:52:00	6274	3.2	16732	814	639	4	54	553	632	678	719	752
71119	14:56:00	6256	3.1	16684	802	631	4	56	569	650	702	743	775
71120	15:02:00	6200	2.3	16535	765	628	5	60	661	741	790	825	853
71121	15:07:00	6116	3.0	16311	743	554	5	63	692	772	821	859	884
71124	15:24:00	4854	2.4	12946	599	517	4	73	669	745	785	812	831
71125	15:29:00	4828	2.8	12876	615	481	3	71	579	670	715	741	762
71126	15:34:00	4906	2.5	13084	644	460	3	68	524	595	647	679	706
71127	15:39:00	4940	2.9	13175	683	460	2	65	411	481	532	562	610
71128	15:44:00	4934	3.0	13159	720	446	2	61	349	408	454	484	525
71129	15:51:00	4988	2.6	13303	760	406	2	57	306	359	401	430	464
71130	15:56:00	5120	2.1	13655	826	402	1	54	226	282	324	353	307
71134	16:23:00	3358	3.0	8956	422	382	6	57	696	740	770	799	816
71135	16:28:00	3360	3.0	8962	413	431	6	62	749	795	822	846	858
71137	16:48:00	3394	3.0	9052	447	403	3	71	552	613	649	676	694
71138	16:53:00	3404	3.0	9079	465	410	2	69	468	534	574	607	626
71139	17:00:00	3418	3.0	9116	494	343	2	65	387	445	486	508	533

TABLE 2 - CO2

REACTOR WALL TEMPERATURES

7-5,6,10,11-1986 REACTOR 2T HEATING CO2

Reactor Wall Temperatures - Front

RUN No.	Time	Re	TN0	TN15	TN30	TN45	TN60	TN70	TN85	TN100	TN115	TN130
7504	09:09:00	392	318	476	558	572	589	620	624	666	626	460
7603	11:43:00	722	131	536	753	771	793	831	861	854	850	746
7604	12:03:00	1042	124	547	770	773	790	844	890	925	809	762
71037	16:00:00	946	205	501	634	580	635	629	601	750	724	683
71102	13:16:00	744	121	623	677	723	737	736	757	805	745	620
71103	13:20:00	831	143	667	728	748	768	778	814	867	818	739
71104	13:26:00	927	158	715	769	780	736	809	855	909	869	704
71105	13:33:00	970	173	731	780	783	815	823	868	921	807	813
71106	13:38:00	980	170	679	721	717	743	765	807	864	836	779
71107	13:45:00	1005	166	605	710	709	727	741	770	841	800	750
71108	13:48:00	1045	159	600	650	832	671	677	719	709	761	709
71109	13:55:00	1111	140	546	596	561	616	630	645	727	695	659
71110	14:05:00	1319	118	400	452	393	467	460	467	554	523	491
71111	14:10:00	1532	103	317	306	233	280	326	320	391	399	397
71115	14:39:00	969	102	395	465	413	470	407	459	551	514	462
71116	14:42:00	901	109	490	565	530	521	563	570	656	618	507
71117	14:47:00	846	127	555	821	590	602	620	656	731	690	597
71118	14:52:00	814	149	639	702	692	693	723	757	821	704	690
71119	14:56:00	802	159	857	714	700	714	740	773	840	807	731
71120	15:02:00	765	179	740	798	795	791	818	850	914	880	793
71121	15:07:00	743	192	785	816	818	821	843	863	935	906	823
71124	15:24:00	599	206	709	740	762	769	790	819	870	841	784
71125	15:29:00	615	190	628	656	666	609	707	737	793	772	743
71126	15:34:00	644	175	582	819	810	636	657	604	740	726	678
71127	15:39:00	603	157	479	500	490	512	549	573	646	632	609
71128	15:44:00	720	139	426	460	434	451	403	499	500	550	520
71129	15:51:00	760	123	376	415	305	404	432	443	526	490	474
71130	15:56:00	826	113	311	303	260	324	340	356	405	424	424
71134	16:23:00	422	172	713	760	703	759	762	823	871	827	710
71135	16:28:00	413	198	754	804	821	898	813	862	905	868	767
71137	16:40:00	447	100	565	590	611	629	844	873	722	704	655
71138	16:53:00	465	168	490	521	521	543	570	592	450	638	607
71139	17:00:00	494	148	413	442	446	466	491	508	507	554	538

Reactor Wall Temperatures - Back

RUN No.	Time	TNb0	TNb15	TNb30	TNb45	TNb60	TNb70	TNb85	TNb100	TNb115	TNb130
7504	09:09:00	323	465	526	356	592	615	805	610	811	416
7603	11:43:00	144	594	728	791	832	852	866	883	867	742
7604	12:03:00	130	585	700	767	800	831	857	802	879	760
71037	16:00:00	193	500	536	595	669	653	665	696	714	600
71102	13:16:00	114	570	603	661	688	703	712	720	739	612
71103	13:20:00	140	637	646	700	733	750	791	820	808	720
71104	13:26:00	162	875	605	750	777	793	821	849	841	772
71105	13:33:00	180	696	702	764	794	809	848	867	664	799
71106	13:38:00	176	643	642	701	735	753	782	810	815	763
71107	13:45:00	171	823	620	872	707	725	753	701	789	737
71108	13:48:00	163	576	565	621	666	679	786	737	751	696
71109	13:55:00	146	502	401	535	570	807	631	862	802	646
71110	14:05:00	112	380	350	394	428	450	469	496	520	400
71111	14:10:00	90	274	250	263	206	311	323	357	392	309
71115	14:39:00	97	307	380	415	442	464	501	527	531	452
71116	14:42:00	106	447	450	493	510	530	546	573	576	495
71117	14:47:00	124	519	526	569	592	607	628	650	659	565
71118	14:52:00	149	597	606	659	603	699	723	752	750	677
71119	14:56:00	161	623	628	602	707	723	740	776	777	713
71120	15:02:00	105	696	702	760	704	790	823	849	853	700
71121	15:07:00	190	726	730	780	826	832	854	877	875	807
71124	15:24:00	207	684	604	744	773	791	808	825	825	760
71125	15:29:00	192	611	602	661	699	721	737	750	766	720
71126	15:34:00	175	581	551	605	641	661	878	702	713	670
71127	15:39:00	156	462	430	486	527	564	500	607	629	596
71128	15:44:00	137	402	370	410	453	408	501	517	541	517
71129	15:51:00	119	353	330	385	399	432	442	465	490	463
71130	15:56:00	107	288	261	206	374	344	359	380	421	415
71134	16:23:00	169	679	600	745	760	770	785	804	792	695
71135	16:28:00	198	728	734	792	800	829	833	840	837	751
71137	16:40:00	179	556	549	604	636	659	660	606	693	647
71138	16:53:00	164	402	463	516	556	590	590	615	632	684
71139	17:00:00	141	407	305	420	465	498	506	525	547	518

TABLE 3 - CO_2

RECEIVER TEMPERATURES AND AVERAGE WALL AND GAS TEMPERATURES

7-5,6,10,11-1988 REACTOR 2T HEATING CO_2

RUN No.	Time	Re	TRuf	TRub	TRdf	TRdb	TRlf	TRlb	TRb	fRr	Pyro *)	TWa0 **)	TWa60	TWa70	TWa85	TWa100	TWa115	Taw1***)	Taw2	Taw3	Taw4	Taw5	Tag1	Tag2	Tag3	Tag4	Tag5
		Receiver Temperatures											Average Wall Temperatures										Average Gas Temperatures				
7504	09:09:00	392	276	281	319	343	300	257	371	47	754	321	591	617	614	641	619	456	604	616	626	630	439	540	578	596	600
7603	11:43:00	722	659	636	449	704	698	630	754	-	919	138	813	842	874	809	863	475	827	850	881	876	360	711	702	829	853
7604	12:03:00	1042	699	663	478	720	736	662	773	-	938	131	803	838	870	904	804	467	820	858	891	894	335	671	754	814	857
71037	16:00:00	946	504	578	403	602	562	562	501	56	721	199	652	641	673	723	719	425	646	657	690	721	329	536	500	629	667
71102	13:16:00	744	48	45	309	467	402	262	429	51	863	110	713	721	735	767	742	415	717	720	751	754	320	634	600	720	742
71103	13:20:00	831	47	47	518	585	532	399	553	54	907	141	751	764	803	844	813	446	757	783	823	828	316	629	700	752	790
71104	13:26:00	927	47	48	813	656	620	496	631	55	923	160	787	801	830	879	855	473	794	820	859	867	335	664	730	790	829
71105	13:33:00	970	48	49	691	714	607	592	690	58	910	177	805	816	854	894	876	491	818	835	874	885	339	678	750	805	847
71106	13:38:00	990	47	48	677	694	657	613	683	58	867	173	739	759	795	837	825	456	749	777	816	831	311	608	605	743	786
71107	13:45:00	1005	48	49	663	678	644	606	664	58	845	169	717	733	766	811	790	443	725	749	780	805	304	593	667	722	764
71108	13:48:00	1045	47	47	631	646	604	594	637	58	884	161	666	678	713	763	758	413	672	695	738	768	269	523	597	652	708
71109	13:55:00	1111	48	50	507	604	559	560	582	58	727	147	597	619	630	695	600	372	600	620	666	692	250	484	554	608	651
71110	14:05:00	1319	48	49	483	581	448	458	469	57	603	115	448	463	468	525	522	281	456	466	497	524	162	311	374	417	454
71111	14:10:00	1532	47	48	427	432	303	409	400	56	646	100	283	318	325	374	396	192	301	322	350	385	112	190	248	275	309
71115	14:39:00	969	48	50	374	408	345	385	369	57	765	99	460	476	480	539	523	208	460	478	510	531	171	326	379	418	454
71116	14:42:00	901	48	49	401	437	379	329	399	57	774	108	520	547	562	615	593	314	533	554	508	604	215	415	469	506	545
71117	14:47:00	846	47	49	477	514	444	390	465	58	829	126	597	614	642	694	675	361	605	620	660	684	243	472	534	579	617
71118	14:52:00	814	48	49	557	598	534	455	550	58	855	149	608	711	740	786	767	419	700	725	763	777	303	592	655	699	736
71119	14:56:00	802	49	49	601	626	598	503	594	58	875	160	711	732	761	803	792	436	721	746	784	808	312	609	676	722	759
71120	15:02:00	765	48	48	674	693	677	571	674	58	933	182	787	808	848	881	866	485	790	824	861	874	368	701	765	807	839
71121	15:07:00	743	49	48	714	729	717	614	713	58	944	195	819	837	860	906	891	507	828	853	887	898	370	732	796	840	872
71124	15:24:00	599	47	46	696	710	683	630	690	57	873	208	771	798	813	847	833	489	781	801	830	848	371	707	765	799	822
71125	15:29:00	615	47	47	649	650	627	611	649	56	795	191	694	714	737	776	769	442	704	725	756	773	325	624	693	720	752
71126	15:34:00	644	47	46	592	613	500	573	599	56	764	175	639	659	681	725	719	407	649	670	703	722	296	560	621	663	693
71127	15:39:00	603	45	45	529	546	502	511	536	55	690	157	520	557	576	627	638	330	538	567	601	620	230	446	506	547	586
71128	15:44:00	720	45	45	475	493	450	457	475	54	604	130	452	488	504	548	558	295	469	493	524	549	205	379	431	469	505
71129	15:51:00	760	44	45	423	445	400	402	414	53	672	121	402	432	442	495	494	261	417	437	469	495	182	333	380	416	447
71130	15:56:00	828	45	44	382	395	354	363	371	52	636	110	314	342	358	397	422	212	328	350	377	410	140	254	303	339	378
71134	16:23:00	422	43	43	555	600	591	444	563	53	896	171	759	766	804	830	809	465	763	705	821	824	377	718	755	785	800
71135	16:28:00	413	43	42	631	671	656	524	639	53	921	197	800	817	840	877	853	502	812	832	862	865	406	772	809	834	852
71137	16:40:00	447	43	43	553	583	535	532	563	51	750	180	633	652	671	704	690	408	642	661	687	701	311	582	631	663	685
71138	16:53:00	465	43	43	503	533	480	493	514	50	687	165	549	580	595	635	635	357	565	588	614	634	260	501	554	591	617
71139	17:06:00	494	43	43	443	473	422	428	440	50	627	144	465	494	506	540	551	304	480	500	526	548	226	416	466	497	521

*) Receiver Temperature, measured by an IR Pyrometer

**) TWa: Avg of front and back wall temp.
Taw: Avg wall temp. in segment
Tag: Avg gas temp. in segment
DT: (Avg) temp. difference between wall and gas in segment
Tdif: Gas temp. difference between exit and inlet of segment

***) 1, 2, 3, 4, 5 - Segments along the Catalyst bed

TABLE 4 - CO2

TEMPERATURE DIFFERENCES, ENERGY INPUT AND FLUX

7-5,6,10,11-1988 REACTOR 2V HEATING CO2

RUN No.	Time	Re	DT1 *)	DT2	DT3	DT4	DT5	Tdif1	Tdif2	Tdif3	Tdif4	Tdif5	Energy input, watt Q1	Q2	Q3	Q4	Q5	Q total	Flux, kW/m2 Flux1	Flux2	Flux3	Flux4	Flux5	Flux t
7504	08:09:00	392	17	56	38	32	22	185	34	25	11	13	332	64	47	21	25	488	7.9	9.1	4.5	2.0	2.4	5.8
7603	11:43:00	722	116	116	76	53	23	617	86	55	39	9	1841	291	190	136	32	2489	43.8	41.5	16.1	13.0	3.0	30.7
7604	12:03:00	1042	132	150	104	77	37	574	97	69	51	36	2464	470	343	258	184	3719	58.7	67.2	32.7	24.6	17.5	44.2
71037	16:00:00	946	96	120	77	69	54	383	31	56	44	31	1445	128	231	184	133	2121	34.4	18.3	22.0	17.5	12.7	24.8
71102	13:16:00	744	95	83	48	31	12	555	73	35	29	16	1590	234	113	97	52	2086	37.9	33.4	10.6	9.2	5.0	25.4
71103	13:20:00	831	130	129	84	72	39	539	87	55	49	27	1770	321	207	160	105	2590	42.1	45.0	19.7	17.9	10.0	31.1
71104	13:28:00	927	130	129	82	69	30	569	90	57	48	30	2147	381	247	213	133	3120	51.1	54.4	23.5	20.3	12.7	37.3
71105	13:33:00	970	152	140	85	68	30	565	90	60	51	33	2264	445	280	230	156	3302	53.9	63.5	26.6	22.7	14.9	40.3
71106	13:38:00	990	145	141	92	73	45	504	91	61	55	32	1987	403	277	251	149	3067	47.3	57.5	26.4	23.9	14.2	36.5
71107	13:45:00	1005	139	132	82	67	41	489	89	80	50	34	1934	393	268	227	150	2980	46.0	56.1	25.6	21.6	15.0	35.3
71108	13:48:00	1045	145	149	90	86	60	420	88	62	40	40	1656	302	277	210	220	2753	39.4	54.5	26.4	20.0	20.9	31.7
71109	13:55:00	1111	122	124	74	59	41	306	82	50	49	37	1560	364	264	227	174	2587	37.1	52.0	25.1	21.6	16.5	30.2
71110	14:05:00	1319	120	145	92	80	70	221	78	47	39	36	902	340	210	177	166	1796	21.5	40.6	20.0	16.9	15.8	20.4
71111	14:10:00	1532	80	103	82	75	76	126	46	38	32	35	524	200	167	143	159	1193	12.5	20.6	15.9	13.6	15.1	12.9
71115	14:39:00	969	109	142	99	92	77	248	61	45	34	37	745	196	148	113	125	1327	17.7	20.8	14.1	10.0	11.9	15.0
71116	14:42:00	901	90	119	86	80	60	334	85	43	36	37	1007	213	144	122	127	1613	24.0	30.4	13.7	11.6	12.1	18.6
71117	14:47:00	846	119	134	94	90	67	305	73	51	39	30	1153	240	171	133	131	1828	27.4	34.3	16.3	12.7	12.5	21.2
71118	14:52:00	814	115	107	70	64	41	499	79	46	41	33	1571	276	166	149	121	2203	37.4	39.4	15.0	14.2	11.5	27.0
71119	14:56:00	802	123	112	71	62	41	513	81	52	41	32	1616	204	107	151	110	2355	38.5	40.5	17.0	14.3	11.2	28.0
71120	15:02:00	765	124	97	59	53	35	601	80	49	35	28	1912	287	170	131	105	2612	45.5	41.0	17.0	12.5	10.0	31.3
71121	15:07:00	743	129	96	56	47	27	629	80	49	39	24	1905	286	177	142	90	2601	47.3	40.0	16.9	13.6	8.6	32.4
71124	15:24:00	599	110	74	36	31	19	596	76	40	27	19	1491	214	115	70	55	1952	35.5	38.6	10.9	7.4	5.3	23.7
71125	15:29:00	615	117	80	33	20	21	507	91	45	26	21	1239	249	125	73	60	1747	29.5	35.6	11.9	7.0	5.7	21.1
71126	15:34:00	644	111	89	49	40	30	455	72	52	32	27	1117	194	143	90	76	1621	26.6	27.6	13.6	8.6	7.3	19.3
71127	15:39:00	603	100	92	60	55	43	345	70	51	30	40	833	185	136	82	133	1368	19.8	26.4	12.9	7.8	12.7	15.4
71128	15:44:00	720	90	90	61	55	44	260	59	46	30	41	604	151	119	79	110	1143	16.3	21.5	11.3	7.6	10.5	12.9
71129	15:51:00	760	80	84	57	53	40	249	53	42	29	34	581	134	109	76	90	1000	14.1	19.2	10.3	7.2	8.6	11.4
71130	15:56:00	826	72	74	47	39	40	173	56	42	29	34	413	140	100	76	98	827	9.8	20.0	10.3	7.2	8.6	9.2
71134	16:23:00	422	88	45	30	30	16	639	44	30	29	17	1107	88	59	50	34	1344	26.4	12.3	5.6	5.5	3.2	16.4
71135	16:28:00	413	97	40	24	20	13	607	40	27	24	12	1204	91	54	49	24	1422	28.7	13.1	5.2	4.6	2.3	17.5
71137	16:40:00	447	95	60	30	25	16	401	61	37	27	18	821	115	70	52	35	1094	19.6	16.5	6.7	4.9	3.4	13.2
71138	16:53:00	485	89	84	34	23	17	399	66	48	33	19	671	122	75	63	38	956	16.9	17.5	7.2	6.8	3.5	11.6
71139	17:00:00	494	78	64	35	29	20	322	50	41	22	25	534	104	75	41	47	801	12.7	14.9	7.1	3.9	4.4	9.4

*) DT: (Avg) temp. difference between wall and gas in segment
Tdif: Gas temp. difference between exit and inlet of segment

TABLE 5 - CO_2

HEAT TRANSFER COEFFICIENTS AND DIMENSIONLESS GROUPS

7-5,6,10,11-1988 REACTOR 2Y HEATING CO_2

RUN No.	Time	Re	Alfa1 *)	Alfa2	Alfa3	Alfa4	Alfa5	Alfaav	Re 1	Re 2	Re 3	Re 4	Re 5	Re avg	Nu 1	Nu 2	Nu 3	Nu 4	Nu 5	Nu avg	Pr1	Pr2	Pr3	Pr4	Pr5
			Heat transfer coefficient, watt/m2.degc																						
7504	09:09:00	392	469	162	117	62	106	103	562	506	493	486	481	506	31.7	9.3	6.5	3.3	5.6	11.3	0.688	0.676	0.673	0.672	0.670
7603	11:43:00	722	379	350	230	247	131	271	1056	763	728	706	696	790	29.4	16.8	10.3	10.2	5.3	14.4	0.699	0.662	0.657	0.654	0.652
7604	12:03:00	1042	444	449	314	319	477	401	1581	1142	1077	1035	1008	1169	36.1	22.0	14.1	13.4	19.2	21.0	0.703	0.665	0.659	0.655	0.652
71037	16:00:00	946	357	166	284	255	236	259	1482	1121	1079	1036	1007	1129	29.3	9.7	15.6	13.1	11.6	15.9	0.705	0.671	0.673	0.668	0.665
71102	13:16:00	744	399	404	270	299	414	357	1082	788	757	740	728	819	33.4	20.8	13.0	13.9	10.7	19.9	0.706	0.668	0.664	0.661	0.660
71103	13:20:00	831	323	356	236	250	257	284	1250	905	461	831	810	932	27.3	18.4	11.2	11.2	11.1	15.8	0.707	0.669	0.663	0.659	0.656
71104	13:26:00	927	370	420	287	296	335	341	1389	1000	956	924	901	1036	30.0	20.8	12.1	12.7	13.9	18.1	0.703	0.666	0.660	0.656	0.654
71105	13:33:00	970	355	454	313	331	395	369	1467	1064	1006	970	945	1091	28.6	22.3	14.1	14.0	16.1	19.0	0.702	0.665	0.659	0.655	0.653
71106	13:38:00	990	325	409	286	327	313	332	1514	1111	1040	1006	977	1131	27.7	21.7	13.8	14.0	13.5	18.3	0.708	0.670	0.664	0.660	0.657
71107	13:45:00	1005	330	425	312	325	366	352	1536	1131	1066	1025	997	1151	28.0	23.0	15.4	15.1	16.2	19.6	0.709	0.672	0.665	0.661	0.658
71108	13:40:00	1045	273	365	269	243	352	300	1635	1217	1140	1092	1054	1227	25.4	21.7	14.5	12.2	16.7	18.1	0.717	0.679	0.671	0.667	0.663
71109	13:55:00	1111	304	420	330	367	402	366	1737	1304	1222	1160	1129	1312	29.6	26.4	19.3	19.5	20.3	23.0	0.722	0.683	0.675	0.670	0.667
71110	14:05:00	1319	179	337	210	211	220	234	2132	1672	1545	1470	1413	1647	22.0	20.7	16.5	14.0	15.0	19.4	0.749	0.709	0.698	0.692	0.687
71111	14:10:00	1532	155	270	195	182	190	202	2465	2071	1929	1828	1743	2007	22.4	30.0	19.6	16.0	16.9	21.2	0.771	0.737	0.725	0.716	0.709
71115	14:39:00	969	163	197	142	118	154	155	1532	1200	1124	1074	1035	1193	19.5	16.3	10.6	8.2	10.2	13.0	0.746	0.706	0.697	0.691	0.687
71116	14:42:00	901	244	257	188	145	204	202	1394	1063	1004	966	934	1072	25.8	18.1	10.3	8.0	11.7	15.0	0.731	0.692	0.685	0.680	0.676
71117	14:47:00	846	231	256	173	141	106	197	1308	982	926	890	862	994	22.9	16.4	10.1	7.8	9.7	13.4	0.724	0.684	0.678	0.673	0.670
71118	14:52:00	814	324	388	224	220	200	283	1224	901	857	830	809	924	28.1	19.9	11.2	18.5	12.8	16.5	0.709	0.672	0.666	0.663	0.660
71119	14:56:00	842	112	362	252	232	275	207	1206	866	842	814	794	900	26.6	19.2	12.3	10.7	12.2	16.2	0.707	0.670	0.665	0.661	0.658
71120	15:02:00	785	388	425	289	234	287	320	1123	819	783	762	747	847	28.4	20.1	12.8	9.9	11.8	16.6	0.698	0.663	0.658	0.655	0.653
71121	15:07:00	743	366	427	308	208	323	341	1085	798	757	737	723	819	27.4	19.6	12.0	11.0	12.0	16.9	0.696	0.660	0.656	0.653	0.651
71124	15:24:00	599	381	415	388	237	282	307	868	638	613	600	592	662	22.9	19.5	13.2	10.1	11.8	15.5	0.697	0.662	0.650	0.656	0.654
71125	15:29:00	615	251	440	305	240	270	316	915	675	642	626	616	695	20.0	23.3	17.5	11.4	12.1	17.0	0.705	0.669	0.663	0.661	0.659
71126	15:34:00	844	240	311	279	213	245	258	967	724	688	666	652	740	21.1	17.8	14.5	10.8	11.8	15.1	0.711	0.675	0.669	0.668	0.663
71127	15:39:00	803	190	206	215	142	298	220	1062	813	765	730	713	818	19.8	19.1	13.1	8.2	16.3	15.3	0.725	0.688	0.680	0.676	0.672
71128	15:44:00	720	182	239	185	137	235	196	1120	874	824	793	760	875	19.7	17.9	12.6	8.8	14.4	14.7	0.734	0.697	0.690	0.685	0.681
71129	15:51:00	760	177	228	181	136	188	180	1102	936	863	840	820	934	20.5	18.8	13.5	9.5	12.0	14.8	0.742	0.705	0.697	0.692	0.688
71130	15:56:00	828	137	271	219	108	217	206	1317	1073	999	953	917	1052	17.9	28.2	19.8	15.8	16.5	18.9	0.750	0.721	0.711	0.704	0.699
71134	16:23:00	422	298	276	189	151	203	224	597	438	427	419	413	459	22.4	12.8	8.5	6.6	8.6	11.8	0.696	0.661	0.659	0.657	0.655
71135	16:28:00	413	296	324	218	164	184	237	577	423	413	408	402	444	21.1	14.2	9.2	8.8	7.5	11.8	0.691	0.658	0.655	0.653	0.652
71137	16:48:00	447	208	275	223	208	207	222	655	491	472	461	453	507	17.8	15.1	11.5	9.9	10.0	12.8	0.708	0.673	0.668	0.666	0.664
71138	16:53:00	465	179	273	213	257	201	225	698	530	505	490	479	549	16.8	16.0	12.1	13.9	10.6	14.0	0.717	0.681	0.675	0.672	0.678
71139	17:00:00	494	182	234	207	134	188	179	749	581	551	534	523	588	18.7	16.4	13.4	8.3	9.5	12.9	0.728	0.692	0.685	0.682	0.679

*) 1, 2, 3, 4, 5 - Fragments along the Catalyst bed

TABLE 1-2V - REFORMING

REACTANT FLOW RATES

7-8-88 REACTOR 2V

RUN No.	Time	CO2 l/h	CH4 l/h	Feed l/h	CO2/CH4	GHSV h-1	Re	Products l/h	P,atg.
7801	10:04:00	2291	1993	4284	1.15	11424	339	6490	2.6
7802	10:12:00	2280	1995	4275	1.14	13113	344	6134	2.4
7803	10:20:00	2570	2198	4768	1.17	12715	373	7311	3.0
7804	10:36:00	3432	3016	6448	1.14	17195	517	8970	3.6
7805	10:44:00	3303	2890	6193	1.15	18997	508	8139	2.8
7806	10:51:00	3346	2916	6262	1.15	16699	503	8734	2.5
7807	10:59:00	3290	2938	6228	1.12	19104	508	8191	2.6
7808	11:07:00	3308	2855	6163	1.16	16435	495	8639	3.0
7809	11:15:00	4553	3788	8340	1.21	25583	693	10285	2.5
7810	11:23:00	4828	4188	9016	1.15	24043	738	11587	2.4
7811	11:31:00	4941	4174	9115	1.19	27960	763	11127	3.1
7812	11:38:00	4962	4246	9208	1.17	24555	754	11831	3.2
7814	11:54:00	4768	4078	8845	1.17	27133	737	10761	3.7
7815	12:02:00	4949	4239	9188	1.17	24500	752	11742	3.7
7816	12:17:00	5220	4568	9788	1.14	26101	796	12054	2.4
7817	12:26:00	5775	4895	10670	1.18	32730	899	12501	2.0
7818	12:33:00	5807	4438	10245	1.31	27320	865	12637	4.2
7819	12:41:00	5131	4476	9607	1.15	29469	805	11278	3.5
7820	12:49:00	5380	4618	9998	1.16	26661	826	12402	3.5
7821	13:05:00	1746	1551	3297	1.13	8792	252	5283	3.1
7822	13:13:00	1711	1495	3206	1.15	9836	251	5008	3.2
7823	13:21:00	1864	1604	3468	1.16	9248	263	5707	3.7
7824	13:28:00	1826	1584	3410	1.15	10461	270	5037	3.6
7825	13:36:00	1858	1587	3445	1.17	9187	268	5274	3.8
7826	13:44:00	1818	1571	3389	1.16	10394	276	4487	4.1
7827	13:52:00	1804	1577	3381	1.14	9016	271	4604	3.5
7828	14:00:00	1584	1419	3003	1.12	9212	250	3597	3.0
7829	14:08:00	1549	1350	2899	1.15	7731	241	3489	3.9

TABLE 2-27 - REFORMING

RADIATION, DOOR OPENING AND TEMPERATURES

7-8-88 REACTOR 2F

RUN No.	Time	Radiation mrem/h	Door m.	Gas Temperatures TG0	TG60	TG70	TG85	TG100	TG115	Reactor Wall Temperatures - Front TH0	TH15	TH30	TH45	TH60	TH70	TH85	TH100	TH115	TH130	Reactor Wall Temperatures - Back THb0	THb15	THb30	THb45	THb60	THb70	THb85	THb100	THb115	THb130
7001	10:00:00	705	6	396	635	643	670	698	740	435	735	897	866	820	815	926	918	868	691	407	745	823	827	818	809	829	842	857	674
7002	10:12:00	750	6	403	637	645	673	701	752	441	739	898	467	823	816	928	922	872	694	414	748	826	829	822	812	832	844	861	677
7003	10:18:00	763	6	412	644	654	683	713	768	450	751	914	881	836	830	940	937	884	706	423	758	836	839	832	823	844	857	874	689
7004	10:38:00	703	6	365	619	624	650	675	721	411	714	886	858	819	811	919	923	859	671	383	729	813	821	816	801	821	829	840	652
7005	10:44:00	771	6	351	615	619	646	671	715	396	704	889	860	817	807	917	925	854	684	368	719	807	817	811	790	817	824	843	644
7006	10:51:00	760	6	349	610	621	648	673	719	395	706	894	864	820	812	921	931	859	667	366	722	812	820	816	801	821	828	847	647
7007	10:59:00	765	6	348	619	621	648	674	720	394	708	903	869	822	815	923	931	862	667	365	722	813	822	817	803	823	829	848	648
7008	11:07:00	766	6	347	620	623	650	676	723	393	709	907	872	826	816	925	932	864	669	364	724	816	825	819	805	825	831	851	649
7009	11:15:00	782	6	337	613	617	644	669	715	391	659	906	866	822	818	919	928	860	664	359	717	810	821	816	801	828	826	846	644
7010	11:29:00	785	6	304	597	598	623	647	686	355	566	887	850	807	790	905	908	838	642	327	684	783	803	800	764	802	805	824	622
7011	11:31:00	775	6	299	599	598	623	640	687	349	663	869	850	807	790	906	908	837	642	319	680	782	804	800	764	803	804	821	622
7012	11:38:00	700	5	297	590	597	621	648	666	347	661	882	847	809	784	903	896	835	640	318	679	781	803	800	783	802	804	826	620
7014	11:54:00	804	6	296	603	600	624	650	691	346	664	893	854	814	783	908	905	838	642	317	682	783	800	803	787	805	806	829	677
7015	12:02:00	779	5	295	601	597	621	646	667	345	661	880	849	800	775	902	902	836	640	315	679	780	802	800	783	802	803	827	619
7016	12:17:00	730	6	275	507	505	607	631	669	328	641	874	837	803	761	893	893	825	627	299	663	762	798	790	773	790	791	815	606
7017	12:26:00	742	6	264	501	580	601	625	662	310	632	862	827	790	753	888	889	821	621	287	651	750	781	783	765	784	784	819	600
7018	12:33:00	825	6	273	594	598	613	636	677	323	644	877	841	807	763	859	890	831	632	293	664	765	793	794	776	796	797	825	611
7019	12:41:00	768	6	271	590	509	610	635	674	323	641	856	834	808	761	896	897	828	629	294	661	759	789	791	773	791	793	810	609
7020	12:49:00	700	6	271	593	590	613	637	676	224	646	866	835	809	764	890	899	831	631	293	664	763	792	793	775	794	795	821	610
7021	13:05:00	743	5	425	671	670	700	748	802	453	765	905	860	843	814	933	941	866	718	429	770	842	845	839	830	846	859	875	678
7022	13:13:00	799	5	453	681	689	717	753	810	484	769	917	890	861	825	944	951	967	736	456	787	853	857	852	844	862	877	898	728
7023	13:21:00	702	5	460	680	690	730	760	837	500	800	924	901	810	835	951	959	919	754	474	797	860	864	859	852	870	885	909	744
7024	13:28:00	803	4	478	665	673	699	729	791	505	762	874	845	829	787	897	902	860	720	481	764	828	826	824	817	832	845	871	710
7025	13:36:00	772	4	481	603	670	696	726	701	506	754	873	836	823	760	860	892	855	710	404	755	818	814	812	805	819	831	854	699
7026	13:44:00	765	3	466	628	632	654	676	718	503	702	805	757	759	715	810	821	787	669	404	705	745	750	750	750	756	766	793	658
7027	13:57:00	700	3	485	624	626	647	688	707	500	690	801	748	745	697	799	807	760	650	482	691	731	736	744	735	742	750	774	638
7028	14:00:00	704	2	486	506	505	599	614	644	493	631	740	678	670	622	719	732	692	599	480	618	644	646	662	657	650	662	689	588
7029	14:00:00	742	2	488	576	574	560	601	628	490	622	728	661	664	611	706	717	678	583	477	608	633	632	649	646	637	648	673	572

TABLE 3-2V - REFORMING

RADIATION, DOOR OPENING AND RECEIVER TEMPERATURES

7-8-88 REACTOR 2V

RUN No.	Time	Radiation watt/m2	Door m.	TRuf	TRub	Receiver Temperatures TRdf	TRdb	TRlf	TRlb	TRb	TRr	Pyro *)
7801	10:04:00	785	6	732	688	497	769	815	702	810	59	1038
7802	10:12:00	750	6	748	702	519	779	830	716	815	59	1040
7803	10:20:00	763	6	762	715	535	791	846	729	826	60	1049
7804	10:36:00	703	6	769	718	547	792	848	732	829	59	1041
7805	10:44:00	771	6	767	715	547	788	846	730	829	59	1042
7806	10:51:00	768	6	769	714	549	790	850	731	831	59	1044
7807	10:59:00	785	6	772	716	552	793	854	734	832	59	1045
7808	11:07:00	766	6	774	718	555	794	857	736	834	59	1045
7809	11:15:00	782	6	776	719	557	792	856	736	835	59	1040
7810	11:23:00	785	6	770	714	556	786	849	731	825	59	1036
7811	11:31:00	775	6	765	707	552	783	846	726	824	59	1036
7812	11:38:00	788	6	764	705	550	782	845	725	821	58	1036
7814	11:54:00	804	6	764	703	549	785	846	725	821	57	1039
7815	12:02:00	779	5	763	704	548	784	843	723	815	56	1036
7816	12:17:00	730	6	760	700	545	784	839	719	807	55	1033
7817	12:26:00	742	6	757	697	543	782	836	718	802	55	1031
7818	12:33:00	825	6	757	696	543	785	838	718	801	55	1036
7819	12:41:00	766	6	758	698	543	765	838	719	799	55	1035
7820	12:49:00	788	6	759	698	543	787	838	720	794	55	1035
7821	13:05:00	743	5	738	696	528	782	800	712	778	57	1038
7822	13:13:00	799	5	755	713	536	798	816	726	795	57	1043
7823	13:21:00	782	5	765	726	543	805	822	735	798	58	1047
7824	13:28:00	803	4	750	721	538	788	773	723	774	58	989
7825	13:36:00	772	4	723	697	516	769	749	702	743	58	987
7826	13:44:00	765	3	687	672	489	730	686	673	692	59	905
7827	13:52:00	780	3	650	637	457	704	652	639	656	58	901
7828	14:00:00	704	2	605	606	424	660	584	573	597	57	800
7829	14:08:00	742	2	569	572	393	624	547	522	555	57	803

*) Receiver Temperature, measured by an IR Pyrometer

TABLE 4-2V - REFORMING

COMPOSITION, CONVERSION AND ENERGY INPUT

7-8-88 REACTOR 2V

RUN No.	Time	Re	Product gas composition, mole % H2	CO	CH4	CO2	H2O	% Conversion of CH4	Reaction rate *)	Qheat	Energy Inputs, watt **) Qreac 1	Qreac 2	Q reac t	Q total	Flux Kw/m2
7801	10:04:00	339	30.6	37.3	13.3	15.3	3.3	56.0	2.98	1142	3161	102	3263	4405	55.5
7802	10:12:00	344	26.3	34.3	16.2	19.2	4.0	48.3	2.96	947	2730	115	2845	3792	54.9
7803	10:20:00	373	31.5	38.1	10.6	16.6	3.3	62.2	3.65	1291	3873	113	3986	5277	66.5
7804	10:36:00	517	24.3	31.9	20.0	19.9	3.8	41.2	3.32	1641	3519	160	3679	5320	67.0
7805	10:44:00	508	19.7	28.2	23.8	24.2	4.3	33.5	2.97	1366	2739	163	2902	4267	61.8
7806	10:51:00	503	24.5	32.1	19.7	19.9	3.8	41.8	3.25	1644	3454	158	3611	5255	66.2
7807	10:59:00	508	19.7	28.2	23.6	24.2	4.3	33.7	3.03	1398	2799	165	2964	4362	63.1
7808	11:07:00	495	24.8	32.6	19.3	19.5	3.9	42.6	3.25	1645	3446	159	3605	5250	66.1
7809	11:15:00	633	15.2	22.6	29.0	29.5	3.7	24.6	2.86	1839	2639	180	2819	4658	67.4
7810	11:23:00	738	18.5	25.8	26.3	25.7	3.7	23.7	3.31	2303	3518	199	3717	6020	75.8
7811	11:31:00	763	14.5	21.7	30.3	30.0	3.6	23.0	2.95	2068	2719	109	2908	4975	72.0
7812	11:38:00	754	18.4	26.0	25.2	26.6	3.8	30.5	3.46	2376	3670	213	3883	6259	78.8
7814	11:54:00	737	14.2	21.4	29.8	31.0	3.6	23.0	2.87	2018	2652	182	2834	4853	70.2
7815	12:02:00	752	18.1	25.5	25.7	27.1	3.7	29.8	3.37	2381	3573	205	3778	6158	77.6
7816	12:17:00	796	14.8	22.8	22.2	36.2	4.0	29.7	3.62	2437	3845	228	4073	6510	82.0
7817	12:26:00	893	11.7	17.6	31.3	36.5	2.9	19.0	2.85	2396	2627	173	2800	5196	75.2
7818	12:33:00	865	15.3	22.5	30.0	28.5	3.6	24.0	2.84	2683	3012	214	3226	5909	74.4
7819	12:41:00	805	12.1	17.5	34.3	33.4	2.7	17.8	2.44	2207	2250	143	2333	4600	66.6
7820	12:49:00	826	15.6	23.1	29.8	27.6	3.7	24.5	3.02	2621	3204	219	3423	6044	76.1
7821	13:05:00	252	34.7	40.5	7.7	14.2	2.9	71.0	2.94	968	3119	73	3192	4160	52.4
7822	13:13:00	251	31.8	40.2	6.8	15.1	4.2	67.1	3.08	766	2840	98	2938	3705	53.6
7823	13:21:00	263	36.2	42.3	5.6	12.9	3.1	77.9	3.33	1028	3539	83	3622	4650	58.6
7824	13:28:00	270	27.4	37.2	11.9	18.6	4.9	57.5	2.80	678	2580	117	2696	3374	48.8
7825	13:36:00	268	30.5	38.8	9.9	16.6	4.1	63.6	2.69	820	2857	103	2960	3700	47.6
7826	13:44:00	276	19.5	29.4	19.0	27.1	5.0	39.2	1.89	489	1742	105	1847	2336	33.8
7827	13:52:00	271	21.6	31.6	17.4	24.5	5.0	43.4	1.82	569	1936	109	2044	2613	32.9
7828	14:00:00	250	12.3	20.7	27.3	35.4	4.2	23.2	1.01	278	932	71	1003	1281	18.5
7829	14:08:00	241	12.5	21.3	27.2	34.6	4.4	23.7	0.85	297	907	73	980	1277	16.1

TABLE 5-2V - REFORMING

HEAT TRANSFER DATA

REACTOR 2V 7,9-88

RUN No.	Feed l/h	Twall5	TG115	Q total watt	Re	HT Area m2	Q watt *)	DT **)	Alfa w/m2*degC	Nu	Pr
7605	5616	838	710	4733	452	0.069	3947	219	263	9.317	0.800
7606	5184	854	729	4527	412	0.069	4136	221	273	9.371	0.792
7607	8448	817	677	5711	700	0.064	4898	223	343	12.815	0.805
7608	8424	827	679	5758	695	0.064	4956	227	341	12.750	0.804
7609	2628	919	841	3746	198	0.076	3648	183	262	7.346	0.719
7610	2724	878	788	4051	404	0.076	4037	170	313	8.920	0.760
7801	4284	863	748	4405	339	0.076	4196	192	288	9.149	0.756
7803	4768	879	768	5277	373	0.076	5087	192	348	10.872	0.743
7804	6448	854	721	5320	517	0.069	4891	223	321	11.077	0.781
7806	6262	853	719	5255	503	0.069	4783	226	309	10.667	0.780
7808	6163	858	723	5250	495	0.069	4778	229	305	10.461	0.777
7810	9016	831	686	6020	738	0.064	5119	226	354	13.279	0.805
7812	9208	831	686	6259	754	0.060	5303	223	397	14.930	0.804
7815	9188	832	687	6158	752	0.060	5197	221	393	14.857	0.803
7816	9788	820	669	6510	796	0.062	5383	219	397	16.013	0.818
7818	10245	827	677	5909	865	0.060	4721	217	362	14.125	0.796
7820	9998	826	676	6044	826	0.060	4872	216	376	14.613	0.813
7821	3297	881	802	4160	252	0.076	4059	171	311	9.212	0.727
7823	3468	914	837	4650	263	0.076	4625	167	365	10.411	0.707
7825	3445	855	781	3780	268	0.076	3782	143	349	10.946	0.741
7827	3381	771	707	2613	271	0.079	2623	111	300	10.896	0.796
7829	2899	674	628	1277	241	0.076	1287	73	232	9.757	0.845
72301	4532	790	675	4081	388	0.076	3836	179	281	9.207	0.784
72303	4551	837	702	4630	388	0.076	4382	204	282	8.818	0.752
72305	4607	845	705	4851	390	0.076	4629	208	293	8.934	0.756
72306	4582	849	707	4816	386	0.076	4608	208	291	8.853	0.755
72308	4541	862	719	5118	379	0.076	4923	210	308	9.105	0.747
72310	4506	865	722	4982	376	0.076	4801	211	300	8.967	0.745
72311	4494	869	726	5054	374	0.076	4881	212	303	8.889	0.742
72312	4507	866	721	5055	375	0.076	4883	212	304	8.967	0.748
72313	4495	872	727	5158	373	0.076	4989	213	308	9.035	0.744
72314	5085	757	772	3490	442	0.069	3260	109	438	14.456	0.695
	5665	862	704	5232	493	0.069	4873	235	303	9.557	0.735
72317	5763	865	704	5447	493	0.069	5081	238	311	9.915	0.747
72318	5986	864	700	5673	508	0.069	5273	241	320	10.124	0.759
72319	5905	869	700	5601	503	0.069	5194	244	311	10.021	0.753
72320	5876	867	701	5764	501	0.069	5363	243	323	10.116	0.753
72321	5886	871	703	5764	502	0.069	5366	243	322	10.111	0.751
72322	6722	864	690	5761	589	0.069	5273	247	312	10.302	0.747
72323	7091	859	684	5767	631	0.064	5199	246	331	11.174	0.743
72324	7462	852	672	5878	662	0.067	5216	246	316	10.882	0.758

*) Energy input from the point where the gas temperature is 400

**) Total temperature difference for heat transfer

TABLE 5-2V - REFORMING (continued)

HEAT TRANSFER DATA

REACTOR 2V 7,9-88

RUN No.	Feed l/h	Twall5	TG115	Q total watt	Re	HT Area m2	Q watt *)	DT **)	Alfa w/m2*degC	Nu	Pr
72325	7668	845	666	5783	688	0.064	5076	245	324	11.360	0.755
72327	5666	873	725	4915	506	0.069	4456	233	279	9.093	0.704
91502	6252	682	582	2390	532	0.069	1836	127	211	9.139	0.896
91504	6276	687	584	2534	532	0.069	1925	132	212	9.146	0.898
91505	6242	686	584	2502	530	0.069	1888	132	209	9.006	0.897
91506	6316	731	614	3400	529	0.069	2779	167	244	9.744	0.879
91507	6320	753	626	3496	526	0.069	2864	177	236	9.349	0.868
91508	6308	752	625	3501	525	0.069	2870	176	238	9.441	0.870
91509	6227	780	644	3922	514	0.069	3303	192	251	9.562	0.855
91510	6197	788	648	3984	510	0.056	3372	198	304	11.519	0.852
91511	6161	788	648	3966	507	0.069	3363	197	249	9.421	0.852
91512	6278	848	680	5052	506	0.066	4443	233	288	10.010	0.823
91513	6342	855	690	5115	509	0.069	4491	239	274	9.498	0.825
91514	6292	855	690	5264	504	0.069	4644	238	285	9.753	0.825
91515	6194	840	680	4746	504	0.069	4143	228	265	9.405	0.824
91516	6242	836	678	4645	506	0.069	4037	226	261	9.334	0.831
91517	6199	837	679	4808	501	0.069	4210	226	272	9.592	0.831
91518	9880	797	631	5311	819	0.060	4056	220	307	12.273	0.863
91519	9873	798	631	5335	814	0.060	4041	222	304	12.141	0.869
91520	9737	814	641	5715	801	0.060	4437	233	317	12.411	0.860
91521	9610	822	646	5769	789	0.060	4521	236	321	12.454	0.856
91522	9617	820	644	5736	790	0.060	4484	234	319	12.427	0.857
91523	9925	754	605	4205	826	0.060	2895	188	257	10.919	0.883
91524	9746	733	595	4038	834	0.060	2746	176	260	11.234	0.871
91525	9934	727	591	3989	848	0.060	2672	172	259	11.259	0.876
91526	9986	709	580	3623	856	0.062	2293	160	231	10.221	0.882
91527	9969	697	573	3549	852	0.060	2209	152	242	10.812	0.891
91528	9778	694	573	3428	844	0.060	2126	150	236	10.563	0.885

*) Energy input from the point where the gas temperature is 480

**) Total temperature difference for heat transfer

TABLE 1-UV - REFORMING

REACTANT FLOW RATES

10-13-88 REACTOR UV:

RUN No.	Time	CO2 l/h	CH4 l/h	Feed l/h	CO2/CH4	GHSV h-1	Re	Products l/h	P,atg.
101301	08:37:50	2520	2166	4686	1.16	43794	1326	5350	3.10
101302	08:54:22	2424	2130	4554	1.14	42561	1280	5982	3.00
101303	09:02:39	2400	2130	4530	1.13	42336	1266	6024	3.00
101304	09:10:58	2406	2094	4500	1.15	42056	1251	6162	3.00
101306	09:27:00	2376	2100	4476	1.13	41832	1242	6167	3.00
101307	09:34:00	2392	2156	4548	1.11	42505	1256	5780	3.00
101308	09:43:00	2643	2301	4944	1.15	46206	1410	6415	3.00
101309	09:52:00	2329	2246	4576	1.04	42763	1251	6219	3.00
101310	10:00:00	2392	2252	4644	1.06	43402	1277	6241	3.00
101311	10:33:00	2671	2282	4954	1.17	46295	1419	5922	3.08
101312	13:06:00	2919	2487	5406	1.18	50523	1661	6067	3.25
101313	13:14:00	2728	2269	4997	1.20	46699	1434	5580	3.10
101314	13:32:00	2745	2373	5118	1.16	47832	1477	5991	3.00
101315	13:41:00	2588	2160	4748	1.20	44374	1324	6575	3.00
101316	13:48:00	2573	2114	4687	1.22	43804	1303	6636	3.00
101317	13:56:00	2698	2318	5016	1.16	46879	1393	6828	3.10
101318	14:03:00	1581	1248	2829	1.27	26439	799	4168	2.75
101319	14:12:00	1475	1223	2698	1.21	25215	746	3981	2.90
101320	14:20:00	1458	1197	2655	1.22	24813	724	4246	2.98
101321	14:29:00	1451	1188	2639	1.23	24659	718	4272	3.00
101322	14:37:00	1443	1188	2631	1.21	24589	715	4247	3.00
101323	14:46:00	1569	1202	2771	1.31	25893	788	3773	3.00
101324	14:53:00	1541	1204	2744	1.28	25649	783	3663	3.10
101325	15:02:00	1580	1223	2802	1.30	26187	818	3436	3.03
101326	15:10:00	1569	1229	2798	1.28	26145	819	3359	3.00

TABLE 2-07 - REFORMING

RADIATION, DOOR OPENING AND TEMPERATURES

10-13-88 REACTOR 07

RUN No.	Time	Radiation watt/m2	Door s.	Gas Temperatures TG0	TG23	TG57	TG79	TG92	TH12.5	TH23	TH45	TH57	Reactor Wall Temperatures TH79	TH92	THb12.5	THb23	THb45	THb79	THb92	Receiver Temperatures TRa	TR4	TRcb	TRb	TRlb	Pyro *)
101301	08:37:50	783	4	34	315	380	611	875	595	787	810	783	840	785	510	815	786	791	827	-	-	-	-	-	1018
101302	08:54:22	689	4	36	368	611	634	702	847	847	844	805	882	823	573	800	814	830	867	-	-	-	-	-	1033
101303	09:02:39	754	4	38	376	618	840	711	665	835	850	833	889	832	588	694	824	843	876	854	799	113	725	701	1047
101304	09:10:50	716	4.2	37	494	633	654	729	693	874	889	850	922	860	614	727	840	867	903	753	830	116	753	731	1064
101306	09:27:00	526	4.2	39	407	635	855	731	692	893	882	850	925	882	622	733	854	869	905	882	836	118	751	726	1064
101307	09:34:00	829	4.2	40	407	642	663	739	899	899	893	858	932	871	833	744	865	870	916	897	856	122	763	738	1034
101308	09:43:00	398	4.2	40	368	610	929	874	856	838	831	802	870	789	460	554	788	737	798	878	704	123	727	727	890
101309	09:52:00	785	4.2	46	418	644	684	742	711	984	988	866	941	878	832	743	866	888	918	899	860	127	762	737	1083
101310	10:00:00	798	4.2	39	398	627	854	734	684	874	882	840	922	860	597	782	841	864	900	840	814	122	788	695	1072
101311	10:33:00	739	3	40	312	576	685	869	585	774	788	767	821	782	523	614	758	783	814	773	728	115	637	626	987
101312	13:00:00	453	4.5	37	218	461	514	511	441	653	627	599	898	844	261	312	451	529	572	828	509	85	453	420	884
101313	13:14:00	619	4.5	37	387	577	811	878	584	810	805	756	839	756	521	613	762	787	822	737	678	100	578	533	980
101314	13:32:00	555	4.5	37	284	555	588	649	549	788	788	721	888	788	466	547	692	726	778	733	862	100	599	581	950
101315	13:41:00	738	6	38	401	629	658	748	698	932	904	845	936	482	624	734	856	874	909	877	833	112	715	674	1060
101316	13:48:00	711	6	39	429	837	664	749	788	948	913	854	946	893	836	749	866	882	917	987	862	115	755	714	1063
101317	13:56:00	785	5.5	40	397	838	657	739	698	935	903	852	935	881	626	733	857	475	909	910	870	116	773	740	1053
101318	14:03:00	685	4	42	438	614	641	717	621	857	818	779	838	816	571	688	782	882	827	831	765	109	713	706	961
101319	14:12:00	881	4	44	489	838	668	752	650	885	842	788	857	845	618	733	819	836	866	826	776	110	701	890	981
101320	14:20:00	886	9	48	527	662	896	787	784	938	892	841	912	888	866	785	858	878	988	847	887	113	716	891	1030
101321	14:29:00	670	5	48	540	858	701	795	719	952	904	851	925	905	888	797	860	886	910	880	838	114	743	715	1030
101322	14:37:00	664	5	46	942	868	702	726	718	950	902	851	921	902	888	796	867	885	918	884	837	114	748	720	1026
101323	14:46:00	859	3.5	48	458	619	840	713	594	836	791	761	884	796	566	674	770	798	814	885	739	106	888	881	924
101324	14:53:00	857	3.5	45	430	684	631	781	573	818	776	742	787	781	541	650	752	773	798	769	708	103	850	846	912
101325	15:02:00	638	3	44	386	568	594	653	504	753	789	681	718	722	475	571	684	713	736	718	636	97	881	808	851
101326	15:10:00	678	3	43	347	558	585	842	482	731	691	883	783	787	453	545	863	893	716	679	599	93	561	585	841

*) Receiver Temperature, measured by an IR Pyrometer

TABLE 3-UV - REFORMING

COMPOSITION, CONVERSION AND ENERGY INPUT

10-13-88 REACTOR UV

			Product gas composition, mole %					% Conversion	Reaction		Energy Inputs, watt				Flux
RUN No.	Time	Re	H2	CO	CH4	CO2	H2O	of CH4	rate *)	Qheat	Qreac 1	Qreac 2	Q reac t	Q total	KW/m2
101301	08:37:50	1326	.0	24.8	32.4	30.4	12.4	16.1	3.3	1681	986	313	1298	2979	71.9
101302	08:54:22	1280	21.9	25.8	26.5	23.9	1.9	31.1	6.2	1829	1873	54	1927	3756	90.6
101303	09:02:39	1266	22.8	26.8	25.2	23.2	2.0	33.0	6.6	1853	1988	56	2044	3897	94.0
101304	09:10:58	1251	24.5	29.4	23.0	20.6	2.4	37.0	7.2	1910	2191	71	2262	4172	100.6
101306	09:27:00	1242	25.4	29.4	23.0	20.1	2.0	37.3	7.3	1909	2217	58	2275	4184	101.0
101307	09:34:00	1256	19.5	23.1	28.5	27.1	1.8	27.2	5.5	1916	1660	49	1709	3625	87.5
101308	09:43:00	1410	21.2	24.7	28.2	24.2	1.7	28.9	6.2	1878	1881	53	1934	3812	92.0
101309	09:52:00	1251	24.9	28.0	26.0	19.6	1.6	33.7	7.1	1988	2141	45	2186	4175	100.7
101310	10:00:00	1277	23.8	27.3	26.0	21.1	1.8	33.0	6.9	1982	2104	52	2155	4137	99.8
101311	10:33:00	1419	14.9	17.8	32.8	33.1	1.4	20.0	4.3	1814	1290	39	1329	3143	75.8
101312	13:06:00	1661	9.8	12.0	38.3	38.8	1.1	12.5	2.9	1396	877	31	907	2303	55.6
101313	13:14:00	1434	9.5	11.4	37.5	40.6	1.0	12.2	2.6	1827	786	26	812	2639	63.7
101314	13:32:00	1477	13.4	15.7	34.8	34.9	1.2	17.3	3.8	1801	1164	33	1197	2998	72.3
101315	13:41:00	1324	25.9	29.6	22.0	20.6	1.8	38.7	7.8	2058	2368	57	2425	4483	108.2
101316	13:48:00	1303	27.4	31.4	19.8	19.5	2.0	42.6	8.4	2067	2551	62	2613	4680	112.9
101317	13:56:00	1393	24.7	28.3	23.5	21.7	1.8	36.1	7.8	2159	2369	58	2426	4585	110.6
101318	14:03:00	799	30.0	34.3	16.9	16.7	2.1	48.7	5.7	1195	1721	42	1764	2959	71.4
101319	14:12:00	746	29.9	34.5	16.7	16.6	2.3	49.1	5.6	1204	1700	43	1743	2947	71.1
101320	14:20:00	724	35.6	39.4	11.5	11.7	1.9	61.9	6.9	1281	2098	38	2135	3416	82.4
101321	14:29:00	718	36.2	40.2	11.0	10.6	2.0	63.6	7.1	1293	2137	40	2177	3470	83.7
101322	14:37:00	715	36.3	39.8	11.2	10.9	1.8	63.0	7.0	1291	2117	36	2153	3443	83.1
101323	14:46:00	788	24.0	29.2	20.9	23.4	2.6	38.9	4.4	1125	1323	46	1369	2494	60.2
101324	14:53:00	783	22.5	27.6	22.7	24.6	2.6	35.6	4.0	1089	1213	44	1257	2345	56.6
101325	15:02:00	818	16.3	20.6	29.2	31.8	2.1	24.0	2.7	995	831	35	866	1861	44.9
101326	15:10:00	819	14.7	18.7	30.4	34.2	2.0	21.6	2.5	965	750	32	782	1748	42.2

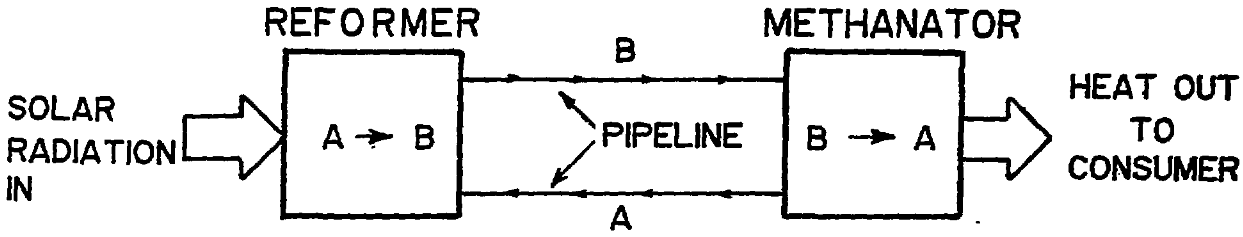
TABLE 4-UV - REFORMING

HEAT TRANSFER DATA

REACTOR UV 10-88

RUN No.	Feed l/h	TWa92	TG92	Q total watt	Re	HT Area m2	Q watt *)	DT **)	Alfa w/m2*degC	Nu	Pr
101201	2106	717	656	1500	629	0.03	1006	105	320	12.255	0.801
101203	1592	784	721	1680	442	0.035	1305	158	236	8.031	0.783
101204	1610	797	731	1792	446	0.035	1413	167	241	7.776	0.778
101205	1581	831	758	2105	430	0.035	1732	194	255	7.518	0.759
101206	1580	879	802	2345	422	0.035	1972	217	259	7.183	0.730
101207	1564	871	794	2337	419	0.035	1968	216	261	7.174	0.733
101208	1587	851	779	1917	430	0.035	1543	185	238	7.244	0.752
101209	1544	931	846	2609	404	0.035	2244	247	260	6.594	0.702
101210	1539	940	860	2602	401	0.035	2239	245	261	6.569	0.696
101301	4686	806	675	2979	1326	0.025	1875	171	439	20.710	0.892
101302	4554	845	702	3756	1280	0.025	2682	213	503	17.956	0.800
101303	4530	854	711	3897	1266	0.025	2829	214	529	18.630	0.796
101304	4500	882	729	4172	1251	0.025	3111	237	526	17.965	0.784
101306	4476	884	731	4184	1242	0.025	3129	243	516	17.397	0.782
101307	4548	893	739	3625	1256	0.025	2552	248	412	14.759	0.791
101308	4944	793	674	3812	1410	0.025	2647	167	635	23.226	0.816
101309	4576	898	742	4175	1251	0.025	3093	250	495	16.609	0.787
101310	4644	883	734	4137	1277	0.025	3040	229	532	18.166	0.790
101311	4954	798	669	3143	1419	0.025	1976	171	461	18.162	0.818
101312	5406	608	511	2303	1661	0.025	1030	50	830	38.219	1.134
101313	4997	810	678	2639	1434	0.025	1462	182	321	13.353	0.815
101314	5118	769	649	2998	1477	0.025	1792	154	467	18.898	0.829
101315	4748	896	740	4483	1324	0.025	3365	254	529	17.702	0.769
101316	4687	905	749	4680	1303	0.025	3576	262	547	17.934	0.761
101317	5016	895	739	4585	1393	0.025	3403	255	534	18.103	0.775
101318	2829	822	717	2959	799	0.028	2294	196	417	13.567	0.773
101319	2698	856	752	2947	746	0.028	2312	216	382	12.143	0.759
101320	2655	898	787	3416	724	0.028	2791	246	405	11.854	0.731
101321	2639	911	795	3470	718	0.028	2849	255	398	11.503	0.726
101322	2631	910	796	3443	715	0.028	2824	253	399	11.495	0.726
101323	2771	805	713	2494	788	0.028	1843	184	359	12.537	0.778
101324	2744	790	701	2345	783	0.028	1700	171	355	12.670	0.788
101325	2802	729	653	1861	818	0.028	1202	129	334	13.145	0.817
101326	2798	711	642	1748	819	0.028	1090	114	342	13.811	0.825

*) Energy input from the point where the gas temperature is 480



$$A \rightleftharpoons B$$

$$CH_4 + CO_2 \rightleftharpoons 2H_2 + 2CO$$

Figure 1

The Chemical Heat Pipe

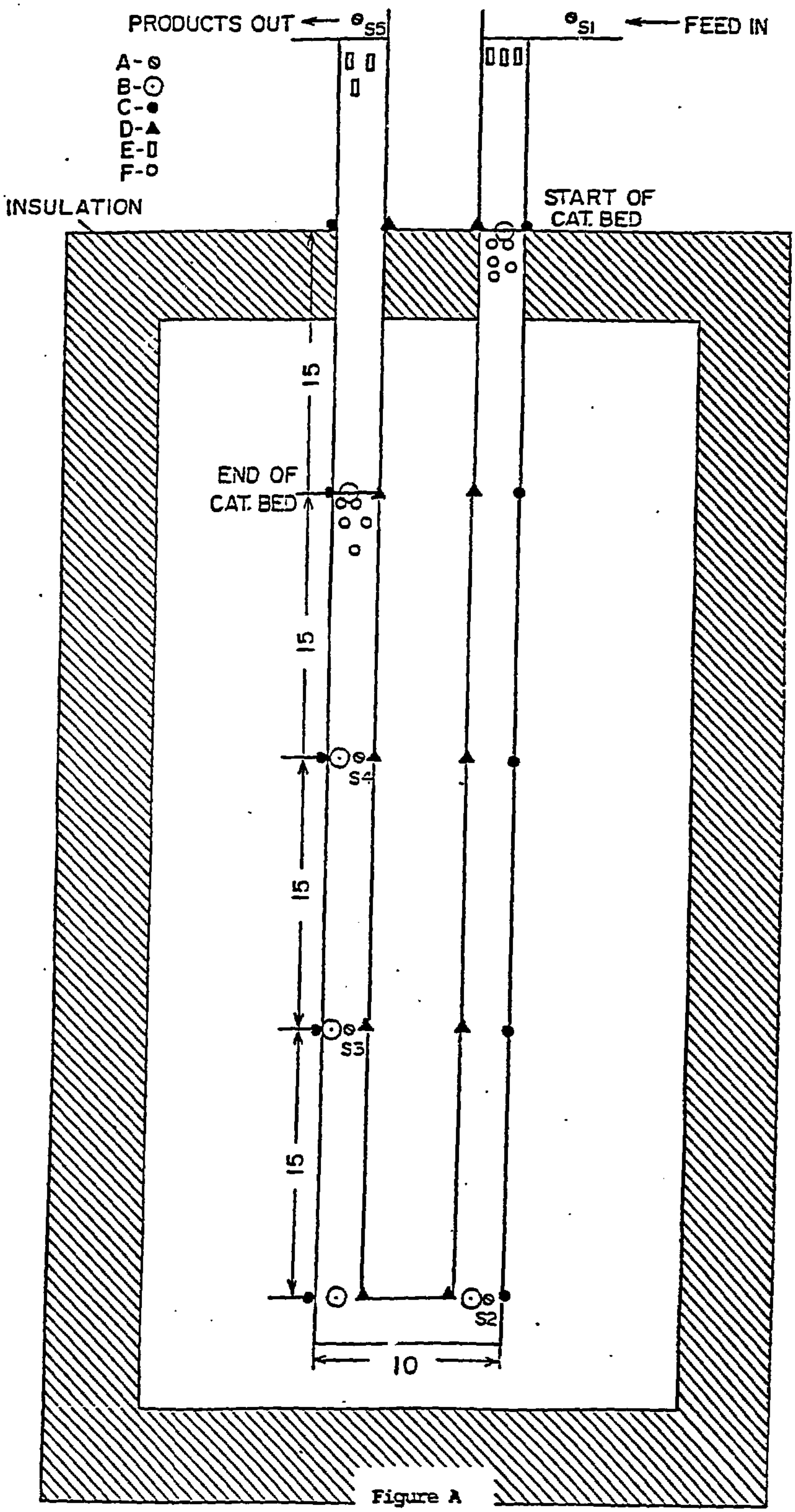


Figure A

Reactor 2V (ID=20 mm) in the Receiver

A. Gas sample; B. Gas temperature; C. Front wall temperature; D. Back wall temperature; E. Alumina pellets; F. Catalyst.

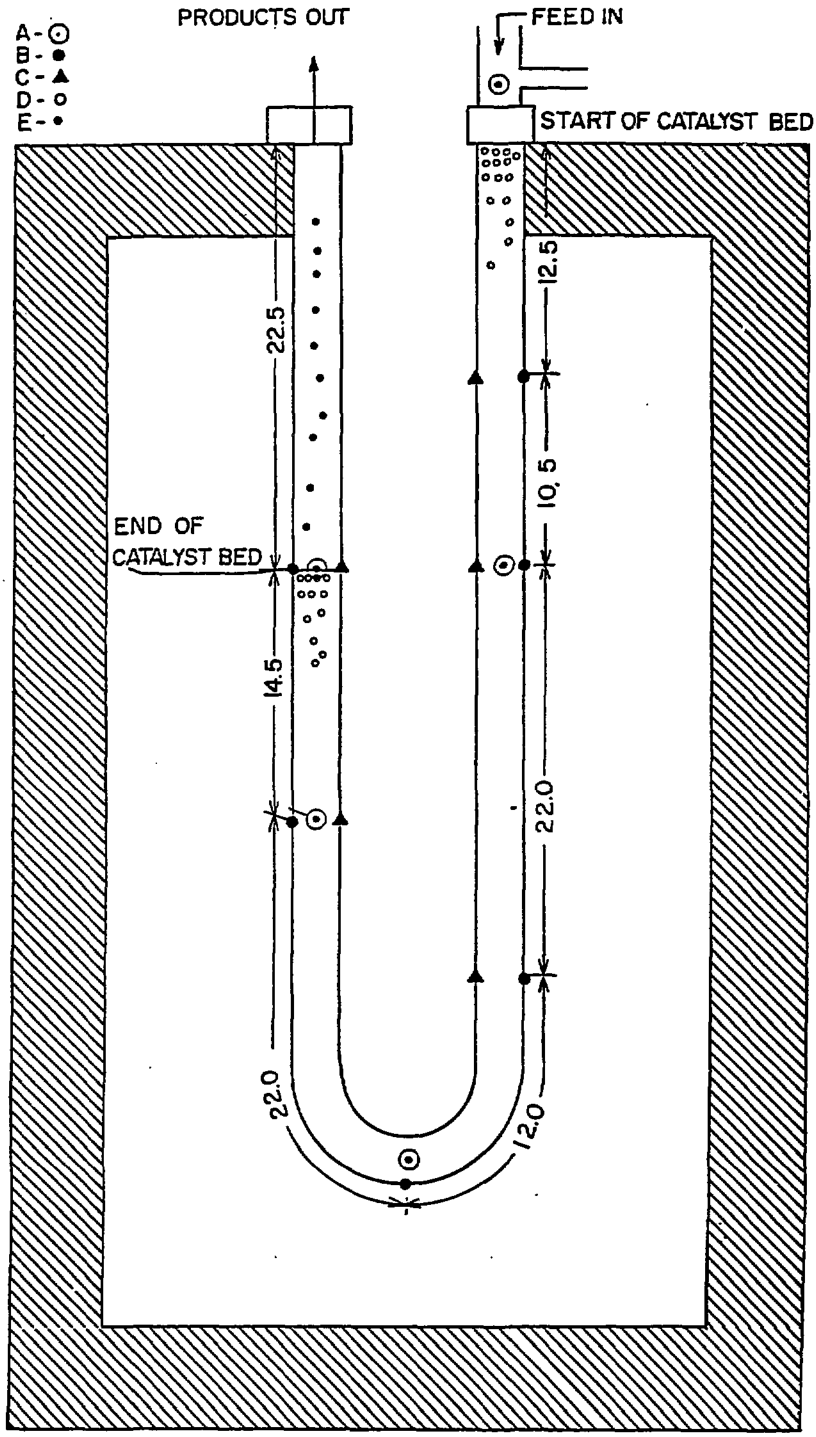


Figure B

Reactor UV (ID=12 mm) in the Receiver

A. Gas temperature; B. Front wall temperature;

C. Back wall temperature; D. Catalyst; E. Alumina pellets.

Feed flow

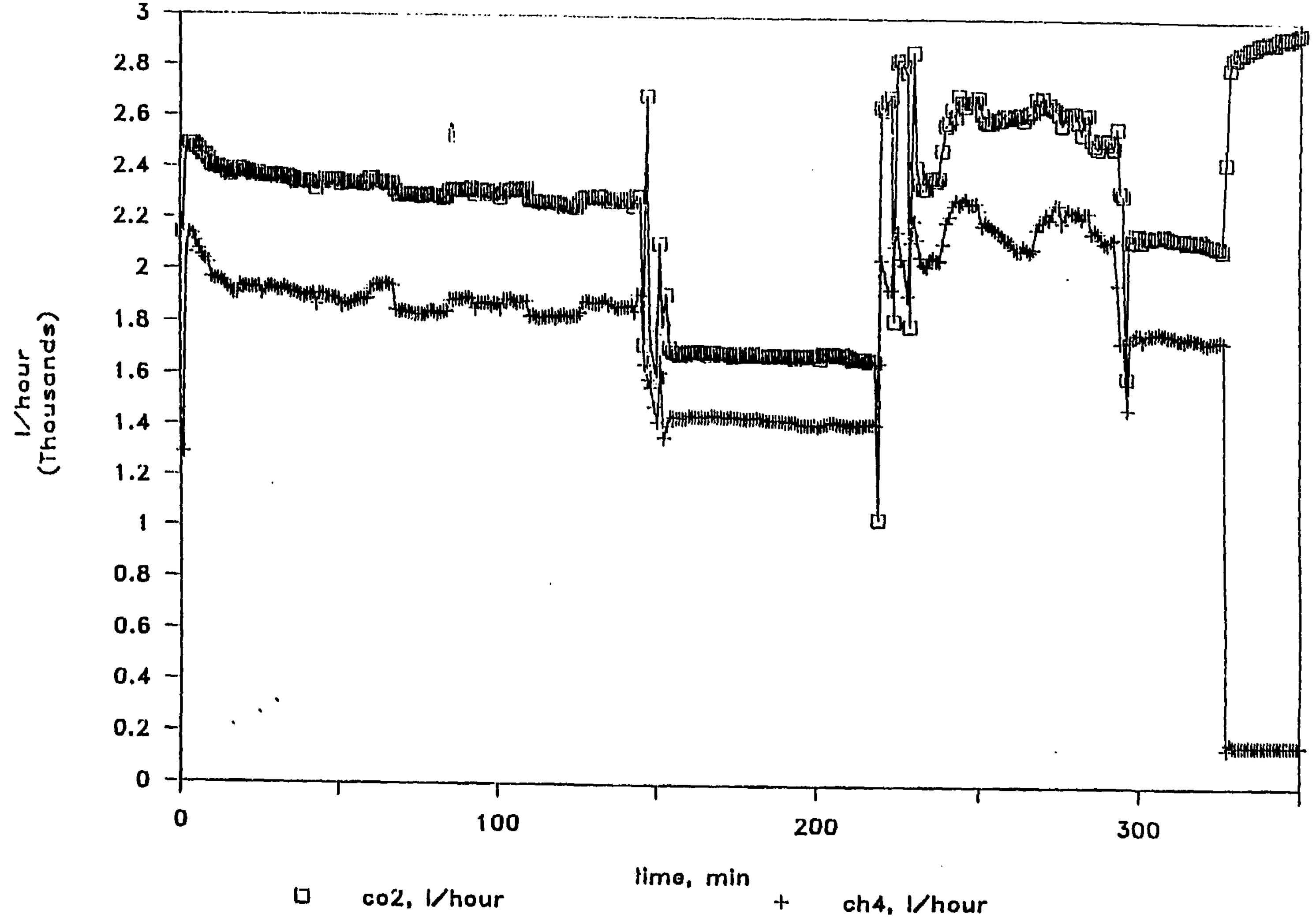


Figure C
Reforming

Data for one day. Feed Flow.

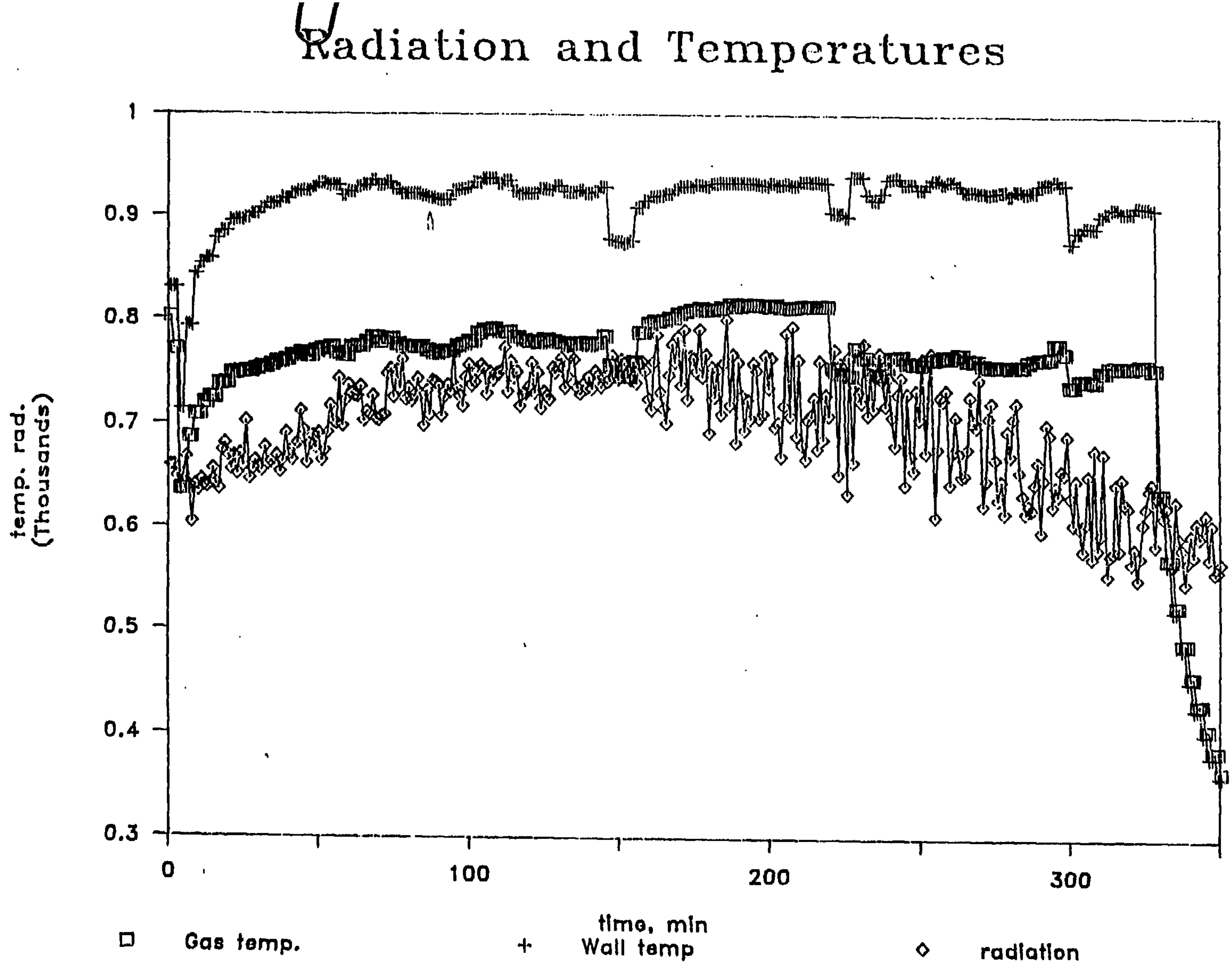


Figure D
Reforming

Data for one day. Radiation and temperatures.

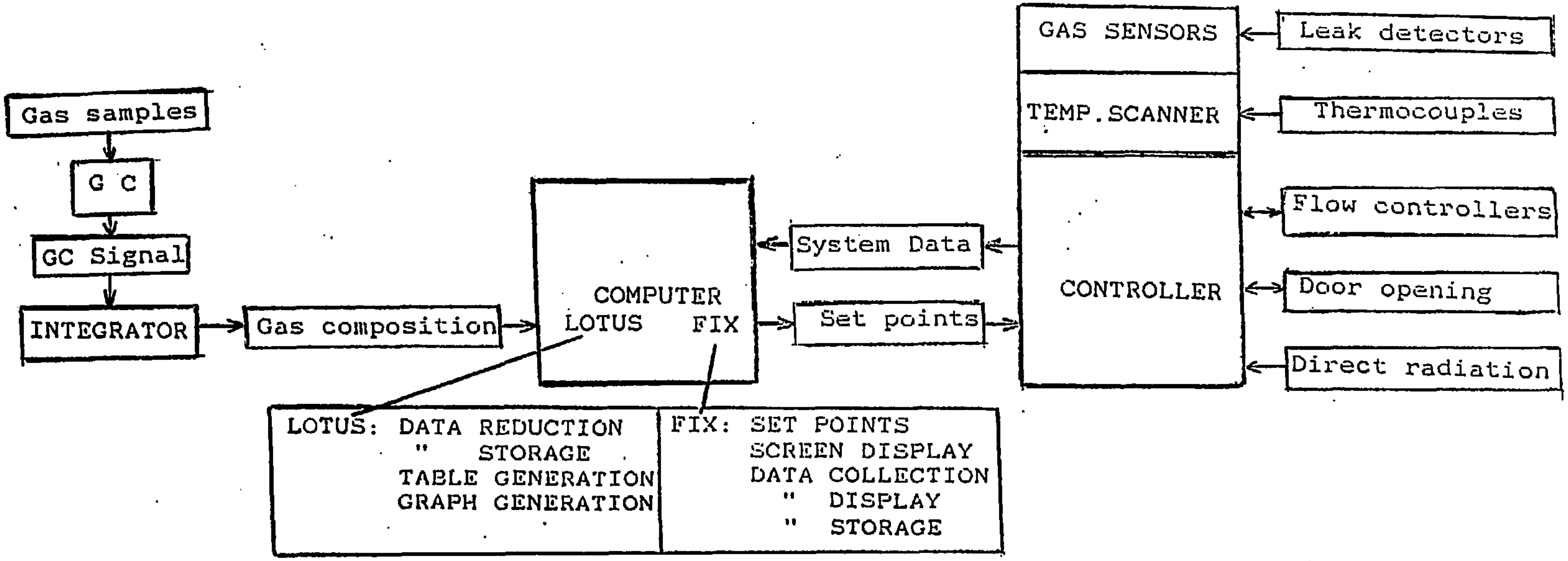


Figure E

Data aquisition, reduction and storage

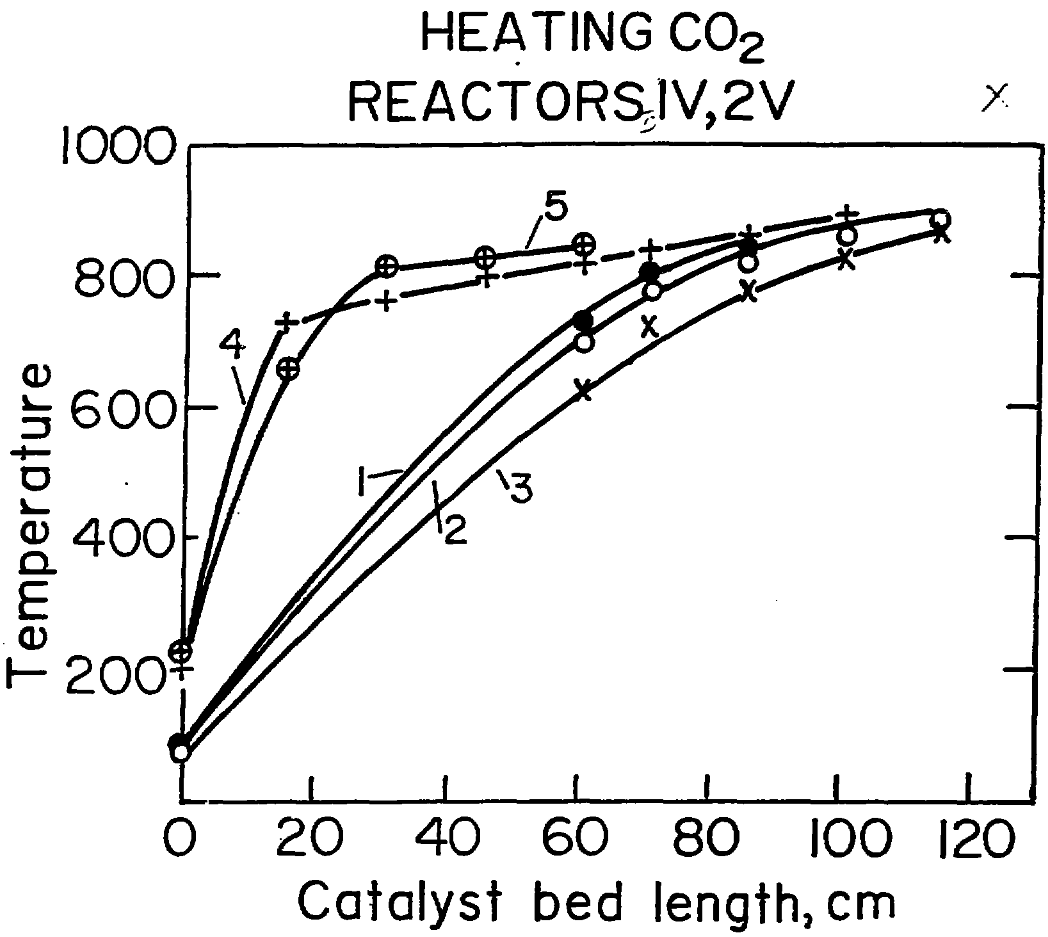


Figure C1

Heating CO_2

Temperature profiles, Reactors 1V and 2V.

1-3 Product gas temperature, Reactor 2V
1. Re = 444
2. Re = 819
3. Re = 1091
4. Wall temperature, Reactor 2V
5. Wall temperature, Reactor 1V

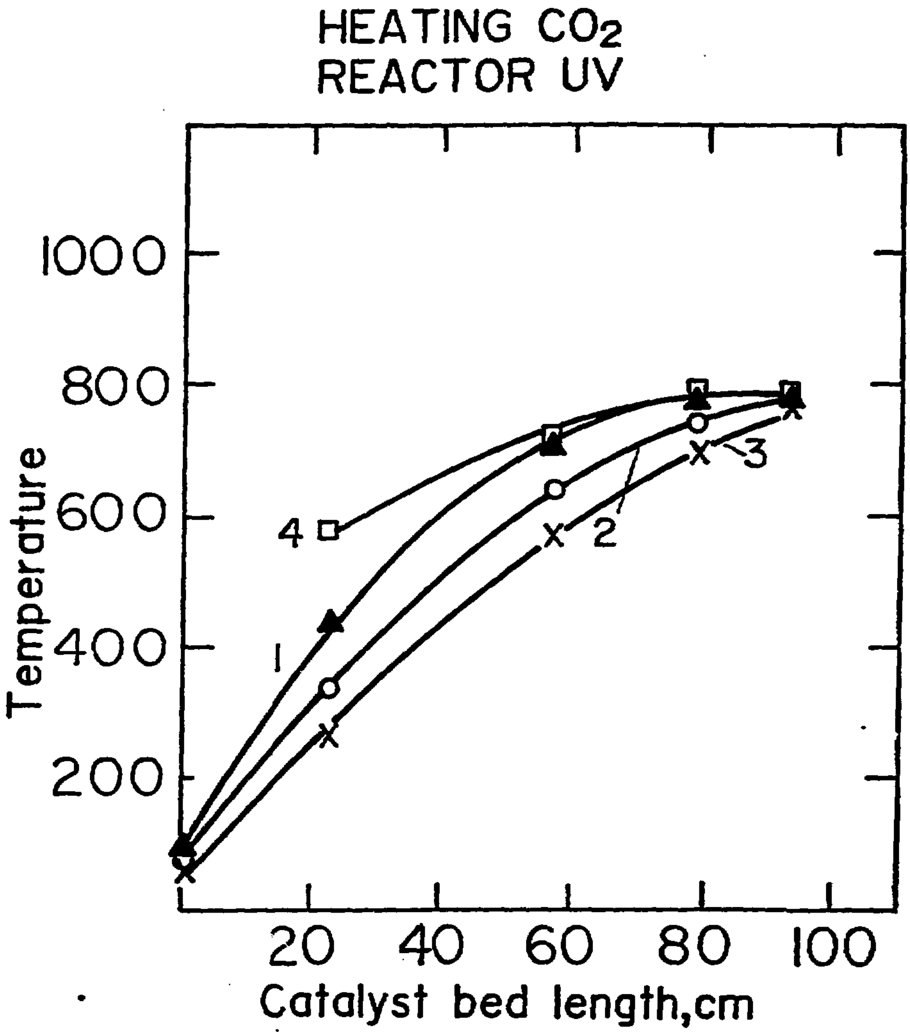


Figure C2

Heating CO_2

Temperature profiles, Reactor UV

1-3 Product gas temperature, Reactor 2V
1. Re = 417
2. Re = 786
3. Re = 1449
4. Wall temperature

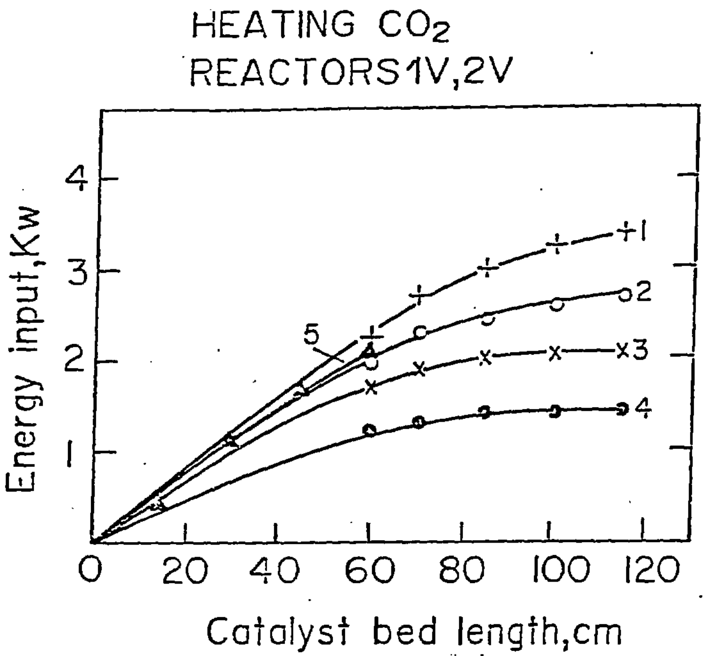


Figure C3

Heating CO_2

Energy input along the reactor

1-4. Reactor 2V — 1. Re = 1091; 2. Re = 819; 3. Re = 630; 4. Re = 444

5. Reactor 1V — Re = 1140.

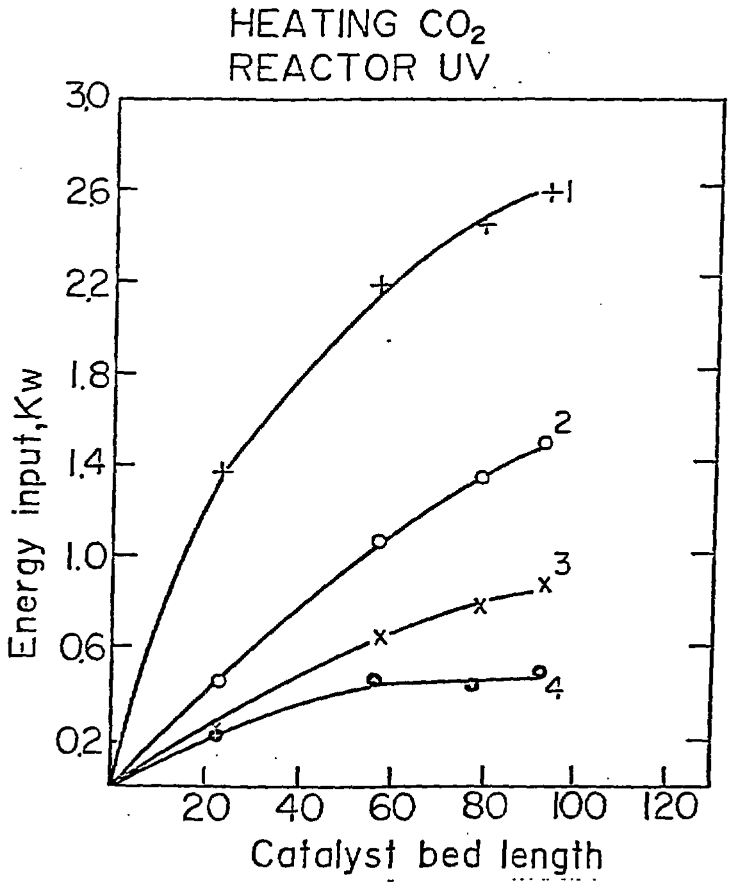


Figure C4

Heating CO_2

Energy input along the reactor UV

1. Re = 1350, final wall temperature = 9[illegible]
2. Re = 1449
3. Re = 785
4. Re = 417

2-4. Final wall temperature = 780-800.

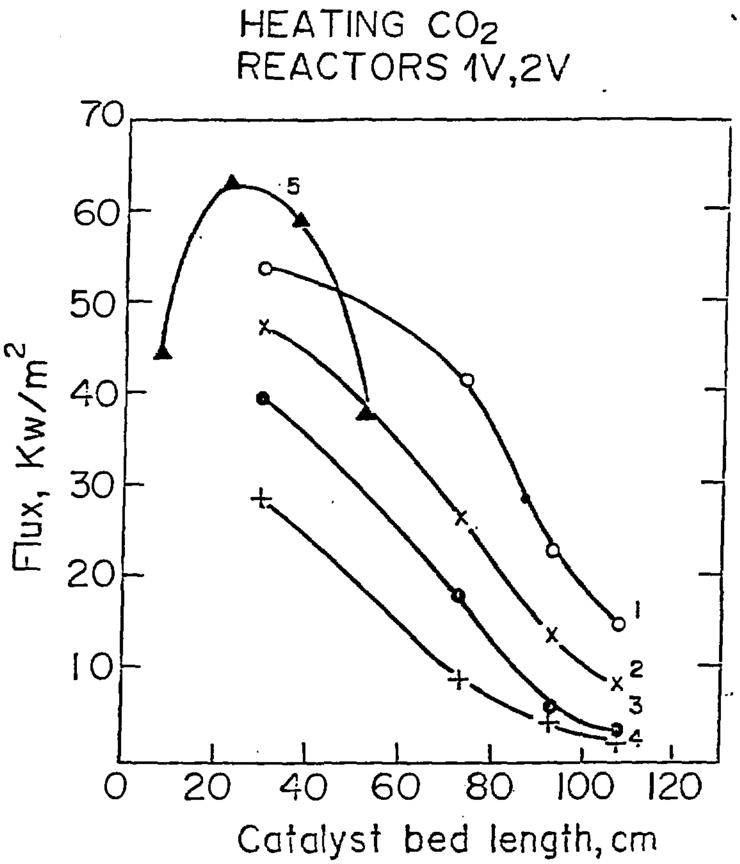


Figure C5

Heating CO_2

Heat flux along the reactor (see text)

1-4. Reactor 2V - 1. Re = 1091
2. Re = 819
3. Re = 630
4. Re = 444
5. Reactor 1V - Re = 1140

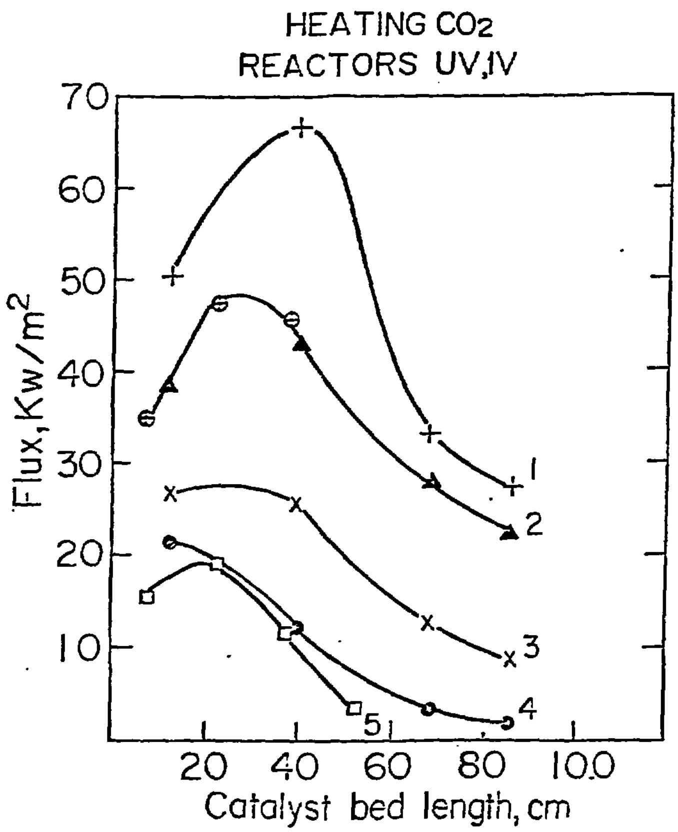


Figure C6

Heating CO_2

Heat flux along the reactor

1-4. Reactor UV - 1. Re = 1350; wall temperature=
2. Re = 1449
3. Re = 785
4. Re = 417
2-4 - wall temperature = 780-800
5. Reactor 1V - Re = 280

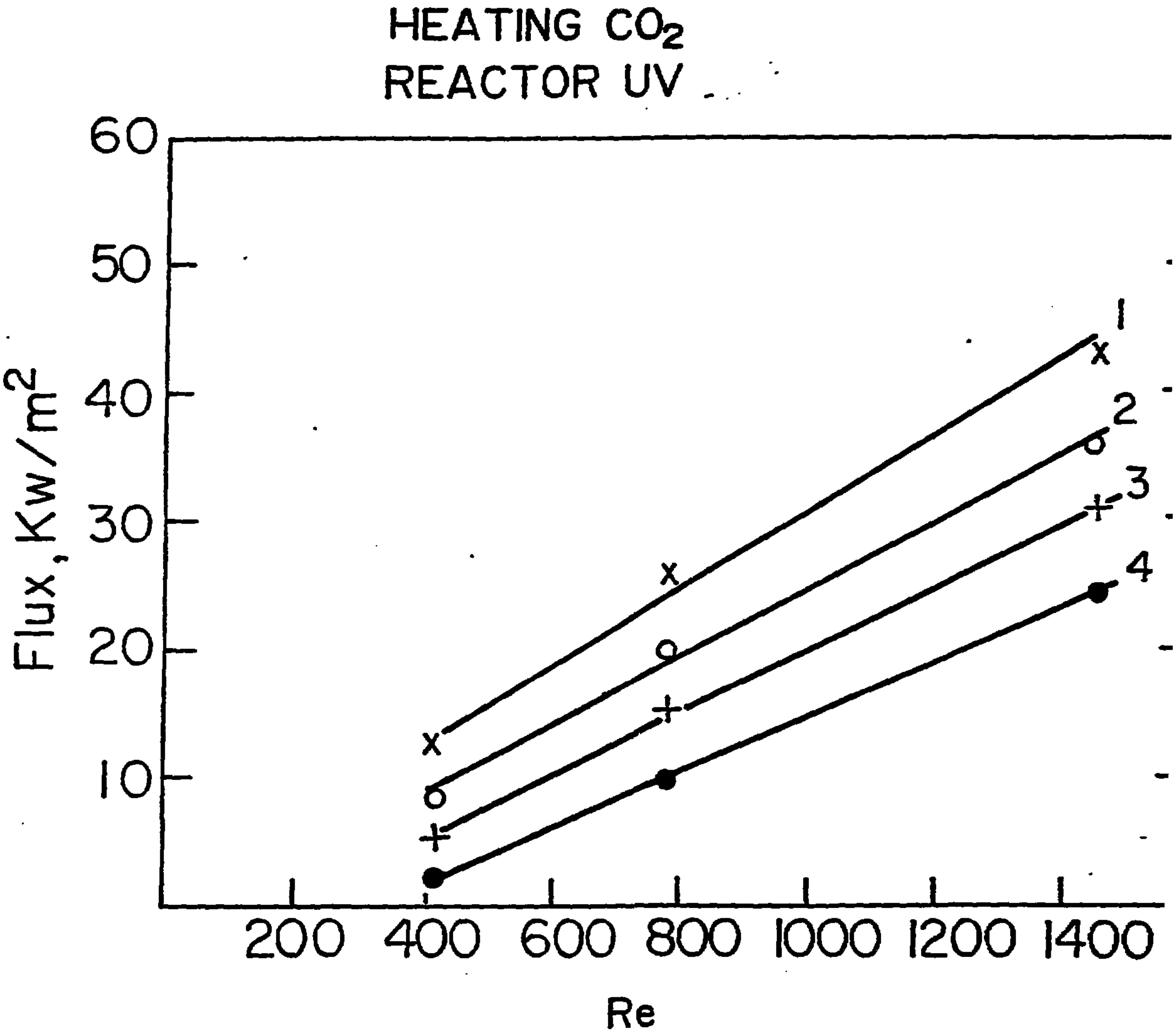


Figure C7

Heating CO_2

Heat Flux vs. Re in Reactor UV, at various locations along the reactor. Catalyst bed length, cm: 1. 40; 2. 50; 3. 60; 4. 80.
Wall temperature: 770-780.

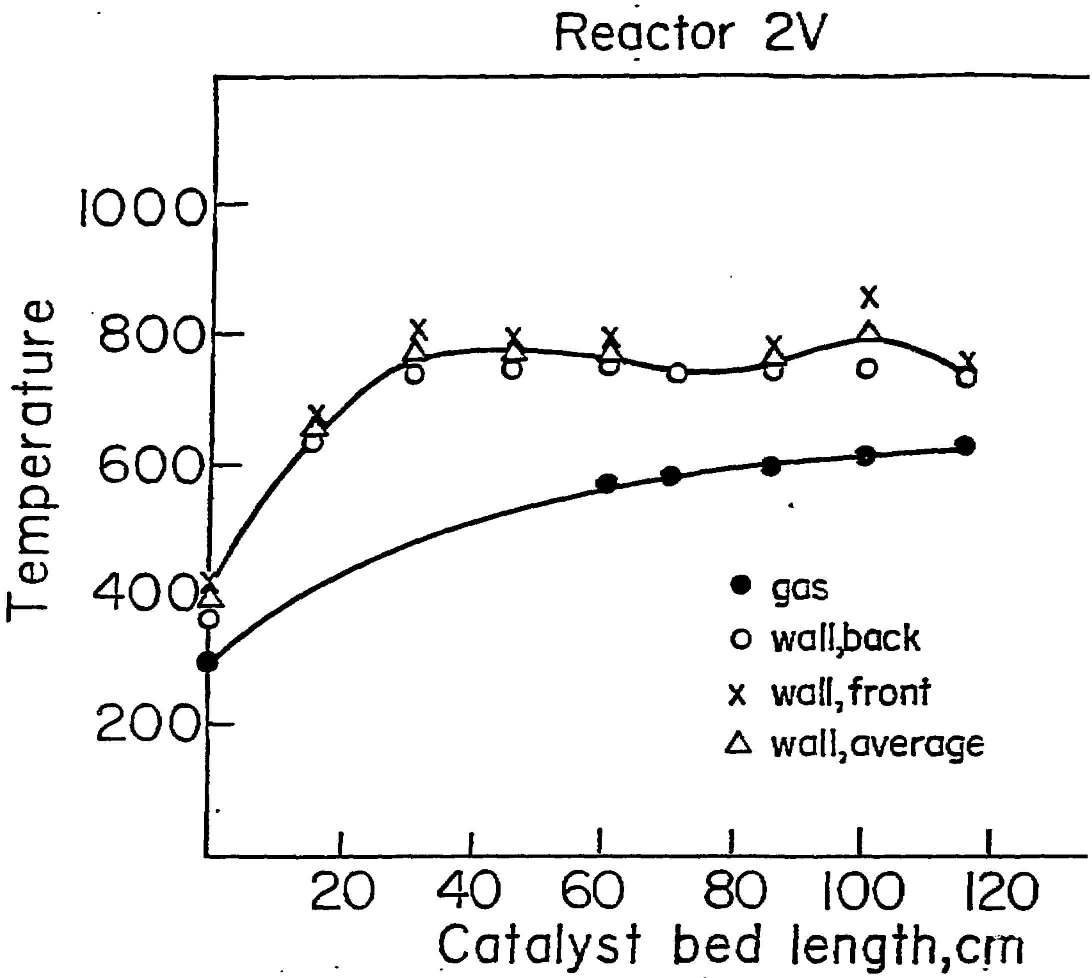


Figure P1

Reforming

Temperature Profiles, Reactor 2V, Re=863

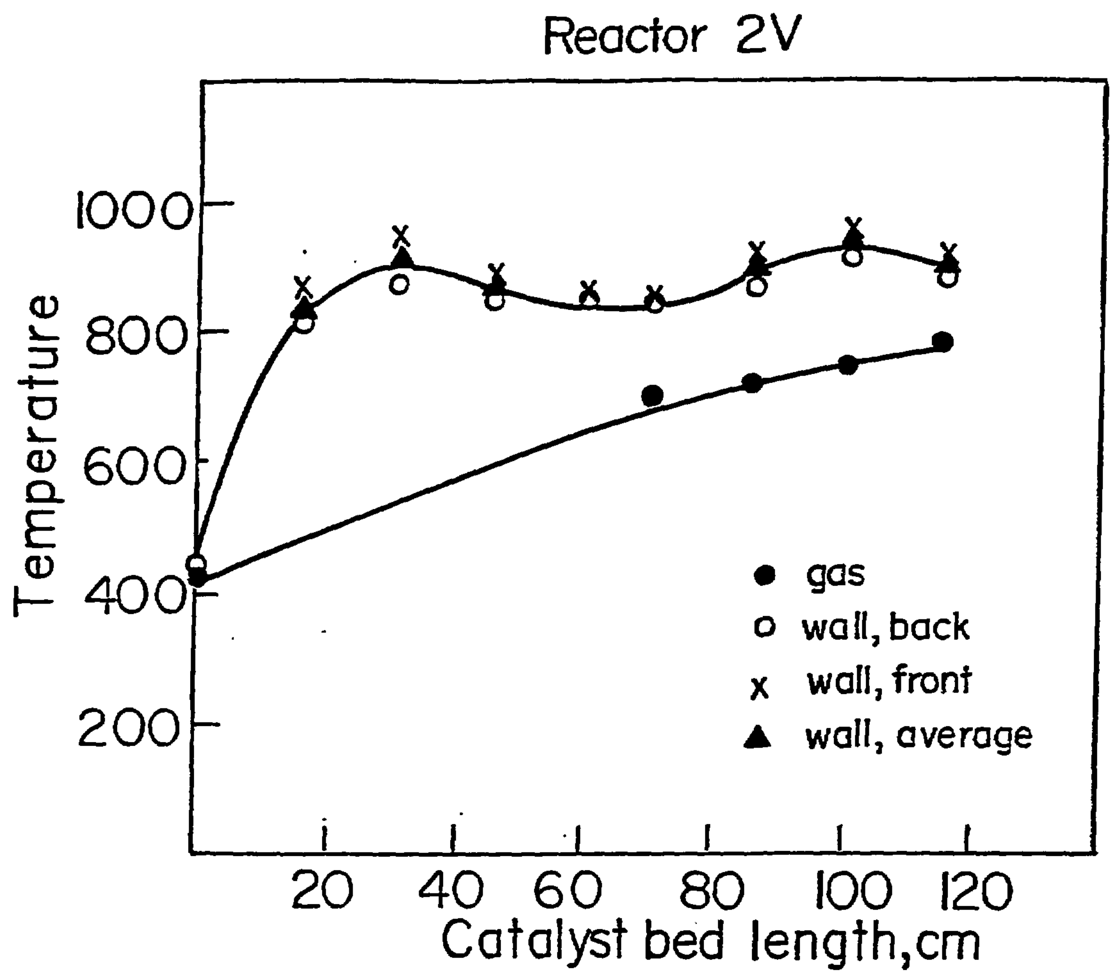


Figure P2

Reforming

Temperature Profiles, Reactor 2V, Re=270

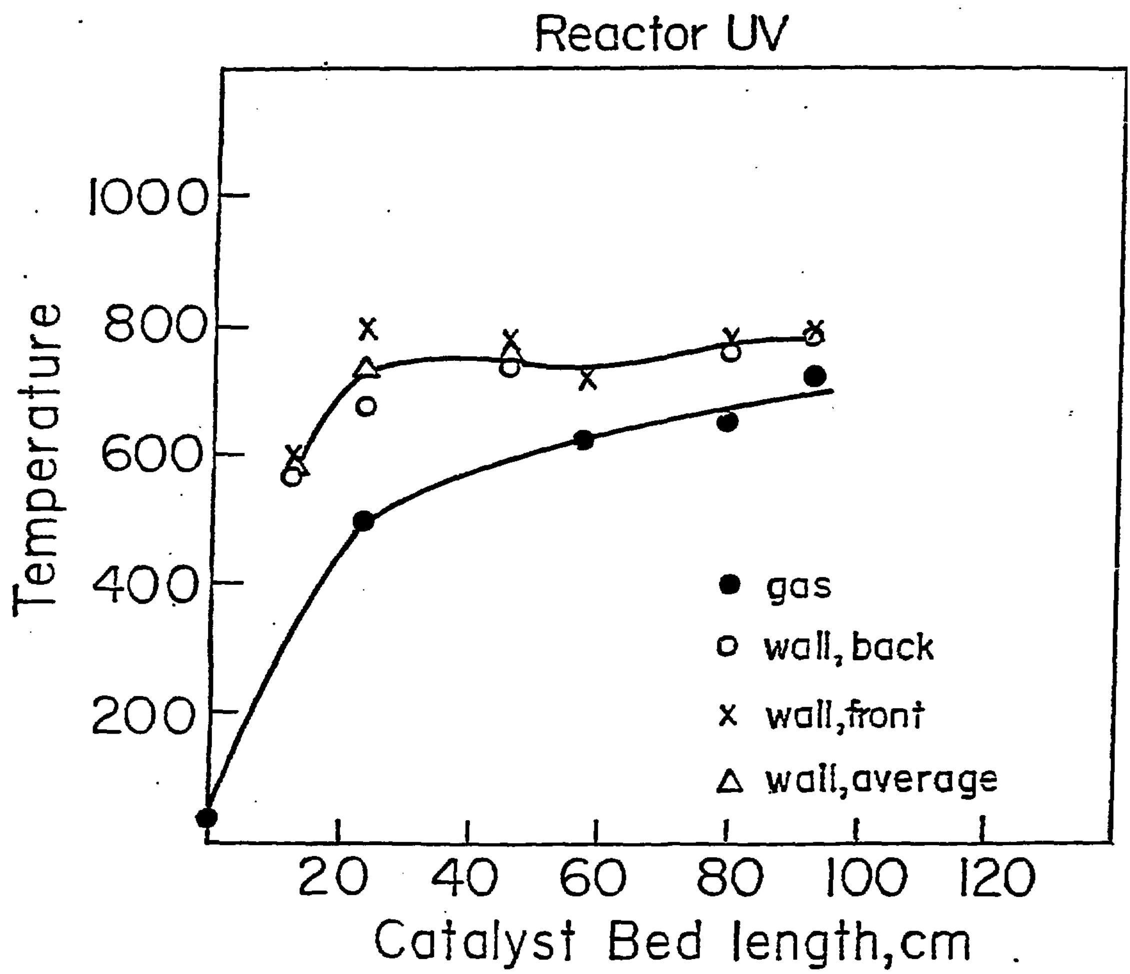


Figure P3

Reforming

Temperature Profiles, Reactor UV, Re=442

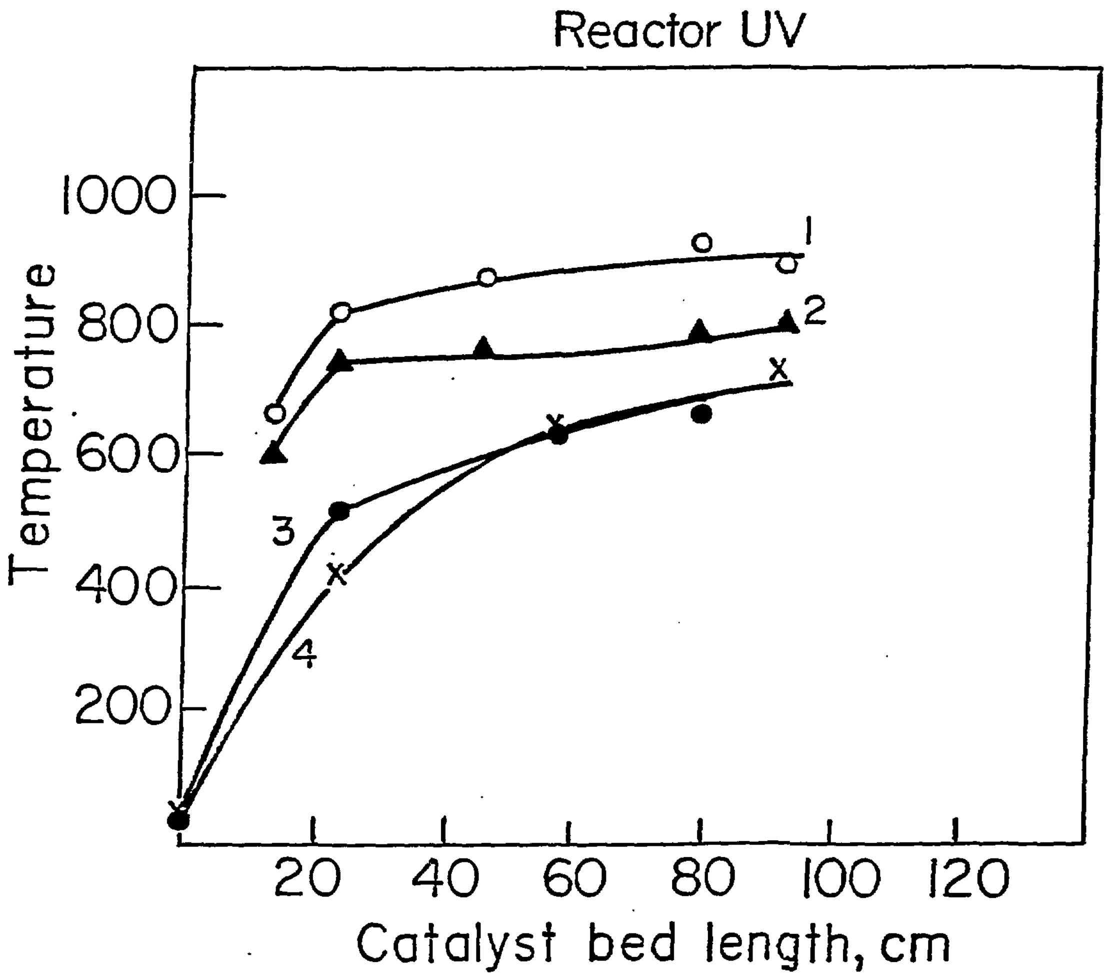


Figure P4

Reforming

Temperature Profiles, Reactor UV

1. Average wall temperature, Re=1242
2. Average wall temperature, Re= 446
3. Product gas temperature, Re= 446
4. Product gas temperature, Re=1242

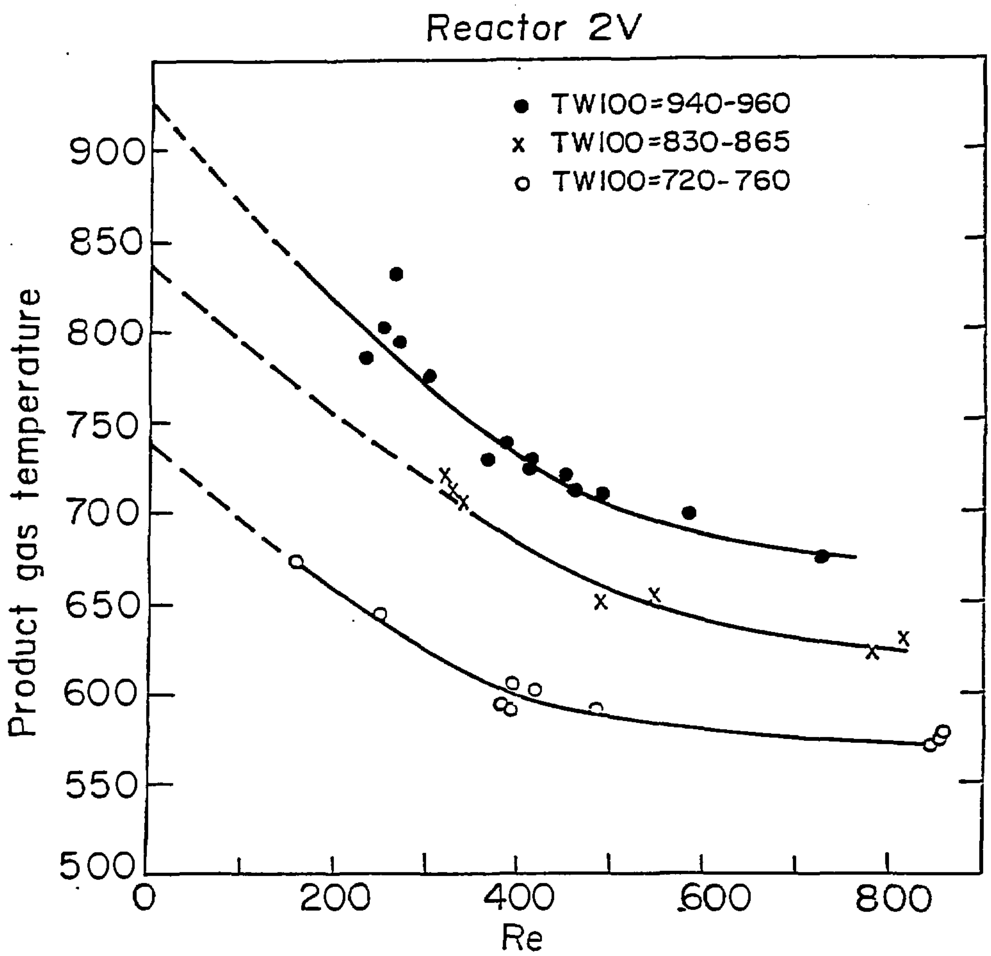


Figure 2

Reforming

Product gas temperature vs. Re, for 3 different wall temperatures
(the hottest point on the wall is taken)

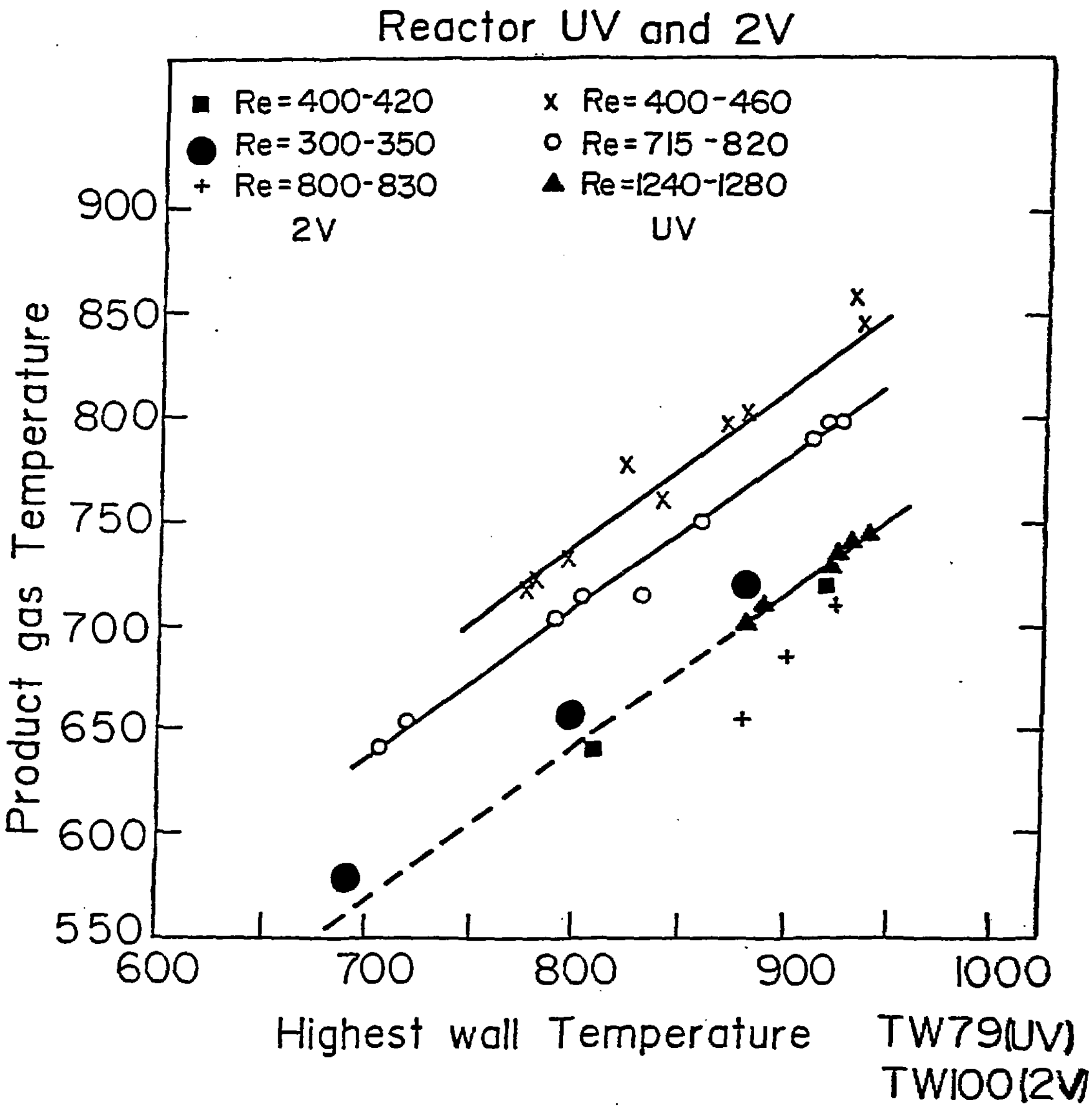


Figure 3

Reforming

Product gas temperature related to the highest wall temperature, for different ranges of Re. For reactor 2V only points are shown (see text)

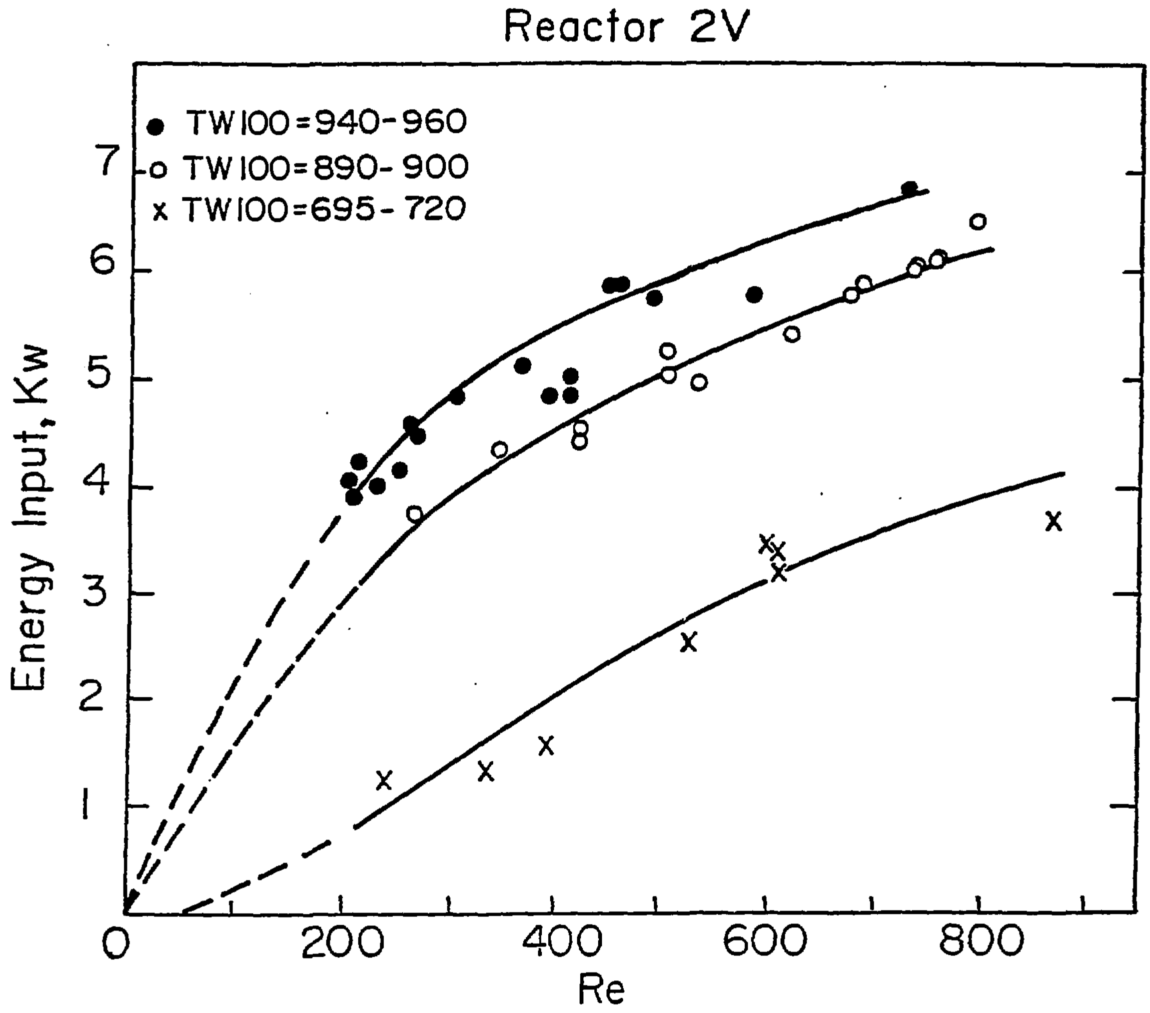


Figure 4

Reforming

Total energy input vs. Re. TW 100 is the hottest point on the reactor wall

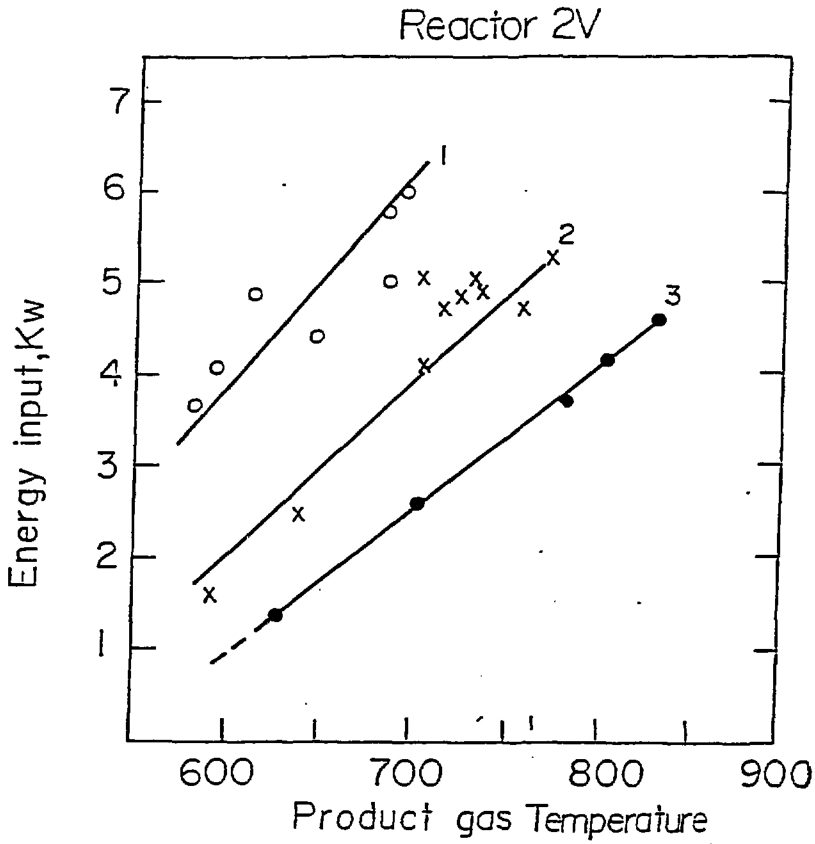


Figure 5

Reforming

Total energy input vs. product gas temperatu

1. Re = 720-800
2. Re = 370-440
3. Re = 240-270

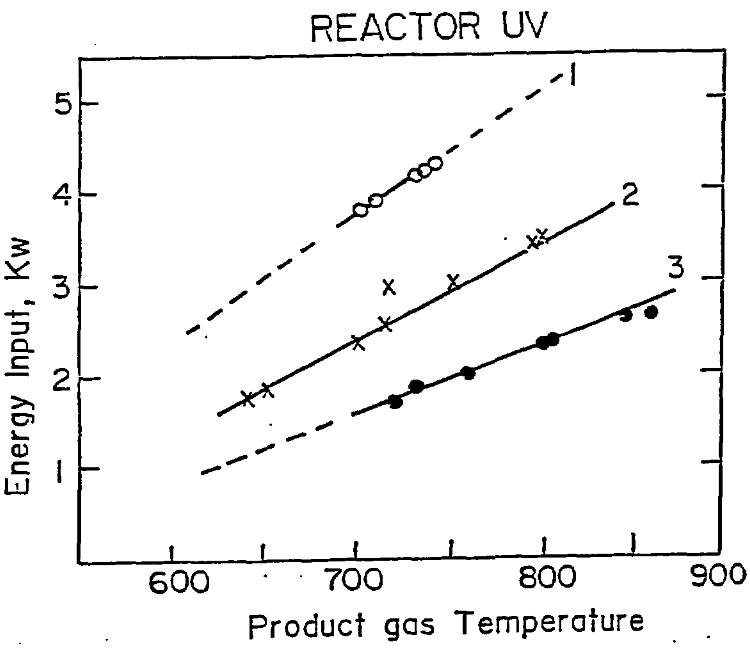


Figure 6

Reforming

Total energy input vs. product gas temperat

1. Re = 1220-1280
2. Re = 715-820
3. Re = 400-460

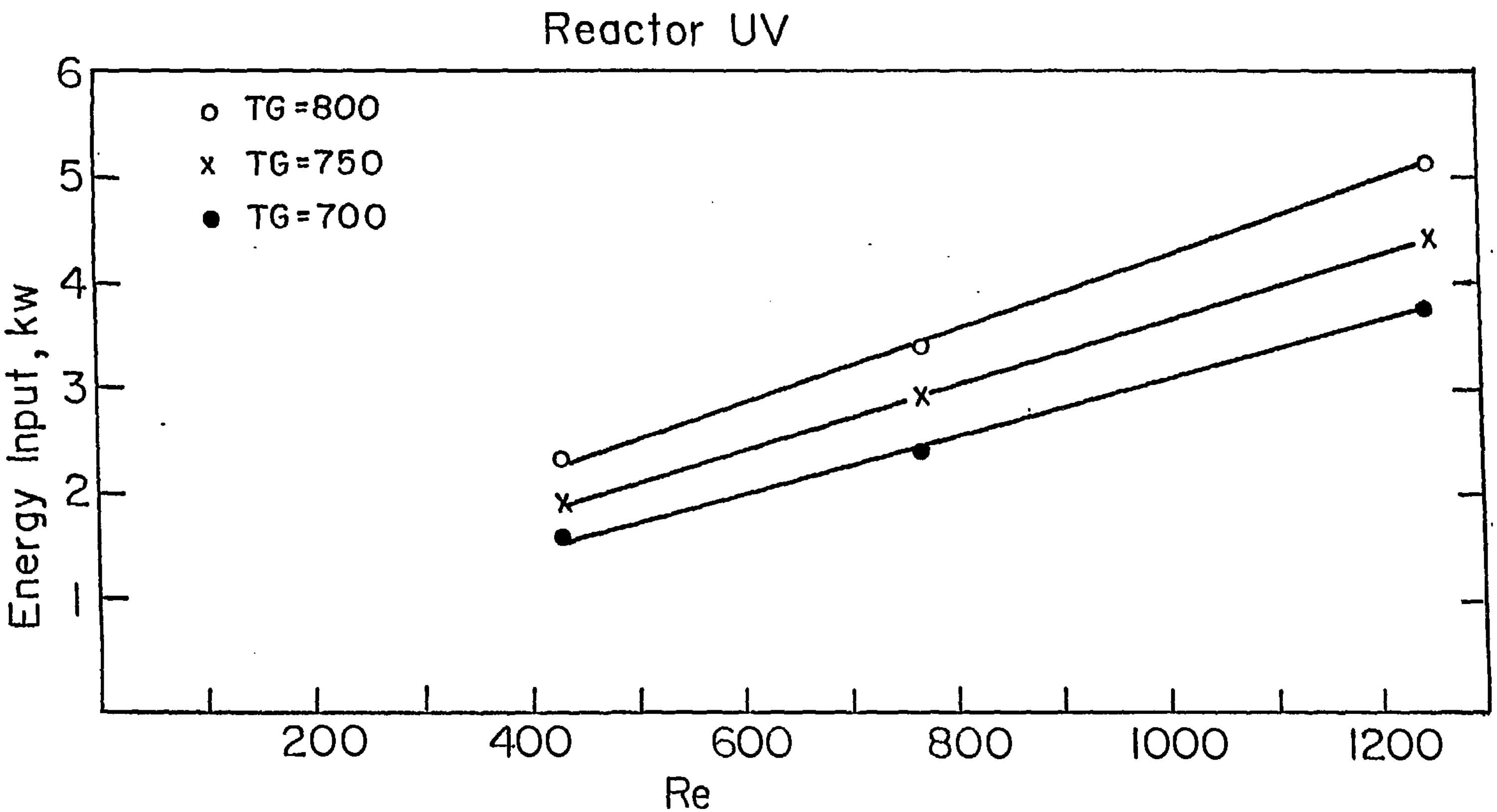


Figure 7

Reforming

Data from figure 6, showing total energy input related to Re (average of range) at three product gas temperatures

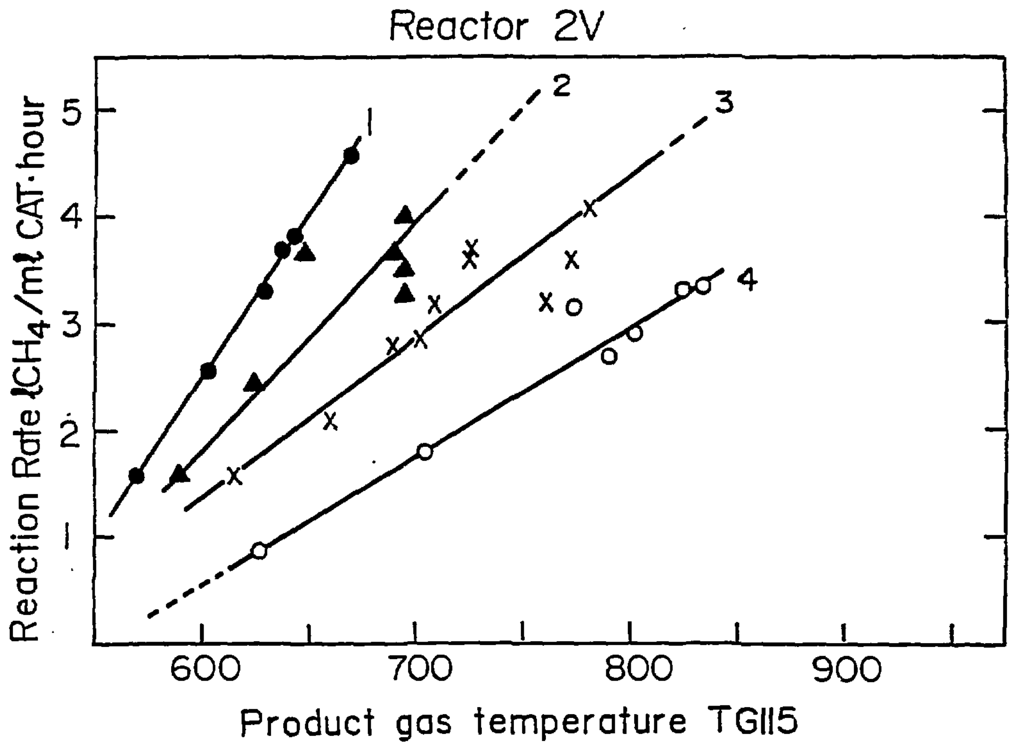


Figure 8

Reforming

Reaction rate vs. product gas temperature

1. Re = 790-865
2. Re = 500-570
3. Re = 300-380
4. Re = 200-275

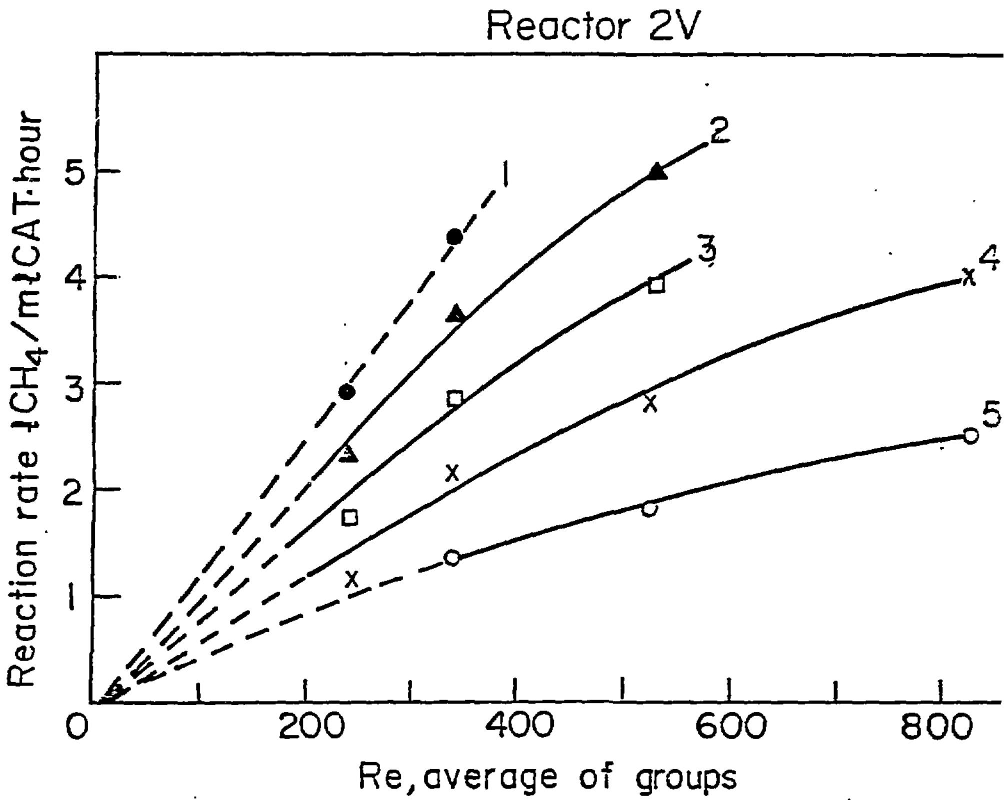


Figure 9

Reforming

Reaction rate vs. Re, at different product gas temperatures
1. 800° 2. 750° 3. 700° 4. 650° 5. 600°

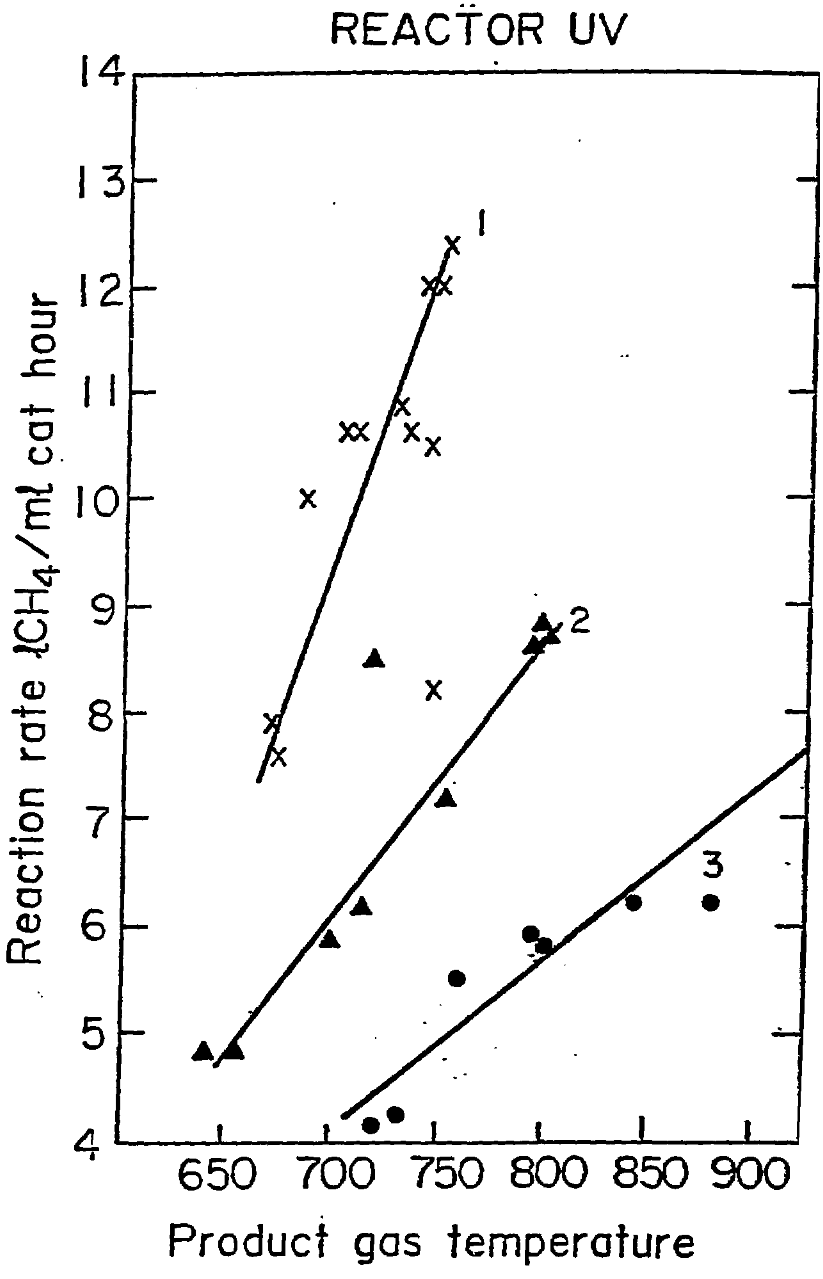


Figure 10

Reforming

Reaction rate vs. product gas temperature

1. Re = 1200-1480
2. Re = 715-800

REACTOR 2V

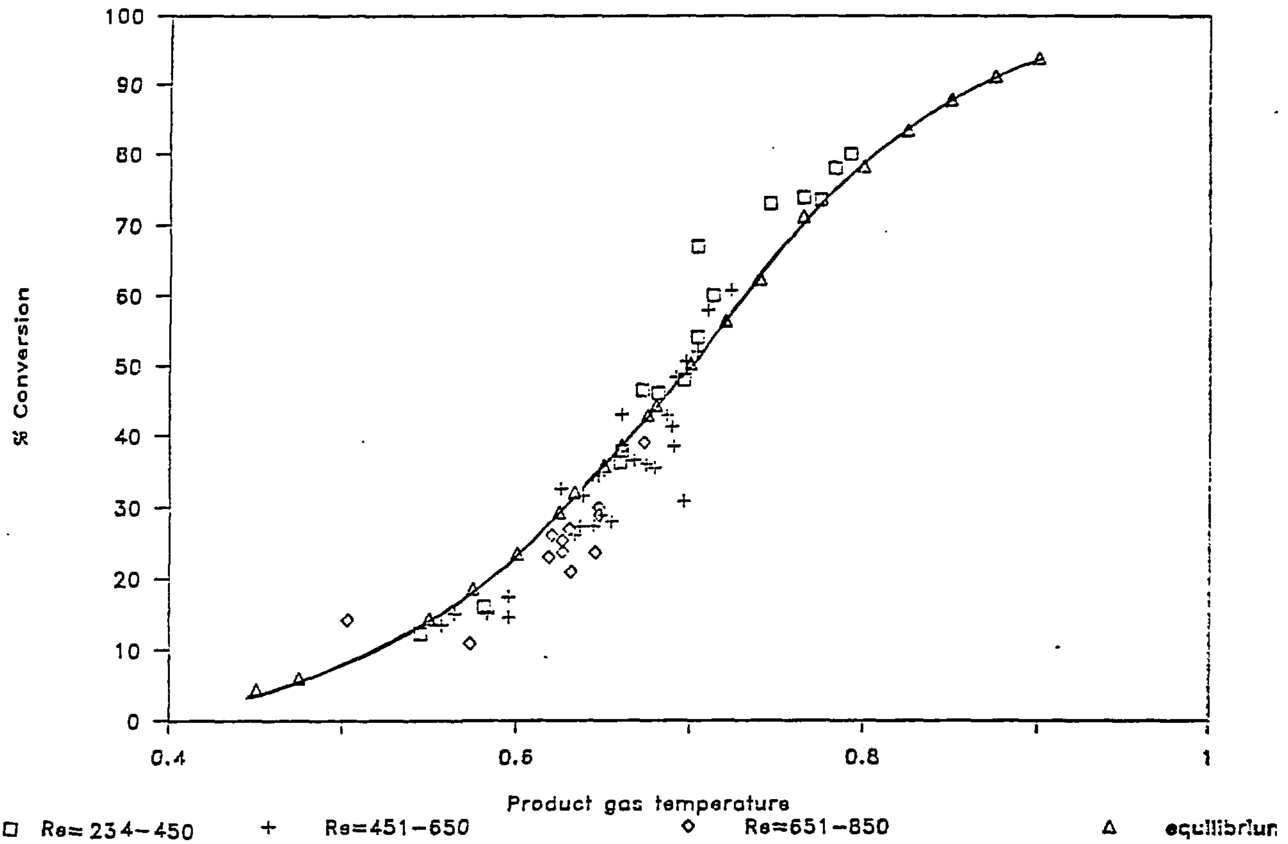


Figure 11

Reforming

Methane conversion vs. product gas temperature. The points are for 9 different runs, and the equilibrium conversion line is shown.

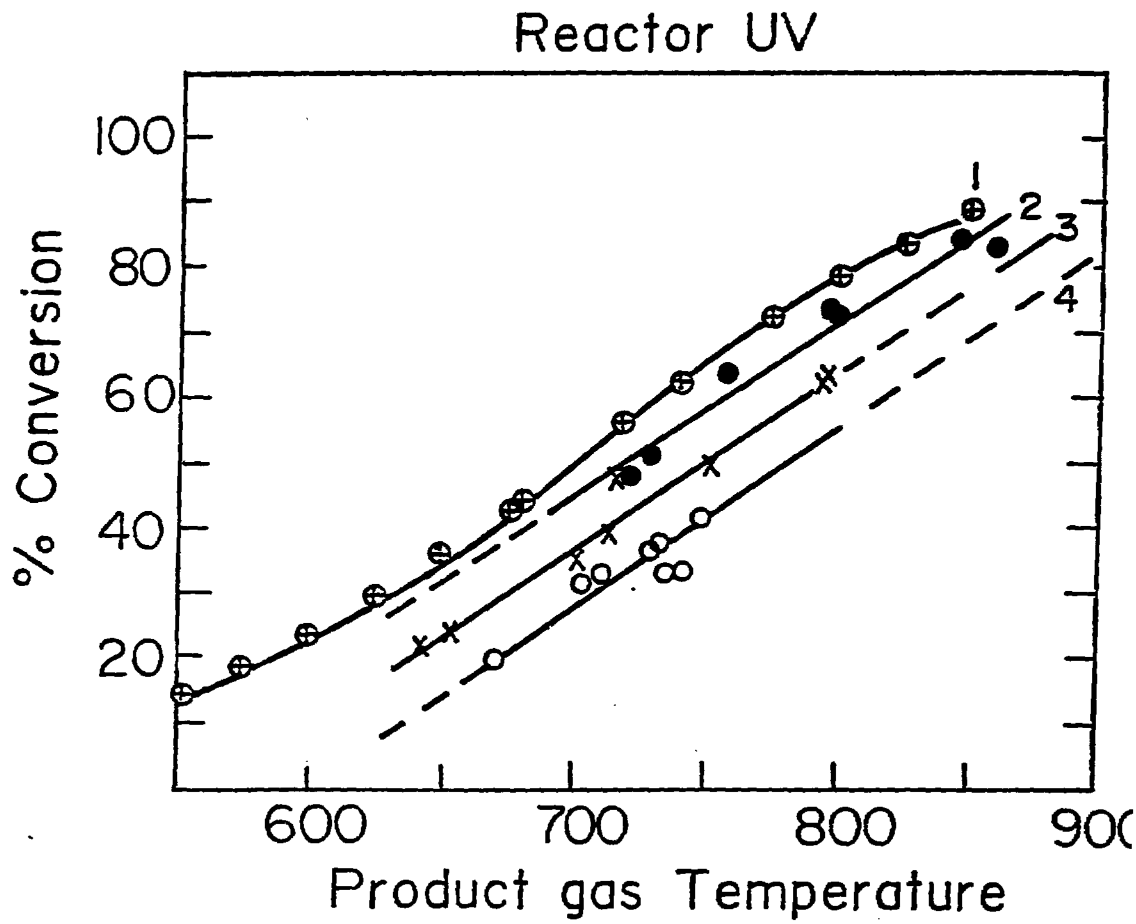


Figure 12

Reforming

Methane conversion vs. product gas temperature

1. Equilibrium conversion
2. Re = 400-460
3. Re = 715-820
4. Re = 1240-1440

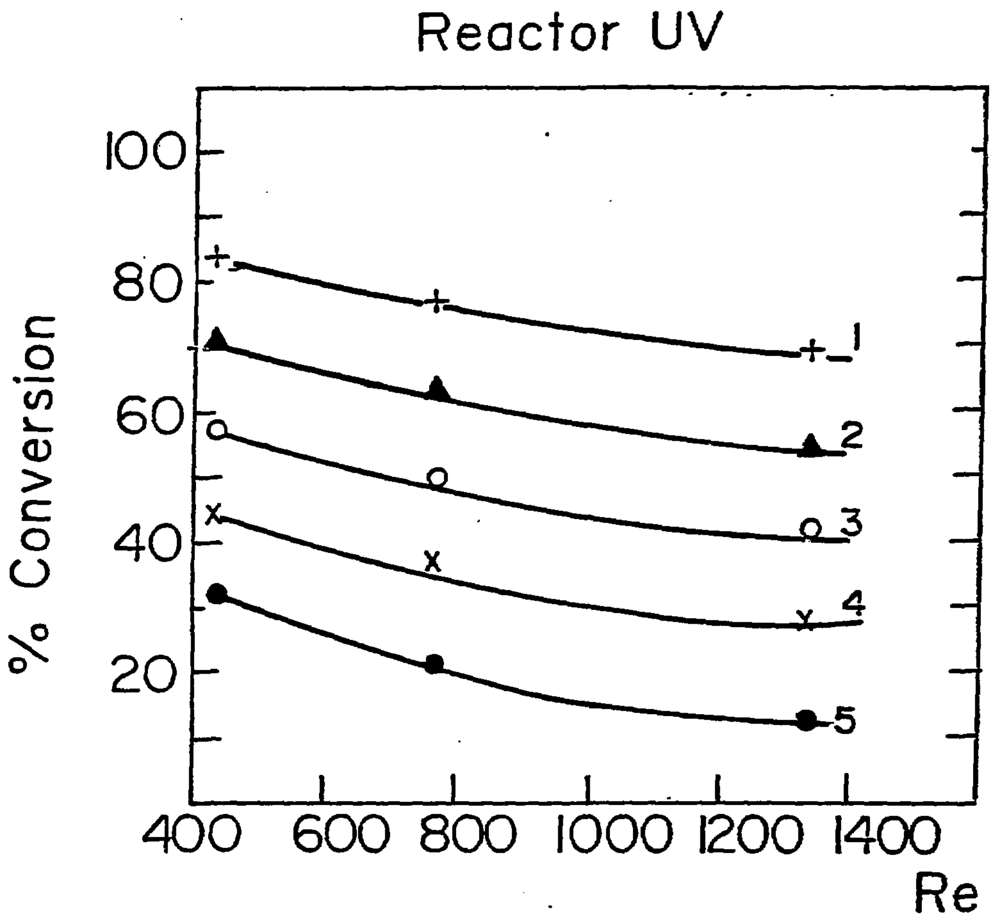


Figure 13

Reforming

Methane conversion vs. Re, at different product gas temperatures

1. 850° 2. 800° 3. 750° 4. 700° 5. 650°

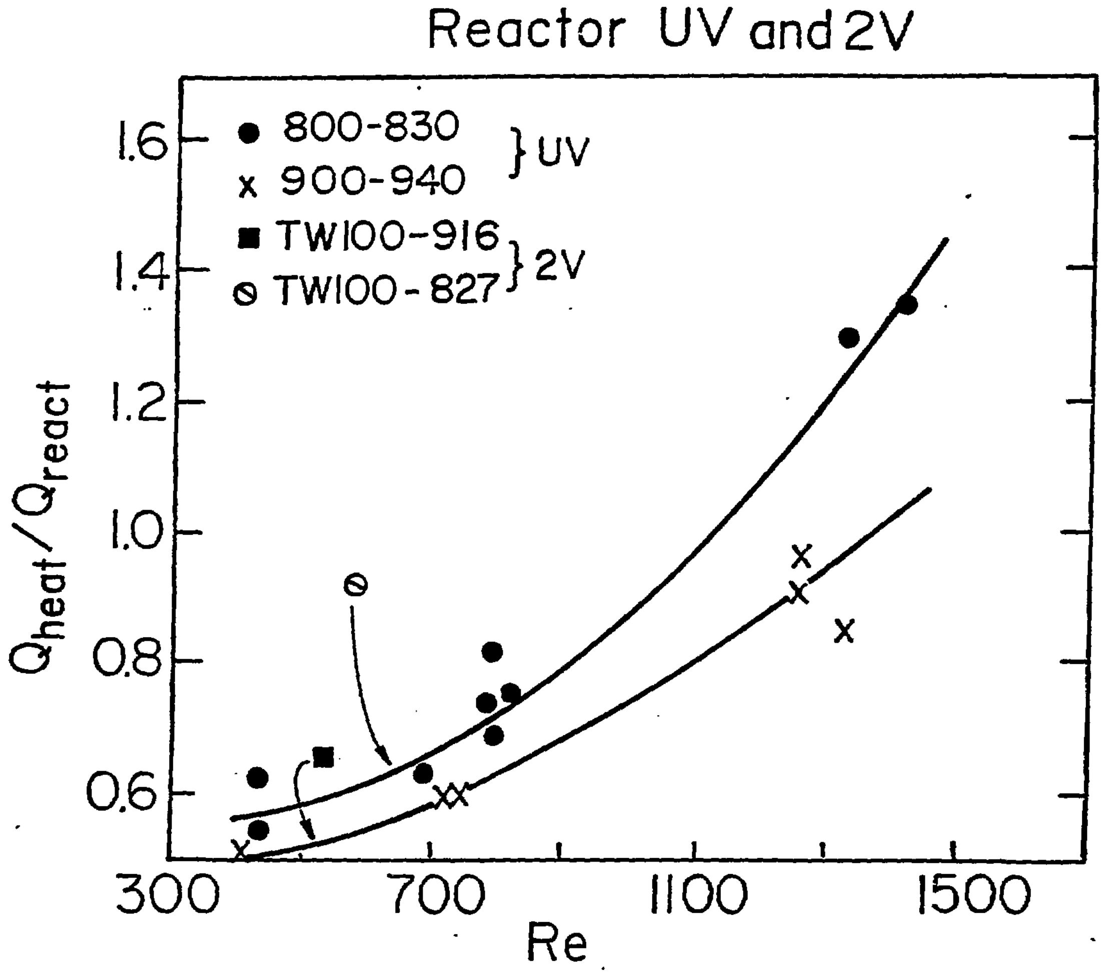


Figure 14

Reforming

Ratio of sensible heat to heat of reaction vs. Re. The 2 lines for reactor UV are for the 2 wall temperatures indicated. 2 points for reactor 2V are shown (see text).

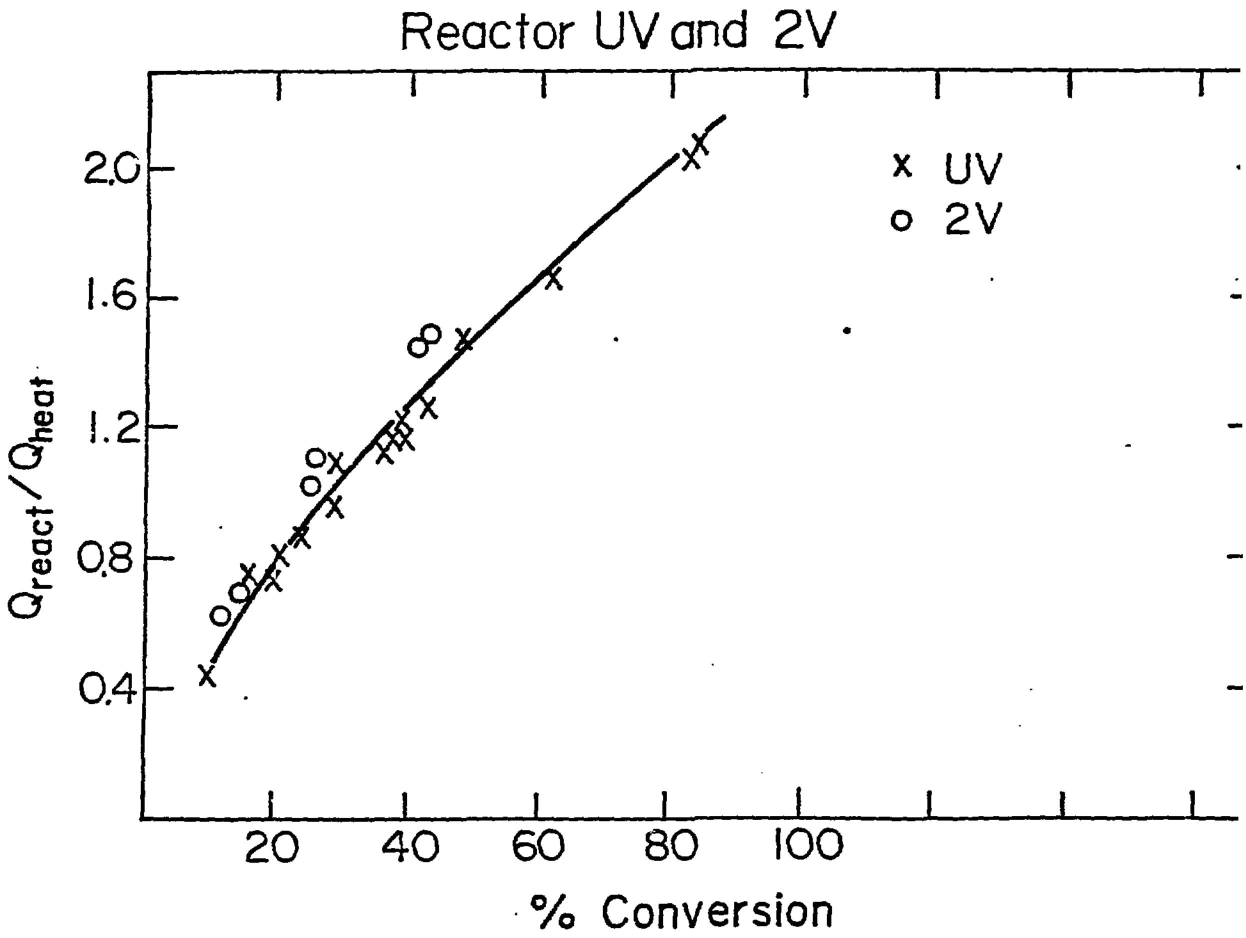


Figure 15

Reforming

Ratio of reaction enthalpy to sensible heat vs. methane conversion.
Points for 2 reactors.

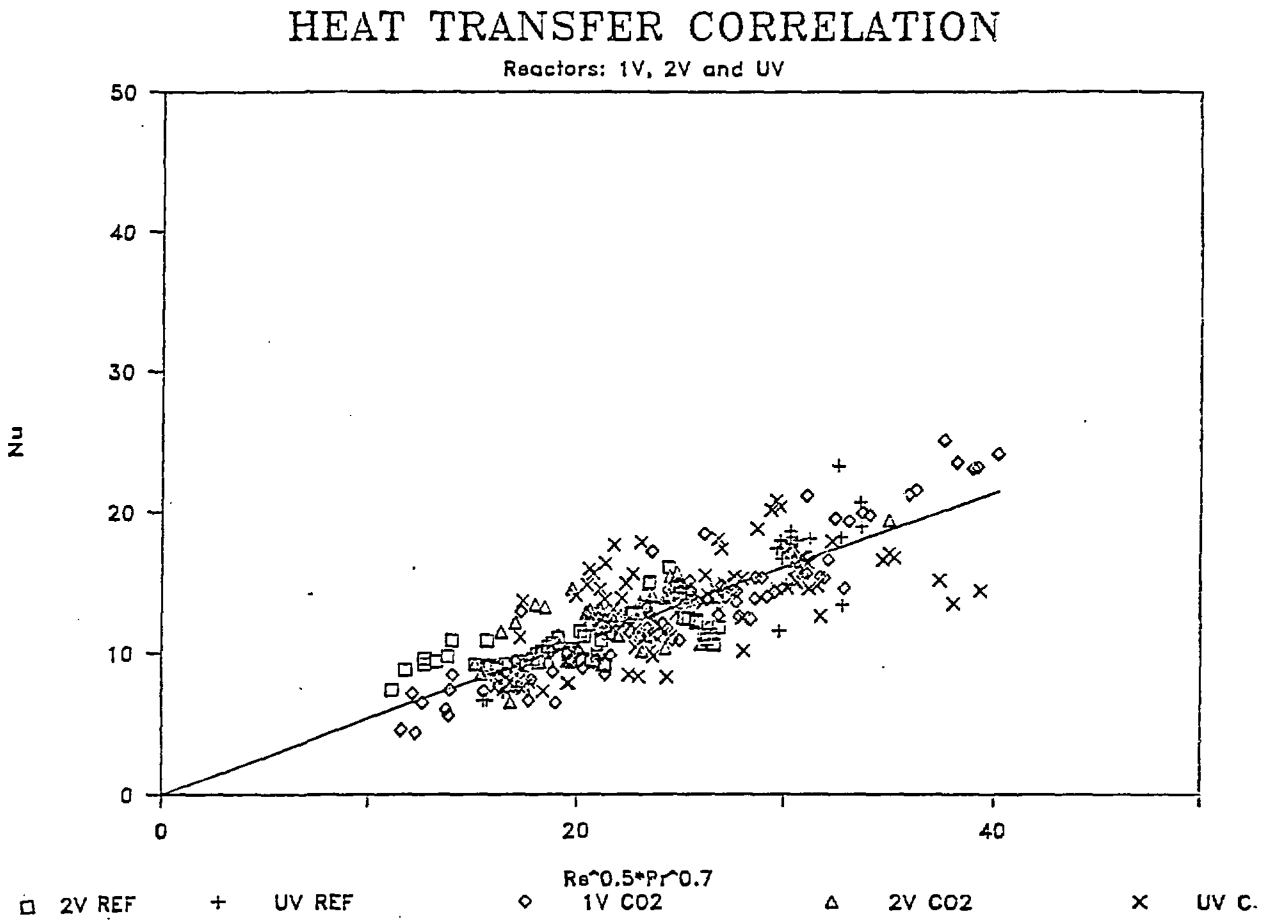


Figure 16

General heat transfer correlation, three reactors, reforming and CO_2 heating.

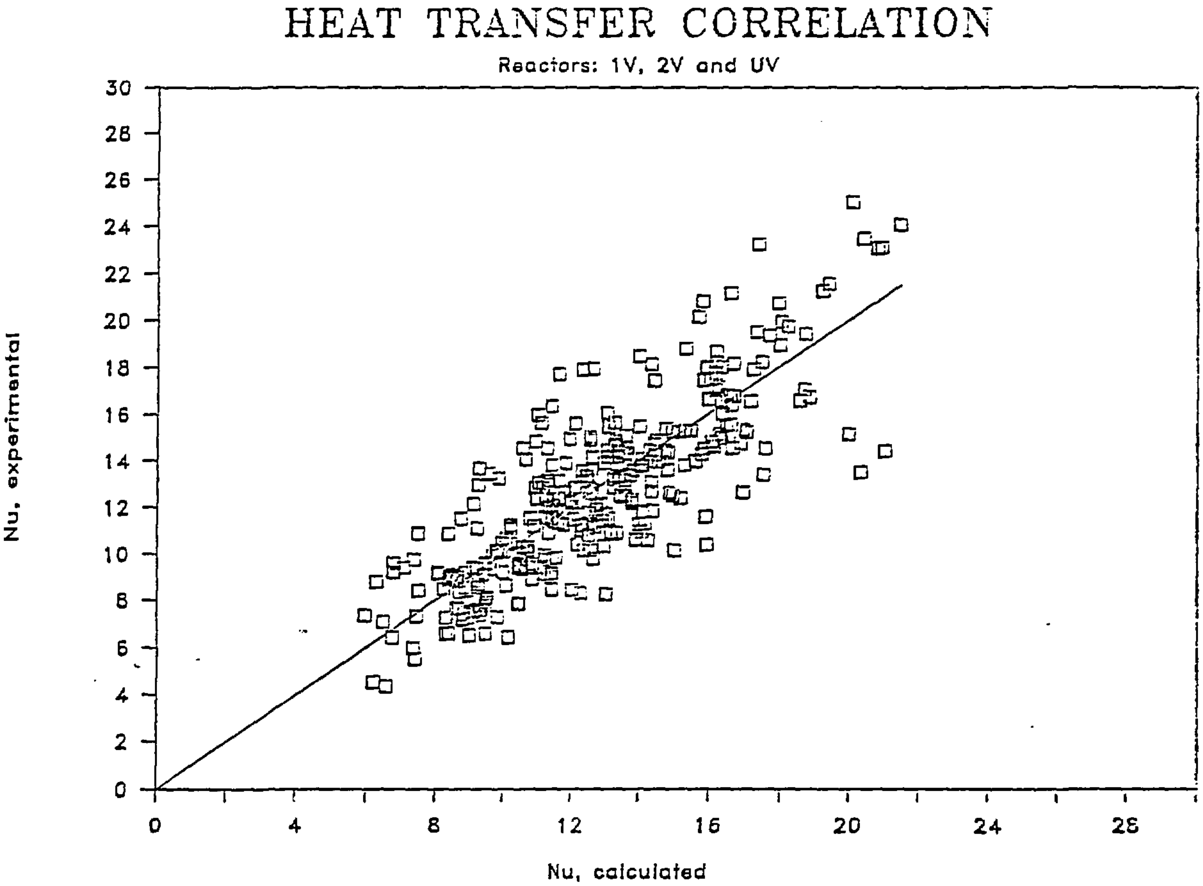


Figure 17

Nu, experimental points vs. Nu calculated from the correlation equation:
$Nu = 0.534\ Re^{0.5} \times Pr^{0.7}$.
The line "y = x" is shown.

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16. Abstract (Limit: 200 Words)

Tubular catalytic reactors were tested in a vertical receiver in the Schaeffer Solar Furnace. The reactors were used for heating CO_2 and for the endothermal reforming reaction. 3.8 KW were absorbed by the CO_2 The maximum energy absorbed by the reforming reaction was 6.9 KW, with methane conversion of 38%. Conversion of 84% was obtained with low reactant flow rates.

The heat transfer correlation for the reactors was calculated from the experimental data.

Reformer operating conditions in which the product gas can be fed directly to a methanator, were found.

The complete report is hereby submitted.

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