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by

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ABSTRACT

Trials on the burning of Syncrude coke (solid residue of Athabasca oil sands after processing at the Syncrude plant, Fort McMurray, Alberta), were performed in an atmospheric fluidized bed combustion (AFBC) pilot plant (bed area 0.155 m^2). The coke is high in sulphur, up to 7% by mass, and reduction of SO_2 emissions is therefore necessary. An Athabasca limestone was used as the SO_2 sorbent. The conditions of the trials were mean coke particle diam. 0.26 mm; mean limestone particle diam. 0.34 - 0.94 mm; fluidizing velocity 0.8 - 1.3 m/s; excess air, up to 7%; recycle ratio (fraction of cyclone catch recycled) 0 - 0.83; Ca/S mole ratio 1.7 - 2.9; bed temperature 966 - 1105°C. The high bed temperatures were needed to achieve stable burning and reasonable combustion efficiency. The combustion efficiency as measured by carbon burnup was 77 - 97%. At these temperature levels, sulphur capture was influenced most strongly by bed temperature. The capture was unexpectedly good up to 1050°C then fell sharply, practically to zero above 1100°C.

It is concluded that Syncrude coke can be burned by AFBC with acceptable combustion efficiency and sulphur capture at bed temperatures of 950-1050°C and fluidizing velocities up to 1.3 m/s. Syncrude coke is high in vanadium, 0.18% by mass, as well as in sulphur. The results indicate that the vanadium is fixed in the ash and is not selectively concentrated in any of the product streams.

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INTRODUCTION

The plant operated by Syncrude Canada Ltd. at Fort McMurray, Alberta, is Canada's largest oil sands extraction plant. The byproduct coke is high in sulphur and vanadium (Table 1). It contains a high proportion of unreactive forms of carbon and is low in volatiles. It is unsuitable for combustion by established technologies, thus the entire production of over 2000 t/d is being stockpiled.

The present work was sponsored by CANMET, Energy, Mines and Resources Canada in order to determine the conditions under which Syncrude coke might be burned by atmospheric fluidized bed combustion (AFBC). AFBC accepts solid fuels of low reactivity and provides abatement of SO_2 emissions by means of a limestone sorbent fed to the combustor with the fuel. CANMET also sponsored an earlier study (Friedrich et al. 1982) of the burning of Syncrude coke by atmospheric circulating fluidized bed combustion (ACFBC). This process employs high fluidizing velocities together with total recycling of the cyclone catch. The cyclone, large and refractory lined, is run hot. Syncrude coke consists of relatively fine particles (Fig. 1) and is subject to high elutriation rates in a fluidized bed; this problem is well handled by ACFBC. It was thus judged that ACFBC would be better than the conventional "bubbling bed" AFBC for such a fuel. Encouraging results were indeed obtained. However, since an AFBC pilot plant supported by CANMET was available for trials at Queen's University, it was thought worthwhile to give AFBC a test rather than dismiss it out of hand. The objectives set were to determine:

1. suitable ranges of bed temperature and fluidizing velocity,
2. sulphur capture using a limestone sorbent from the Fort McMurray region,
3. combustion efficiency as indicated by carbon burnup,
4. the fate of the vanadium present in the coke,
5. the conversion of fuel nitrogen to NO_x.

MATERIALS

The coke and limestone analyses are summarized in Tables 1 and 2. The coke particle size distribution was fixed as received (Fig. 1). The limestone was crushed and screened into the size distributions shown in Fig. 2.

PILOT PLANT

The pilot plant, schematically illustrated in Fig. 3, is described in detail elsewhere (Becker and Code 1982). The combustion chamber is square in cross-section, 0.155 m^2 in area. The walls are refractory lined. The height from air distributor to top of freeboard is 4 m. Up to 48 in-bed cooling tubes can be inserted to absorb heat from the bed. There is also some cooling capacity in the refractory lined but water cooled wall sections through which the cooling tubes are inserted. Elutriated fines are largely caught by a cyclone separator, and most of the rest is captured in a baghouse. An adjustable fraction of the cyclone catch can be recycled.

OPERATING CONDITIONS

Coke and limestone were injected together through the side of the combustor near the bottom of the bed by means of a screw conveyer. Bed level was controlled by an overflow port 1.2 m above the distributor through which "bed product" was drained.

The trials involved bed temperatures up to 1100°C, and in 500 h operating time produced substantial deterioration in the refractory walls of the combustor around the bed. Some runs were aborted because of problems encountered in operating at such extreme conditions. Eight successful runs, each of about 50 h time on stream from start of continuous removal of bed product, were completed in which Fort McMurray (Athabasca) limestone was used as sulphur sorbent. In addition, one run was performed in which Havelock limestone (Havelock, N.S.) was used to obtain a comparison of the Fort McMurray stone with one that we have well characterized in other work. The operating conditions of these nine runs are summarized in Table 3.

It was found that fluidizing velocities above 1.3 m/s could not be usefully employed. Because of the small particle size of the fuel, elutriation became excessive, combustion efficiency became very poor, and it was difficult to maintain the required high bed temperature.

Control over operating conditions was limited because our combustor, because of its design, had too much bed-cooling capacity. Bed cooling in this combustor occurs by two means:

- in-bed tubes, fed with cooling water. The number of these is variable between zero and 48 and in the Syncrude trials was either zero or one.
- water-cooled, refractory-lined wall containing an array of ports for the insertion and mounting of the aforesaid tubes. The heat loss to this wall cannot be significantly controlled and is virtually fixed. This represents a substantial base cooling load which becomes a limiting factor when low fluidizing velocities are employed. At a given level of excess air, the burning rate is (but for variation in completeness of combustion) virtually proportional to the fluidizing velocity. Reduction in fluidizing velocity then leads to a point at which no in-bed tubes are employed and beyond which bed temperature cannot be maintained.

The Syncrude trials were perforce conducted around the feasible limit of operation in the reduction of fluidizing velocity. In order to attain the required high bed temperatures, compromises had to be made. The major sacrifice here was in the control over the excess air level which could not be maintained constant and in most runs was actually negative (Table 3). It should be noted, though, that because of incomplete combustion, a significant oxygen level in the exhaust gases was nevertheless observed in all runs (Fig. 4). A further ameliorating factor is that the effect of excess air as established in previous trials on coal combustion (Becker and Code 1983) is mild, and there is no reason to suspect that it should be otherwise in the burning of the Syncrude coke. The most important variable here by far is the bed temperature, and this we were able to adequately vary.

CARBON BALANCE

Carbon Content of Solids

Figure 5 shows the carbon content of the solid products from bed, cyclone and baghouse. As in coal combustion, unburnt char is concentrated in the fines, is strongly elutriated, and is thus found in significant quantities in cyclone and baghouse products. Also, the level in the cyclone product is usually significantly higher than in the baghouse product.

Flux Distribution

Figure 6 shows as a function of bed temperature the flux ratio of carbon carried by a given solids stream to the total carbon loss. The cyclone product was the major carrier, by far.

The same results are shown as a function of the recycle fraction in Fig. 7. A high level of correlation is apparent. At high recycle, the proportion of carbon carried by the bed product is increased and that carried by the cyclone product is decreased. Recycle brings char back into the bed and, by effectively increasing char residence time in the bed, provides a greater chance for convective removal with the bed product.

Combustion Efficiency

Combustion efficiency is effectively measured by the completeness of combustion of carbon. Figure 8 shows this measure as a function of bed temperature. It is evident that recycle of cyclone catch was an influential factor. The recycle fraction was either zero or fairly high ($r = 0$ or $r = 0.69$--0.83) (Table 3). In the runs with recycle, 93-97% of the carbon was burned. With no recycle, this percentage fell to as low as 77. Most of the carbon loss was in the overhead (cyclone and baghouse) products. In our earlier work (Becker and Code 1983) on Minto (New Brunswick) and Devco (Nova Scotia) coals an empirical correlation of the total overhead carbon loss with the operating variables was developed:

$$\dot{m}_{C,o}/\dot{m}_{C,f} = C_o\, v^{0.86}\, \hat{D}_p^{-0.74}\, \phi_a^{-0.5} \cdot \exp(-0.36\, r)\, \exp(5200/T_b), \quad (1)$$

where $C_o = 0.000335\ (\mathrm{m/s})^{-0.86}\mathrm{mm}^{0.74}$ (fluidizing velocity v in m/s, limestone particle dia. $\hat{D}_p$ in mm). It would be interesting to see whether this correlation, or one like it, holds for the Syncrude coke as well.

Values of C_0 in Eq. (1) are shown as a function of bed temperature in Fig. 9. Except for two runs, the results show no more deviation from $C_0 = 0.000335$ than our original data (Becker and Code 1983) on the Minto and Devco coals. This close similarity is surprising, and in work currently in progress we are attempting to discover the reasons for it.

Figure 9 also shows values of C_0 calculated from the new results on Evans (Nova Scotia), Devco and TVA (Kentucky) coals (Becker et al. 1985). The new Devco results agree with the previous work, as expected. The data on the TVA coal also show insignificant deviation from $C_0 = 0.000335\ (\mathrm{m/s})^{0.86}\ \mathrm{mm}^{-0.74}$. The data on the Evans coal, however, are consistently low. In the cited report (Sect. 5.2.5) it is shown that these data are best fitted by somewhat different exponents in Eq. 1.

Our results on the Syncrude coke are not statistically sufficient to test a complete refitting of Eq. 1. However, statistical examination suggests, in agreement with the trends in Fig. 8, that recycle and bed temperature are the strongest influences and the effects of the others, for our range of conditions, are insignificant. The resulting simplified correlation, retaining only the strong factors, is:

$$\dot{m}_{C,o}/\dot{m}_{C,f} = 0.00041 \exp(-1.79r) \exp(7600/T_b) \qquad (2)$$

This shows considerably greater effects of bed temperature and recycle than indicated by our earlier correlation for coal combustion (Eq. 1). The difference appears to be in the expected direction; if Syncrude coke is less reactive than the coal chars, then kinetics should influence the burning rate more and heat and mass transfer processes should influence it less, thereby producing a greater temperature effect and a greater sensitivity to residence time (residence time being increased by recycle).

SULPHUR BALANCE

Sulphur Content of Solids

Figure 10 presents the data on sulphur content of the solids in an interesting and apparently meaningful way: the content in the cyclone and baghouse solids is shown as a function of that in the bed product, all on a carbon-free basis (CFB). High correlation is indicated for given limestone of given particle size. Decreasing limestone particle size seems to enrich the cyclone product in sulphur. Both overhead products are richer in sulphur for the Havelock limestone than for the Fort McMurray stone. In all runs except one, the CFB sulphur content of the overhead products is less than that of the bed product. The exceptional run was at the highest bed temperature, 1105°C; there the sulphur content of the bed product was only 0.7% whereas for the overhead products it was about 2%. It appears that this capture in the overhead product may have largely occurred in the exhaust gas train, in the first heat exchanger as the gases passed through the favourable temperature range for SO_2/CaO reaction.

The possible influence of bed temperature is further demonstrated in Fig. 11 which shows the ratio of CFB sulphur content in the overhead products to that in the bed product vs. the bed temperature.

Flux Distribution

Like that of the carbon (Fig. 7) the sulphur flux distribution is highly correlated with the recycle fraction (Fig. 12). The trends are also similar; increasing recycle seems to increase the proportion of sulphur carried by the bed product and decreases that carried by the cyclone product. The explanation again lies in the increased residence time of particles in the bed, providing greater opportunity for removal in the bed product.

Sulphur Capture

In coal combustion in the usual temperature range, 800-900°C, the effect of temperature on sulphur capture is relatively flat and the Ca/S ratio is the most influential parameter for a given limestone of given particle size. Here we designed our experiments so as to be sure to clearly determine the effect of the much higher temperatures. The Ca/S ratio, on the other hand, was only moderately varied (Table 3) just enough so we would be sure to get results in the practical range. This produced the best design that we could execute within our limitations of time and materials.

Figure 13 shows the results in a graph of percentage of sulphur captured vs. bed temperature. In the direction of decreasing temperature, the results are consistent with optimum capture in the usual range, about 850°C. With increasing temperature, the capture decreases but remains good up to about 1050°C. It then drops very rapidly, to practically nothing beyond 1100°C. Limestone particles of 0.34 mm diam. gave somewhat better performance than those of 0.94 mm diam.

NITROGEN BALANCE AND NO_x

Figure 14 shows the exhaust gas NO_x concentration as a function of the exhaust O_2 concentration. Considerable correlation is evident and the results agree with the general observation that NO_x emission is minimized by keeping the exhaust oxygen level low. Limestone characteristics seem to have some effect in that the result from the run with Havelock limestone is significantly higher than the results from runs with the Fort McMurray stone.

The conversion of fuel nitrogen to NO_x (Fig. 15) was very similar to that observed with coal, generally under 25%. No particular correlation of conversion with temperature is evident. There is some indication, though, that free-board char concentration may be influential; the conversion seems to decrease with increasing flux of elutriated carbon.

CARBON MONOXIDE

Carbon monoxide levels in the exhaust gas (Fig. 16) were in the range 0.018-0.028 mole % in all runs except one at the highest temperature, 1105°C, and the lowest exit O_2 level, 0.2 mole %. The O_2 level in the other runs was as low as 0.6 mole % with no apparent effect on the CO concentration.

VANADIUM

Syncrude coke is high in vanadium. The ignited ash, according to the analysis given in Table 1, contained 3.8% V_2O_5. The sample analyzed was taken from the same shipment that provided our lot. This sample also contained 1.5% NiO (Table 1). The resulting mass ratio of V/Ni is 1.81.

At the last moment in processing our data an analysis was received from the Energy Research Laboratories, CANMET, of samples submitted by us of coke and limestone from the lots used in our work. The results for the ash of the coke are somewhat different from those quoted above from Table 1: 4.7% V_2O_5 and 1.23% NiO, giving V/Ni = 2.76 by mass. Table 1 shows our value of the ash content of our lot of coke, 6.9%. The vanadium content of the coke given by these data is 0.182%, and the nickel content is 0.066%. The results for the ash of the limestone are 0.03% V_2O_5 and 0.00% NiO. The ash content we found for our lot of stone is 63.5% (Table 1). The vanadium content of the stone is accordingly 0.011%.

In order to determine the fate of the vanadium from the coke, the solid products from some of the Syncrude coke trial samples were resolved into sieve fractions. There appears to be a definite trend towards vanadium enrichment in the smaller particles. The effect, however, is not large, and it could be accounted for by shifts in the limestone/coke ratio in the origins of the particles making up the various product streams.

FUEL-ASH FLUX DISTRIBUTION

Assuming, as in the preceding section, that nickel is a marker for the fuel ash the flux distribution of the nickel is taken as the measure of the flux distribution of fuel ash. Figure 18 shows the flux fraction of the ash (measured by the Ni) carried by each product stream as a function of the flux fraction of total solid products carried by that stream. As expected, the overhead streams (cyclone and baghouse) tend to be enriched in ash whereas the bed product is lean.

COMPARISON WITH AHLSTROM TRIALS ON SYNCRUDE COKE

System and Test Conditions

Friedrich et al. described trials on Syncrude coke using the Ahlstrom atmospheric circulating fluidized bed combustion (ACFBC) system (Friedrich et al. 1982). This system features high fluidizing velocities and correspondingly high elutriation which is dealt with by recycling all of the cyclone catch (hence the adjective "circulating"). The solid product streams consist of the bed product and the material escaping the cyclone (principally baghouse product when a baghouse is used). The refractory-lined cyclone is run hot, and the resulting additional capacity for combustion could lead to significantly higher combustion efficiency than in our "conventional" AFBC system.

The Gotland (Swedish) limestone used in the Ahlstrom trials was 0.08 mm mass-median diam. The range of fluidizing velocities was 2.4 to 5.5 m/s, and that of the bed temperature was 818 to 948°C. Eight runs were made in total, with 7-10 h of "stable operation" in each. The bed "inventory" (bed mass m_b) was not determined, so it is not possible to judge how closely steady state was approached. Problems in accurately determining the solid product fluxes were also reported. These factors leave considerable uncertainty in the calculated carbon losses.

Carbon Loss

Figure 19 shows the fractional overhead carbon loss as a function of bed temperature for the Ahlstrom trials and ours. The curves represent our correlating Eq. 2 with recycle fractions r (fraction of cyclone catch recycled) of 0, 0.77 (average for our runs with recycle), and 1 (the value in all the Ahlstrom trials). It appears that:

[ ] carbon loss in the Ahlstrom ACFBC process was typically about half that in our AFBC at the same temperature (the Ahlstrom results fall that far below the curve r = 1). Differences of this magnitude may be explained by the further reaction occurring in the hot cyclone in the Ahlstrom process.

[ ] recycling of 75% of the baghouse catch in the Ahlstrom trials gave insignificant reduction in carbon loss.

[ ] the carbon loss in the single Ahlstrom trial where an inert (sand) bed was used was insignificantly different from the losses found for beds established from limestone.

These observations must be regarded with due caution, for we do not know how valid such comparisons are in view of the substantial differences in fluidizing velocity, average bed particle diameter, bed and freeboard dimensions, etc.

Figure 20 shows the fractional carbon loss in the bed product for the two sets of trials. This loss is much smaller than the overhead carbon loss (Fig. 19) and behaves relatively erratically; here multiple regression analysis of our data failed to indicate any significant correlation with the operating parameters. Our data do seem to suggest, though, that recycle of cyclone catch, if anything, increases the bed-product carbon loss. The Ahlstrom results indicate that this also happens when baghouse catch is recycled.

Figure 21 shows the total fractional carbon loss (for the present work, the same data as in Fig. 8). Comparison of Fig. 19 and 21 shows, as already noted, that the bed-product carbon loss makes little difference to the overall result.

Sulphur Capture

Gotland (Swedish) limestone, with 94% $CaCO_3$ and of small particle size, $\hat{D}_p$ = 0.08 mm, was used for SO_2 capture in the Ahlstrom trials. The capture was 89.7 to 93.7%. No effect of bed temperature was evident over the operating range, 818 to 948°C. This result, interestingly, supports our observation of little drop in sulphur capture until bed temperature reaches considerably higher levels (above 1050°C, Fig. 13).

Conversion of Fuel N to NO_x

In the seven Ahlstrom trials in which limestone was fed and formed the basis of the bed material, the conversion of fuel nitrogen to NO_x in five was 11.4 to 18.6%. These results were similar to ours (Fig. 15). In the two other trials it was inexplicably significantly higher, 33.1% and 44.6%. In the one run in which no limestone was fed and a sand bed was used, the conversion was 74.1%.

COMPARISON WITH THE ERL TRIALS ON SUNCOR COKE

Background

The Suncor oil sands extraction plant at Fort McMurray, Alberta is located near the Syncrude plant and processes a similar raw material, but by a somewhat different technology. Burning of the byproduct coke by AFBC has been investigated at the Energy Research Laboratories of CANMET (Anthony et al. 1982), using a relatively small cylindrical pilot plant combustor. The combustion chamber was 24 cm ID by 1.2 m high at the bottom, surmounted by a 1.73 m high freeboard extension increasing in diameter through a conical transition piece to 50 cm ID. In all but one run, the bed was of sand, $\hat{D}_p$ = 1.5 mm. The unexpanded bed depth was 40 cm. The Suncor coke was screened to -6 mm (particle size distribution not reported). The bed was operated in semi-continuous fashion, with no feed of sand and no withdrawal of bed product. The sole solid product stream thus consisted of elutriated material caught in the cyclone, none of which was recycled. The fluidizing velocity was 1.07 to 3.55 m/s and the bed temperature 754 to 954°C. In one run Havelock (Nova Scotia) limestone, screened to -6 mm, was fed with the coke at Ca/S = 3; the limestone residue accumulated in the sand bed and the bed depth increased by 20% during the run because of this.

Carbon Loss

The carbon loss, all overhead, was 1.4 to 22.6% of the fuel carbon. Significant correlation was found only with fluidizing velocity and bed temperature. Multiple linear regression analysis on these variables gave (v in m/s)

$$\dot{m}_{C,o}/\dot{m}_{C,f} = 0.026\ v^{1.2} \exp\ (8500/T_b) \qquad (3)$$

(multiple correlation coefficient 0.73). This is quite similar to our result for coal (Eq. 1). In Eq. 1, set r = 0, $\hat{D}_p$ = 1.5 mm, and o_a = 1, giving

$$\dot{m}_{C,o}/\dot{m}_{C,f} = 0.00024\ v^{0.86} \exp\ (5200/T_b) \quad (v \text{ in m/s}). \qquad (4)$$

Figure 22 shows the fractional carbon loss predicted by this equation as a function of that measured by Anthony et al. in their Suncor coke trials.

With the exception of a single outlier, there is a strong correlation,

$$y(\text{measured}) = 3.3[y(\text{predicted}) - 0.01], \qquad (5)$$

$y \equiv \dot{m}_{C,o}/\dot{m}_{C,f}$. Since our data on burning of Syncrude coke by AFBC agree rather closely (Fig. 9) with the overhead carbon loss predicted by Eq. 1, it appears from Eq. 5 that the losses in burning Suncor coke by AFBC are about three times those for Syncrude coke. If this is a generally valid conclusion, then the difference in combustion characteristics between the cokes is substantial. However, because of certain differences in operating conditions between the two investigations (particularly in the freeboard geometrics), this conclusion must be regarded as tentative.

What is relatively certain is that our correlation (Eq. 2) for Syncrude coke and that of Anthony et al. (Eq. 3), for Suncor are in agreement as to the temperature effect in the burning of Athabasca oil sands cokes, for the difference in the temperature factors, e^{7600/T_b} and e^{8500/T_b}, is statistically insignificant.

Sulphur Capture

The single result reported in the Suncor trials, 80% sulphur capture by Havelock limestone at T_b = 850°C, Ca/S = 3, and otherwise rather unusual operating conditions, is not significantly out of line with our results on Syncrude coke (Fig. 13).

Conversion of Fuel Nitrogen to NO_x

The NO_x emissions were measured in just half of the Suncor trials. The fractional conversion of fuel nitrogen to NO_x was very low in most of these; about 0.009 at 760°C bed temperature and 0.03 at 857°C. At 955°C it was 0.007 at a fluidizing velocity of 1.88 m/s, but 0.22 at 1.25 m/s. The last figure pertains directly to the range of operating conditions of our Syncrude trials and is in the range of our data (Fig. 15). It appears, though, that freeboard conditions in the Suncor trials were likely significantly different from ours, particularly in char concentration and gas residence time. These factors could considerably affect the exhaust levels of NO_x, so a high degree of agreement is not expected.

OTHER STUDIES OF COKE COMBUSTION BY FBC

Battelle Data on Petroleum Coke

The Battelle multisolid fluidized bed combustion process (MFBCP) is a form of ACFBC in which secondary air is employed and the initial combustion zone is fuel rich. Nack et al. (1977) report results on combustion of a petroleum coke which show that prolonging the residence time in the fuel-rich zone strongly reduces NO_x emissions by allowing more reaction between NO_x and char or CO. This is an important observation and points to a significant advantage of staged combustion. Kim et al. (1979) report similar results in the first commercial realization of the process.

Leeds Work on NO_x Emissions from AFBC Combustion of Solid Fuels

Hampartsoumian and Gibbs (1984) studied combustion of a variety of fuels ranging from peat through the various grades of coal, to coke (from coal). Most of the trends they report are similar to those noted here, such as decrease in NO_x emission with decreasing exhaust O_2 level. One interesting observation of theirs, however, is not substantiated by our work. They detected a negative correlation between fuel volatiles content and the conversion of fuel nitrogen to NO_x, coke yielding the highest NO_x levels and peat the lowest. The data presented in support of this finding are for 1000°C bed temperature and 50% excess air. The results on oil sands cokes considered herein, however, show no more NO_x production than in our coal trials, despite a great difference in volatile content; excess air levels in all these trials were generally low, so possibly the effect of volatiles content, if one indeed exists, is evident only at high excess air levels.

CONCLUSIONS

The present work demonstrates that Syncrude coke can be satisfactorily burned by AFBC between 950-1050°C. Sulphur capture by Athabasca limestone and, it appears, by at least some other limestones as well, is strongly reduced by increasing temperature only at levels above 1050°C. Excessive elutriation of the fuel may be a problem at fluidizing velocities above 1.5 m/s. This can be avoided by using ACFBC instead. Use of ACFBC may have further advantages in that combustion can more effectively be staged, if so desired, to further reduce NOx emissions.

NOTATION

Subscripts (codes for material streams)

a	combustion air
b	bed product (material removed directly from the bed, here by gravity overflow)
c	cyclone product (cyclone catch not recycled)
d	cycloned solids (dust catch in cyclone)
e	elutriated solids (dust or "flyash" leaving combustor; cycloned solids d plus baghouse product h)
f	fuel (here coke)
g	stack gas
h	baghouse product (solids)
i	component i (compound or element)
m	the m'th material stream
n	the n'th material stream
o	overhead product solids (cyclone c and baghouse b combined)
p	total product solids (bed b, cyclone c, and baghouse h combined)
r	recycled cycloned solids
s	sorbent (here limestone)

Variables:

C_0	proportionality constant (various units; see definitions in context)
COT	continuous-mode operation time (measured from beginning of fully continous operation, marked by starting of continuous withdrawal of bed product), s
D_p	particle diameter, m. Here determined by sieve analysis
$\hat{D}_p$	characteristic diameter for particles of mixed size, m: defined by $D_p = \hat{D}_p$ at $F_D = \frac{1}{2}$
F_D	distribution function, $F_D = F_D(D_p)$, of particle size in a population: the mass fraction of particles smaller than the argument value of D_p; the "mass fraction undersize". Here determined by sieve analysis
m	mass of material, kg
m_b	bed mass (holdup), kg
$\dot{m}$	mass flux, kg/s
$\dot{m}_m$	mass flux of the m'th material stream, kg/s. See list of subscripts at head of this table for specific codes
$\dot{m}_{i,m}$	mass flux of component i (compound or element) carried by the m'th material stream, kg/s. Some specific components: CO, SO_2, Ca, C, N, Ni, S, V
n	molar mass of material, kmol
$\dot{n}$	molar flux of material, kmol/s

$\dot{n}\theta$	molar flux of the m'th material stream, kmol/s
$\dot{n}_{i,m}$	molar flux of molecular species i carried by the m'th material stream, kmol/s
$n\upsilon$	number of in-bed tubes
r	= $\dot{m}_r/\dot{m}_d$, recycle fraction: fraction of cyclone catch that is returned to combustor
t	time, s
T	temperature, K
$T\lambda$	bed temperature, K
v	superficial gas velocity up combustor, m/s, herein called the fluidizing velocity. Here computed from the molar gas flux at combustor exit with the gas density estimated by ideal gas law from the molar mass at combustor exit, the bed temperature, and the freeboard pressure
w_i	mass fraction of component i (compound or element) in a material
$w_{i,m}$	value of W_i in the m'th material stream
$W_{i,m}$	mass ratio of component i (element or compound) in a material. Here defined only as $W_i = w_i/1 - w_{H_2O})$, thus as the mass fraction d.b. (dry basis)
$w_{i,m}$	value of W_i in the m'th material stream
ε_a	excess air level: $\dot{n}_a/\dot{n}_{a,st} - 1$, where $\dot{n}_{a,st}$ is the stoichiometric (theoretical) air requirement for complete combustion. Also expressed as a percentage

τ_b $= m_b/\dot{m}_b$, estimate of residence time of bed production combustor

τ_b $= m_b/\dot{m}_p$, mean residence time of solid products (in aggregate) in combustor, s

ϕ_a air equivalence ratio: $\dot{m}_a/\dot{m}_{a,st} = 1 + \varepsilon_a$, ratio of air supplied to air theoretically (stoichiometrically) required for perfect combustion

ϕ_{mn} $= \dot{m}_m/\dot{m}_n$, mass flux ratio of the m'th and n'th material streams

$\phi_{i,mn}$ $= \dot{m}_{i,m}/\dot{m}_{i,n}$, mass flux ratio of component i (compound or element) in the m'th and n'th material streams

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Table 1 Composition of Syncrude coke.

Proximate/Ultimate Analysis
(weight %, dry basis)

Reporter	QAFBC[a]	ERL[b]	SC[c]	
MOIS	1.4	1.6	1.6	
ASH	6.9	6.7	7.1	
VCM	6.4	6.8	-	
FCM	86.7	86.5	-	
C	83.7	82.0	79.9	
H	1.6	1.4	1.9	
N	1.9	2.1	1.7	
S	6.8	7.0	6.8	
O	0	0.8	2.6	
HHV(MJ/kg)	32.1	32.2	32.3	(ash-free and moisture free basis)

Sulphur Forms[d]
(weight %, dry basis)

pyritic	0.007
sulphatic	0.016
organic	6.39
total	6.4

Ash Analysis
(weight %, ignited basis)

Reporter	QAFBC[a]	ERL[b]	SC[c]
SiO_2		44.6	41.3
Al_2O_3		25.2	25.1
Fe_2O_3		10.5	10.9
TiO_2		3.0	3.6
CaO	5.6	5.2	3.9
MgO		1.4	
Na_2O		1.3	
K_2O		1.9	
V_2O_5		3.8	3.7
NiO		1.5	1.3
So_3	15.6		

[a] Present lot of coke, average of the analyses of 16 samples.

[b] Anthony (1984), analysis performed on sample from same shipment as present lot (ERL No. 2651-84).

[c] Heaton (1984), based on composite sample collected from production during two months in 1984.

[d] Analysis of single sample by commercial analyst.

Table 2 Compositon of Athabasca limestone

	Composition, wt %				
Reporter	QAFBC[a]	ERL[b]	COMM[c]	MSL[d]	MSL[d]
MOIS	0.6				
LOI	36.5	35.2			
ASH	63.5	65.8			
CO_2	37.1	33.8			
CaO	44.7	41.2	37.6	51.2	42.4
SiO_2		13.6	20.7	6.0	14.4
Al_2O_3		3.3	4.5	1.3	3.9
Fe_2O_3		1.4	2.0	1.0	1.6
TiO_2		0.3			
P_2O_5		0.1			
MgO		0.0	1.1	1.2	1.2
SO_3		1.4		0.3	
Na_2O		0.0		0.03	0.04
K_2O		1.0		0.2	0.9
BaO		0.1			
SrO		0.02			

[a] Present lot of stone, average of the analyses of ten samples.

[b] Anthony (1984), sample no. FMLS-1.

[c] Analysis of single sample by commercial analyst.

[d] Hamer (1983), sample no. SY-1 and sample no. SY-2.

Table 3 Operating conditions of successful runs on Syncrude coke

Run	n_t	Fuel		Stone		Ca/S	Air		r	T_b °C	v m/s	τ_p, h	τ_b, h	COT h
		$\hat{D}_p$, mm	$\dot{m}_f$ kg/h	$\hat{D}_p$, mm	$\dot{m}_s$ kg/h		$\dot{m}_a$, kg/h	ε_a %						
		Syncrude		Havelock										
840605	0	0.34	12.1	0.3	7.4	3.38	134	4.5	0.0	1047	0.9	7.1	22.5	26.2
		Syncrude		McMurray										
840612	1	0.26	16.7	0.34	9.1	2.07	188	7.1	0	1064	1.3	5.5	22.4	40.3
840618	1	0.26	18.2	0.34	8.3	1.73	158	-17.7	0	967	1.0	4.1	12.6	55.5
840703	1	0.26	15.7	0.34	8.5	2.06	142	-13.5	0.69	1061	1.0	4.9	17.1	50.7
840731	0	0.26	17.2	0.94	11.2	2.45	155	-14.4	0.83	1039	1.1	4.5	8.8	43.7
840814	0	0.26	15.1	0.94	11.6	2.90	133	-16.5	0.69	966	0.8	5.0	9.8	47.3
840820	0	0.26	14.7	0.94	7.2	1.85	111	-28.2	0.81	1036	0.8	7.3	17.2	65.0
840827	0	0.26	15.3	0.94	7.9	1.94	130	-19.6	0.83	1105	0.9	7.4	11.3	44.0
840911	0	0.26	17.4	0.94	13.0	2.83	159	-13.3	0.75	1087	1.1	4.4	9.5	48.0

Table 4 Vanadium/nickel ratios in feed and in sieved solid products, Syncrude coke trials

Trial	Stream	Sieve interval, µm	Mass fraction sample	V/Ni
840911	Feed	+0	1.	2.88
	Bed product	+0	1.	2.11
		+177	0.676	1.83
		-177	0.324	2.62
	Cyclone product	+0	1.	2.89
		+177	0.016	2.00
		-177+74	0.237	2.54
		-74	0.747	3.00
840827	Feed	+0	1.	2.84
	Bed product	+0	1.	2.64
		+177	0.882	2.63
		-177	0.118	2.71
	Cyclone product	+0	1.	2.70
		+177	0.082	2.50
		-177+74	0.685	2.62
		-74	0.233	3.05
850814	Feed product	+0	1.	2.89
	Bed	+0	1.	2.76
		+177	0.872	2.92
		-177	0.128	2.15
	Cyclone product	+0	1.	2.88
		+177	0.068	2.64
		-177+74	0.407	2.71
		-74	0.525	3.08
840612	Feed	+0	1.	2.85
	Bed product	+0	1.	2.3
		+177	0.860	2.31
		-177	0.140	error
	Cyclone product	+0	1.	2.5
		+177	0.135	error
		-177+74	0.592	2.58
		-74	0.273	2.57

* Feed is coke and limestone combined, and the recent analysis indicating 0.182% V in the coke and 0.011% V in the stone is used in the calculations.

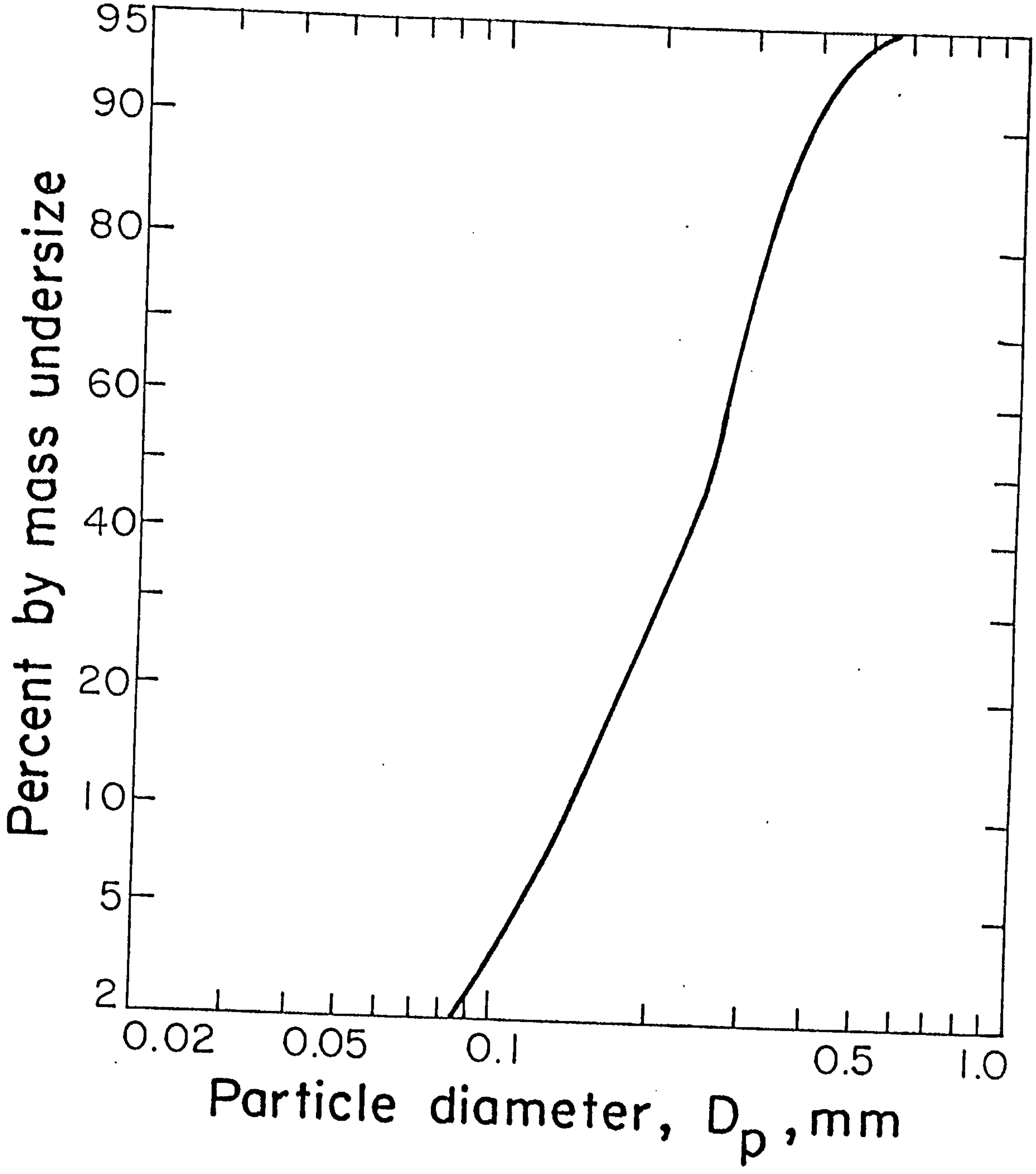

Fig. 1 Particle size distribution of Syncrude coke.

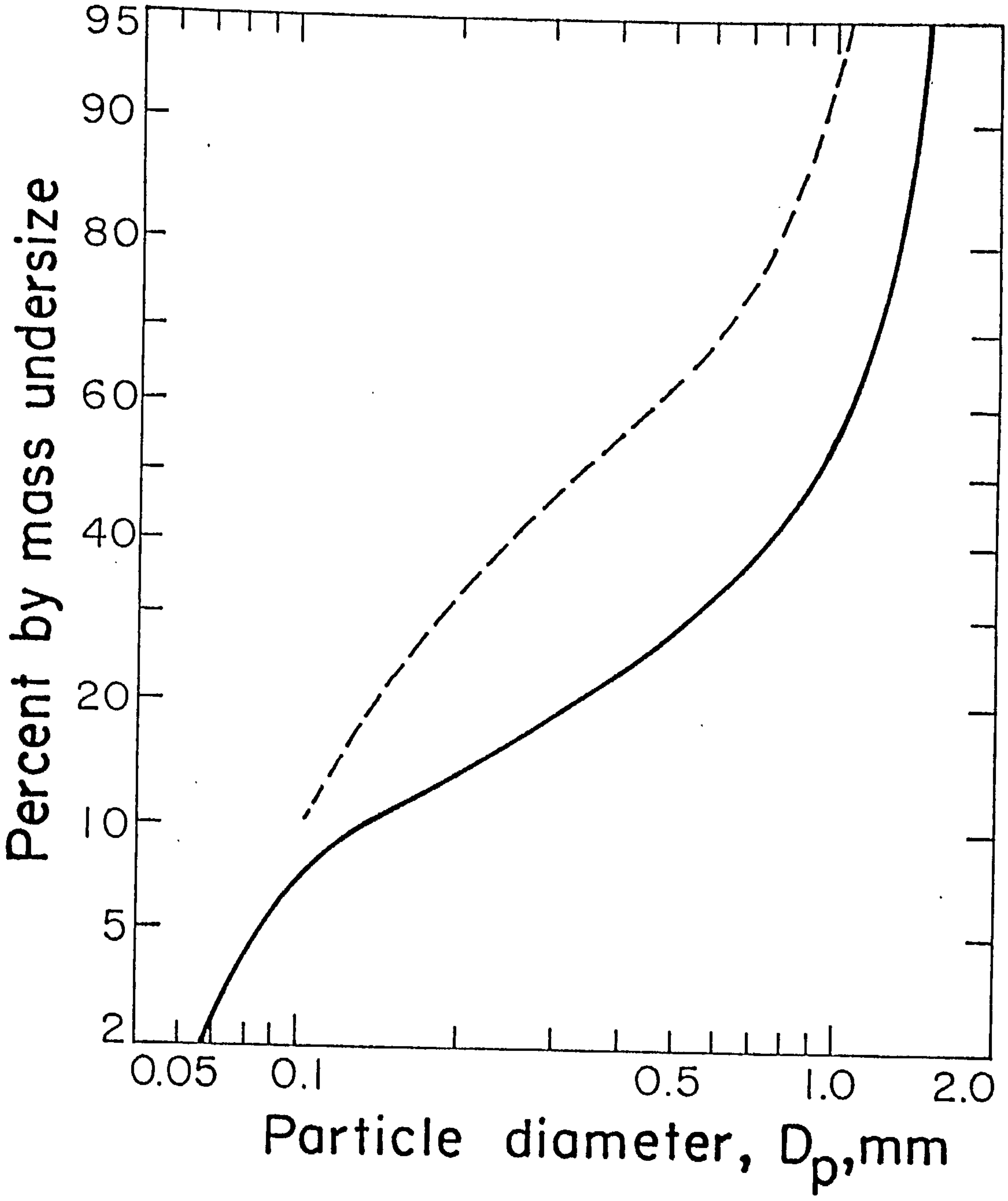

Fig. 2 Particle size distributions of Athabasca limestone sorbents.

Key:

	Nominal size (mesh)	$\hat{D}_p$, mm
— — — —	- 14	0.34
———	- 12	0.94

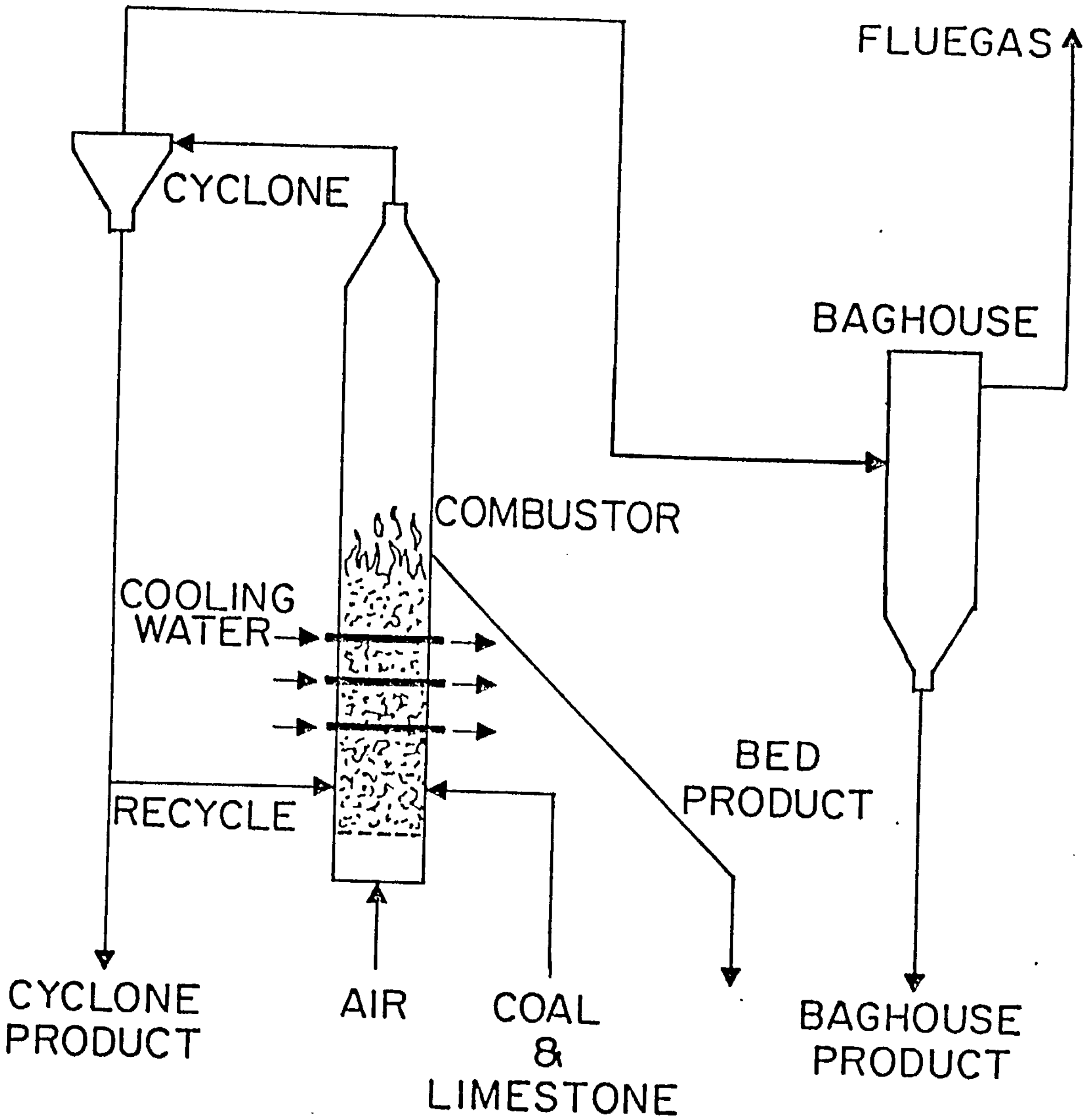

Fig. 3 Schematic representation of the AFBC pilot plant.

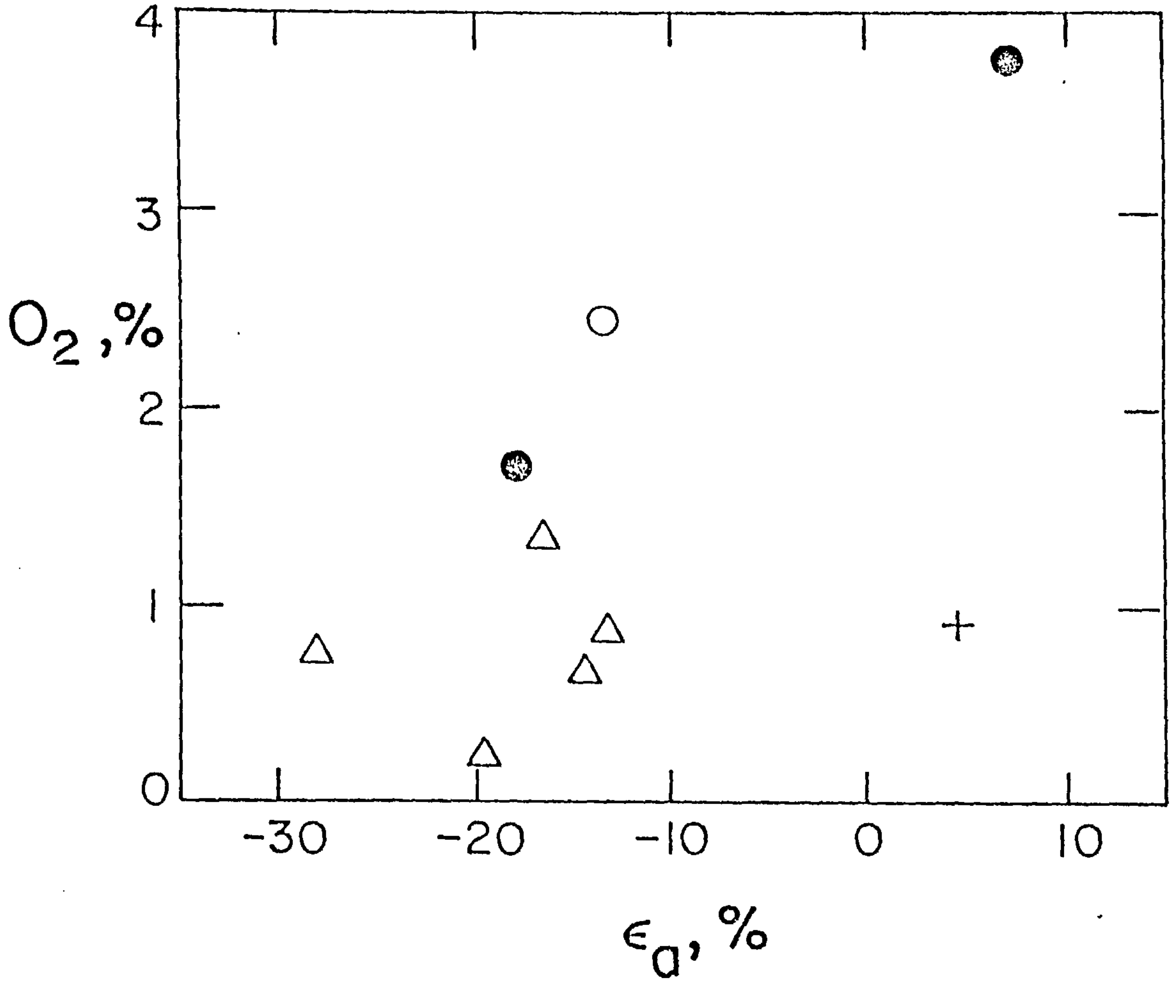

Fig. 4 Oxygen content (dry basis) in the exhaust gases (sampling port 150) as a function of excess air level. Symbols:
Limestone: ○ ● Δ Fort McMurray; + Havelock
Mass-median limestone dia. $\hat{D}_p$, mm: ○ ● +, 0.34; Δ, 0.94
Number of in-bed cooling tubes: Δ +, zero; ○ ●, one
Recycle fraction r: ● +, zero; ○ Δ, 0.69--0.83

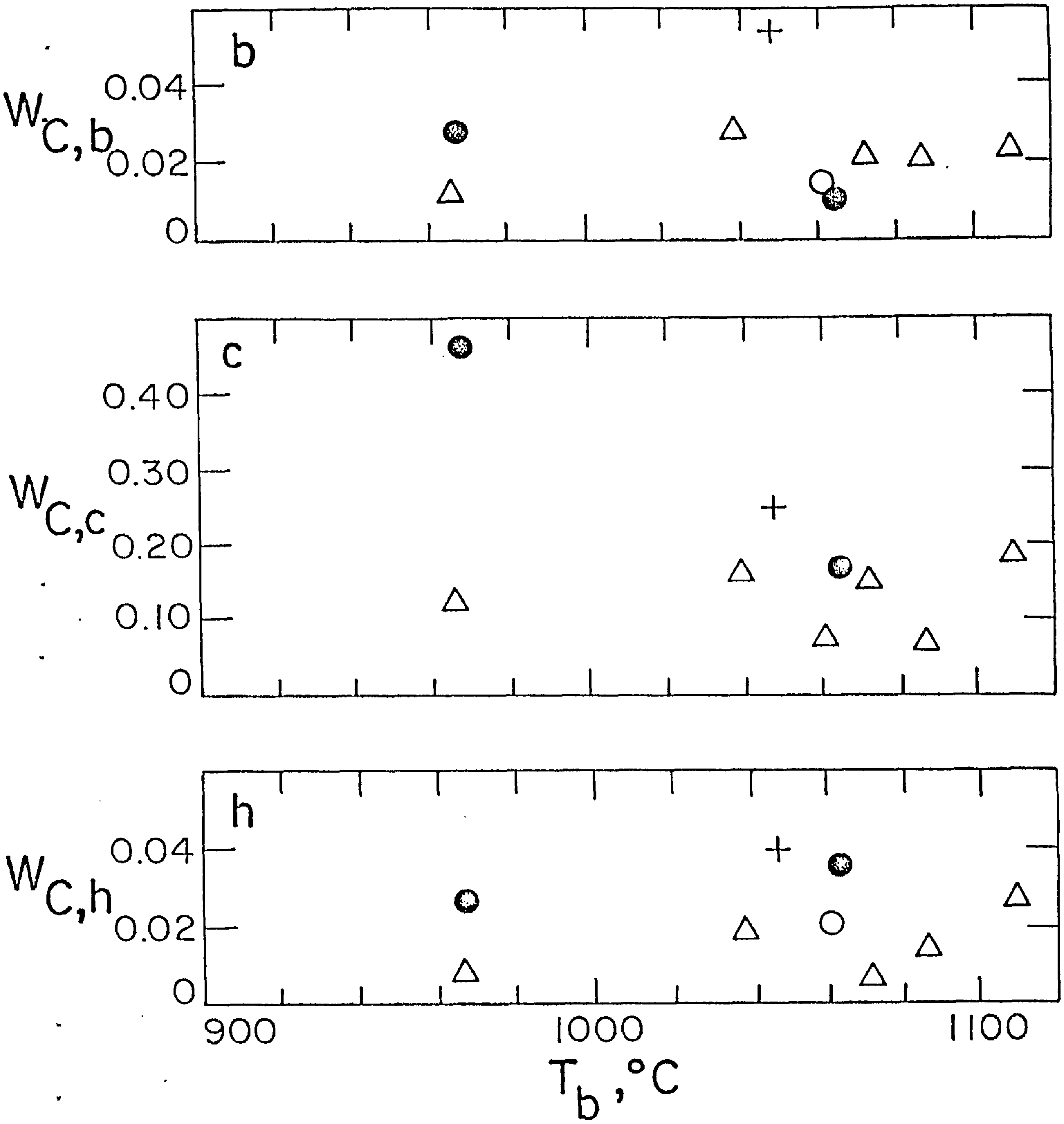

Fig. 5 Carbon content of solid products as a function of bed temperature. Top: m = b, the bed product; middle, m = c, the cyclone product; bottom, m = h, the baghouse product. Symbols: key in Fig. 4.

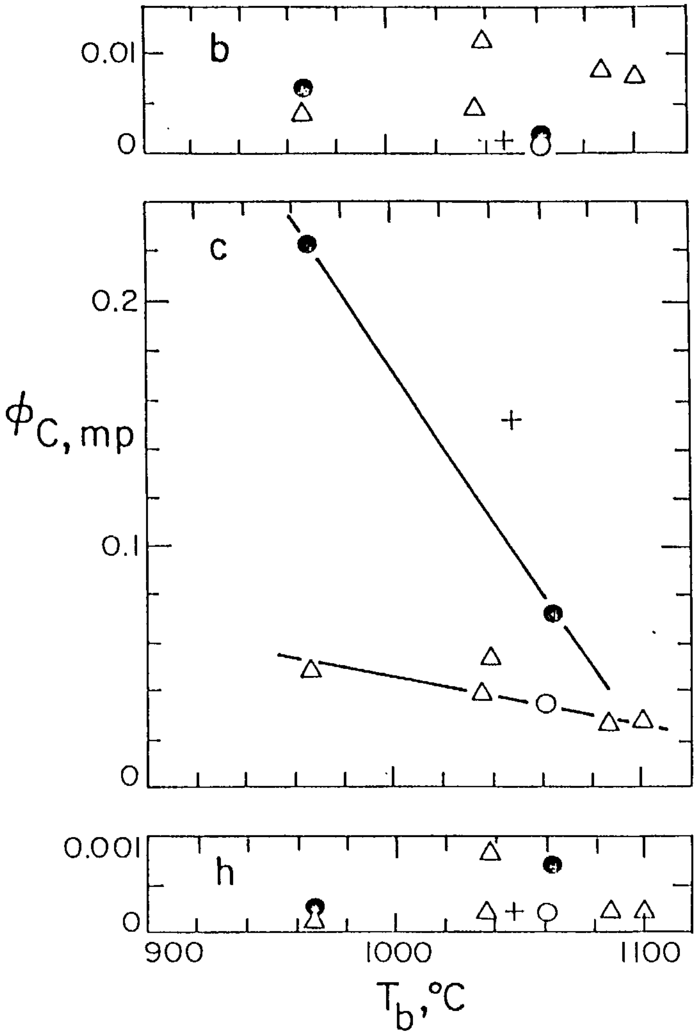

Fig. 6 Flux distribution of carbon in the solid product (m = b, c or h) as a function of bed temperature. Symbols: key in Fig. 4.

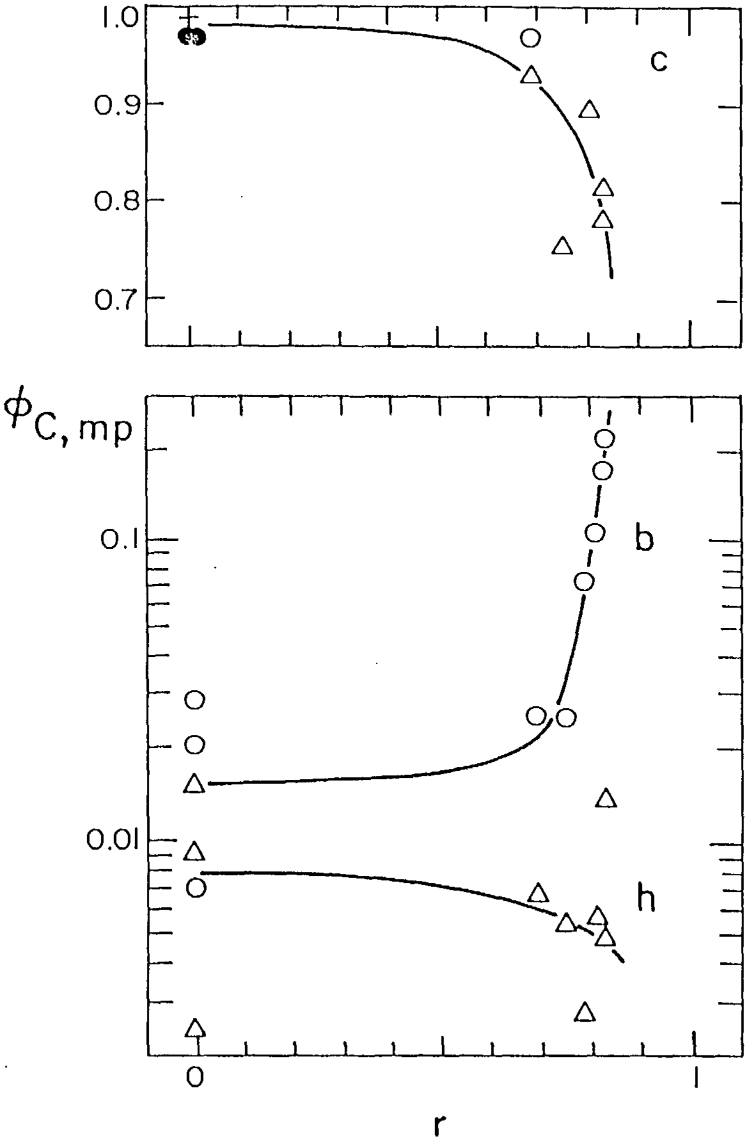

Fig. 7 Flux distribution of carbon in the solid products (m = b, c or h) as a function of the recycle fraction. Symbols in top graph: key in Fig. 4. Bottom: o, bed product; Δ, baghouse product.

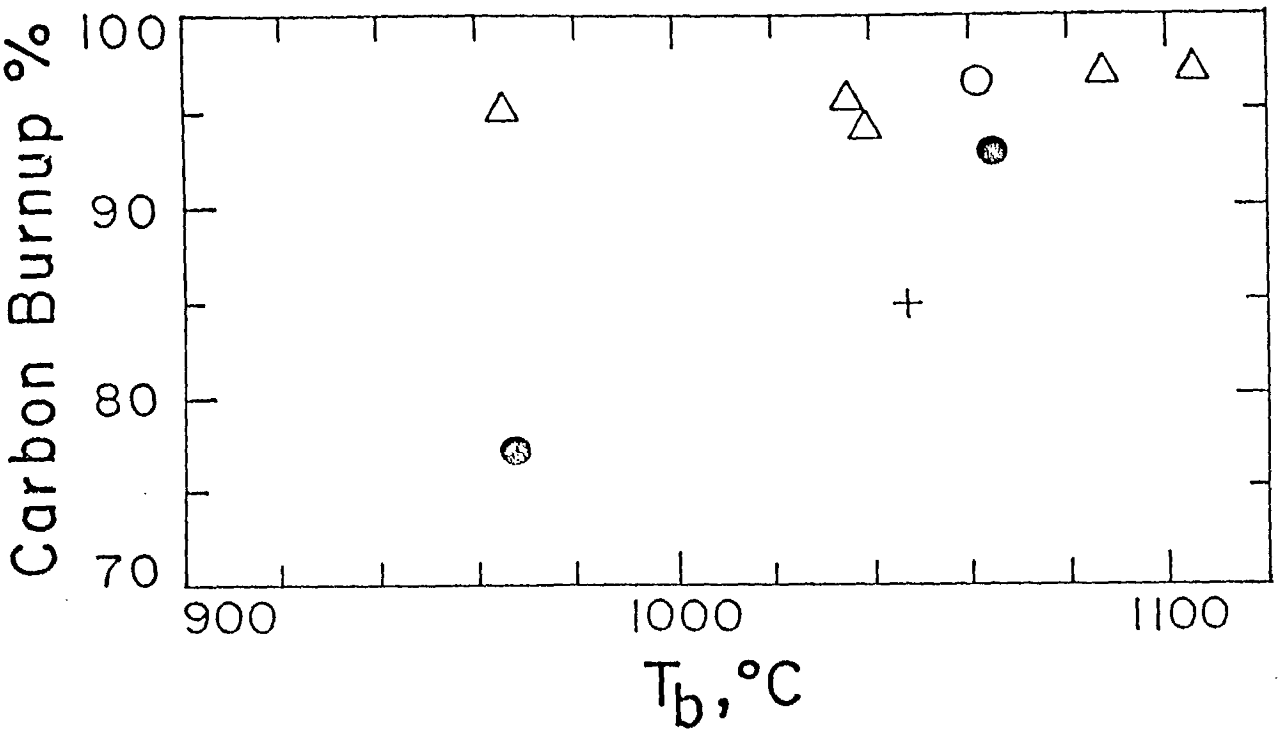

Fig. 8 Percent carbon burnup, 100 $(1 - \dot{m}_{C,p}/\dot{m}_{C,f})$, as a function of bed temperature. Symbols: key in Fig. 4.

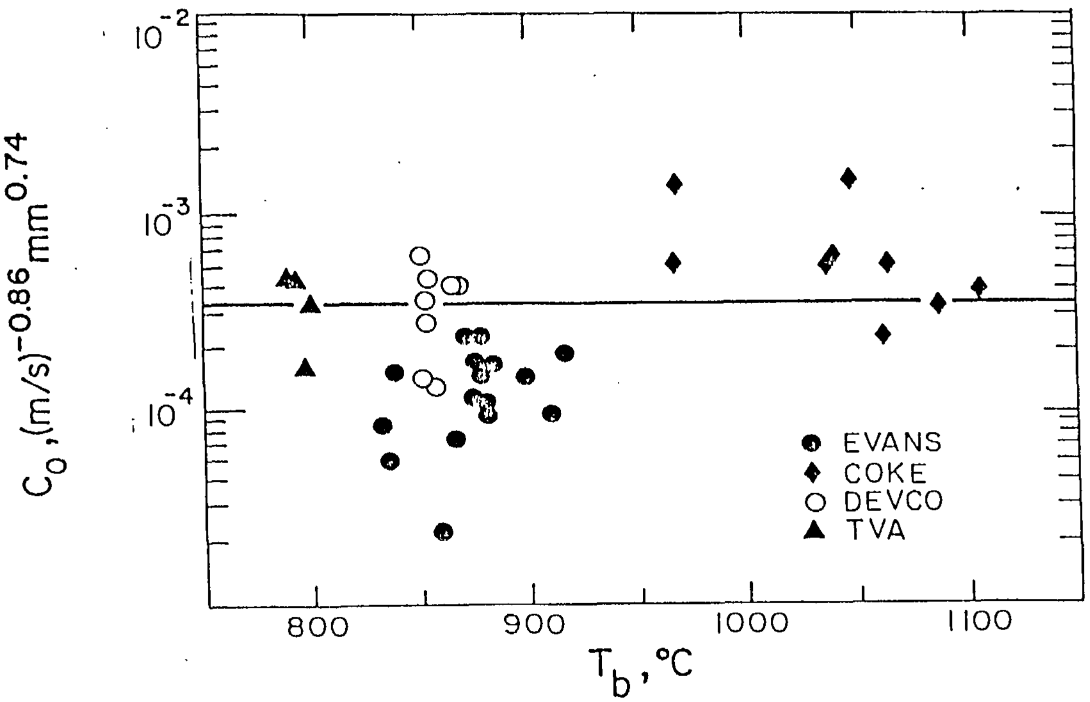

Fig. 9 Correlation of overhead carbon loss: the coefficient C_o in Eq. (1) as a function of bed temperature. Symbols for present trials: o, Devco coal; •, Evans coal; ▲, TVA coal; ◆ , Syncrude coke. The mean value for the earlier Minto and Devco coal trials was 0.000335 $(m/s)^{-0.86}$ $mm^{0.74}$

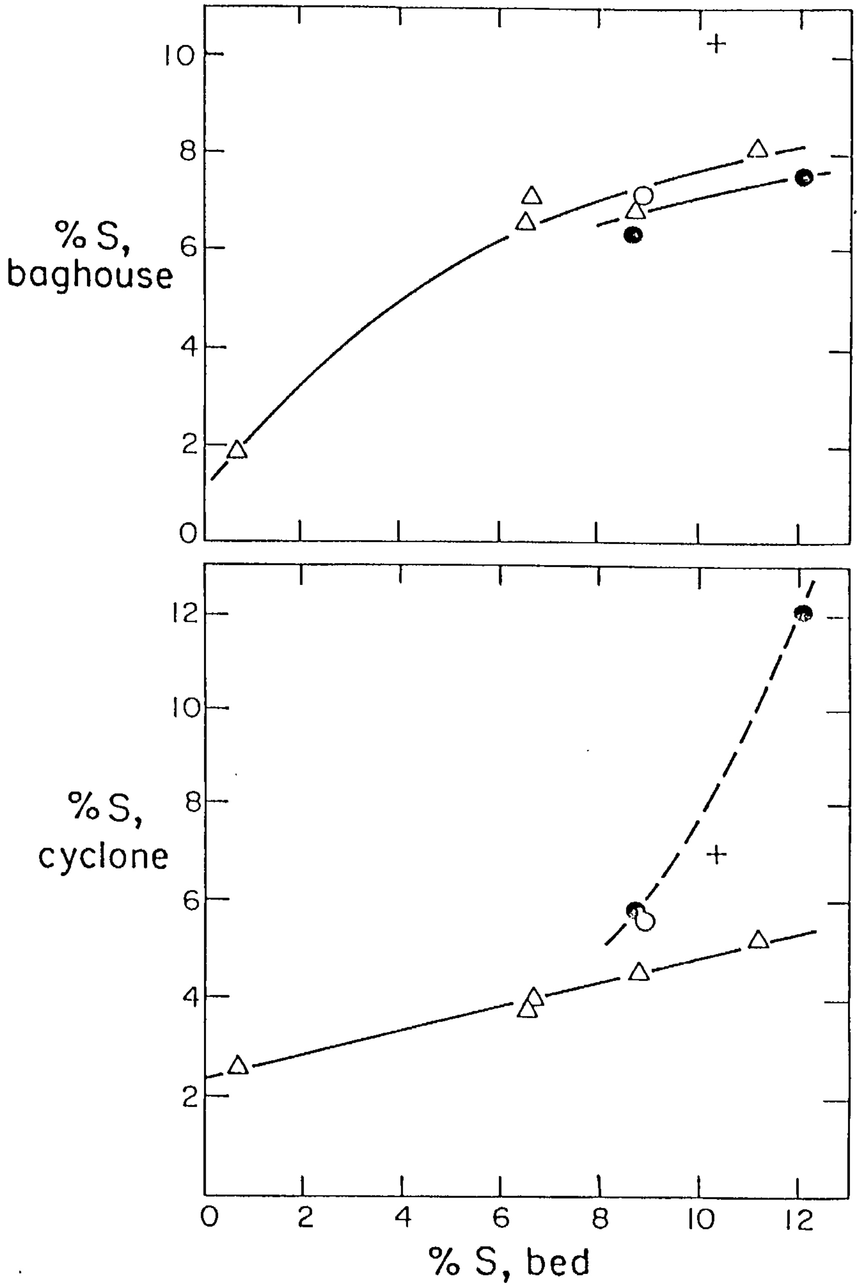

Fig. 10 Sulphur content of the baghouse and cyclone products as a function of that of the bed product, all on carbon-free basis. Symbols: key in Fig. 4.

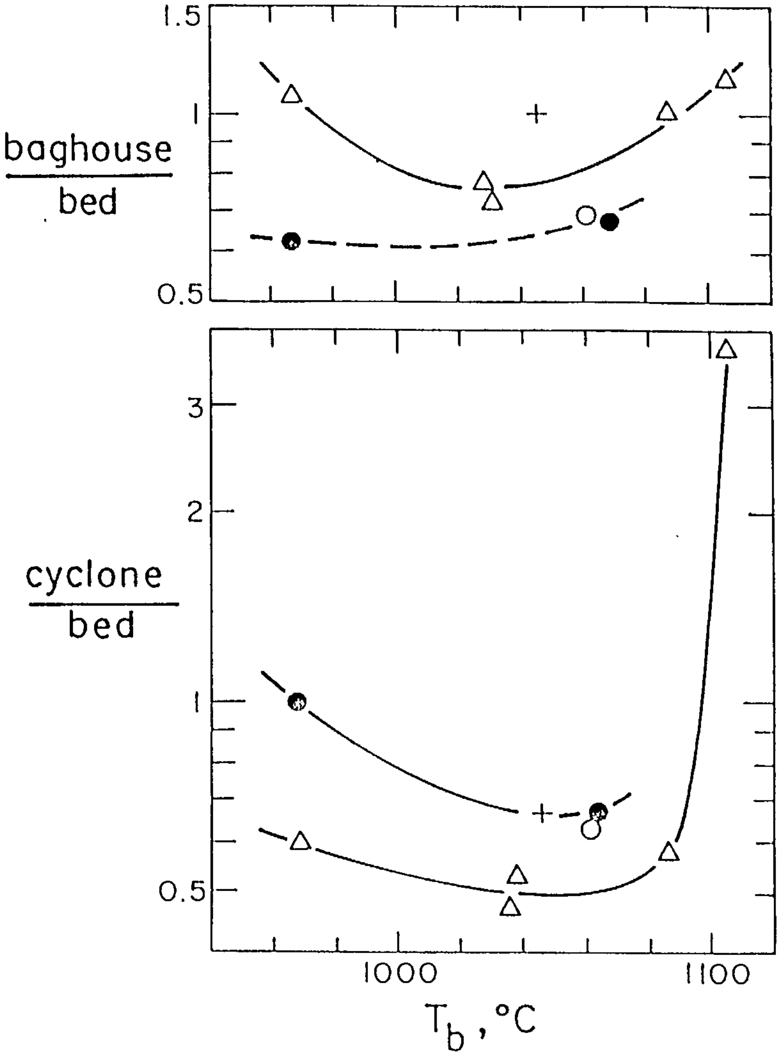

Fig. 11 Ratio of sulphur contents of the overhead product streams to that of the bed product (all on carbon-free basis) as a function of bed temperature. Top: baghouse product. Bottom: cyclone product. Symbols: key in Fig. 4.

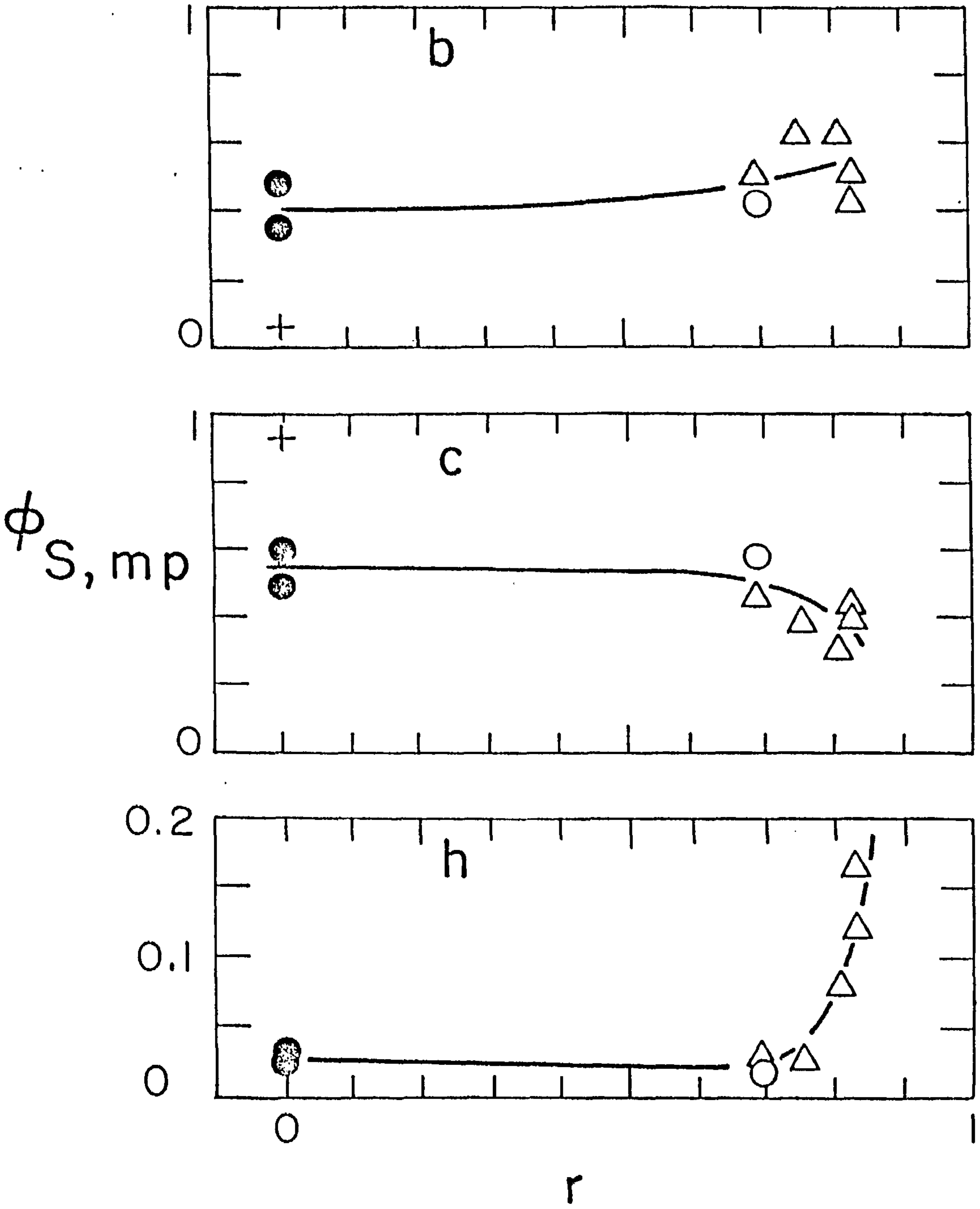

Fig. 12 Distribution of sulphur flux between the bed, cyclone and baghouse solid product streams, as a function of the recycle fraction. Symbols: key in Fig. 4.

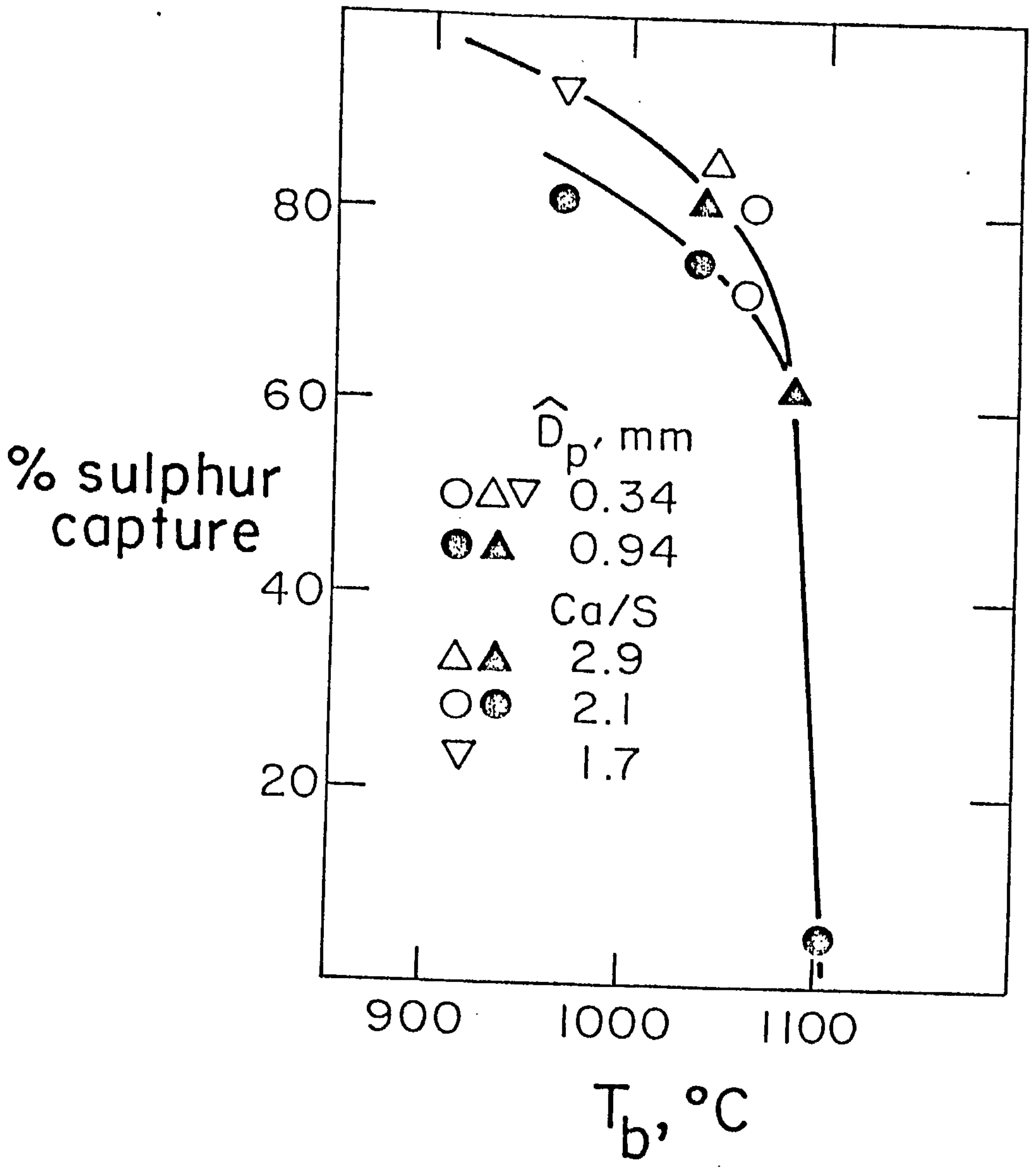

Fig. 13 Percent sulphur capture as a function of bed temperature.

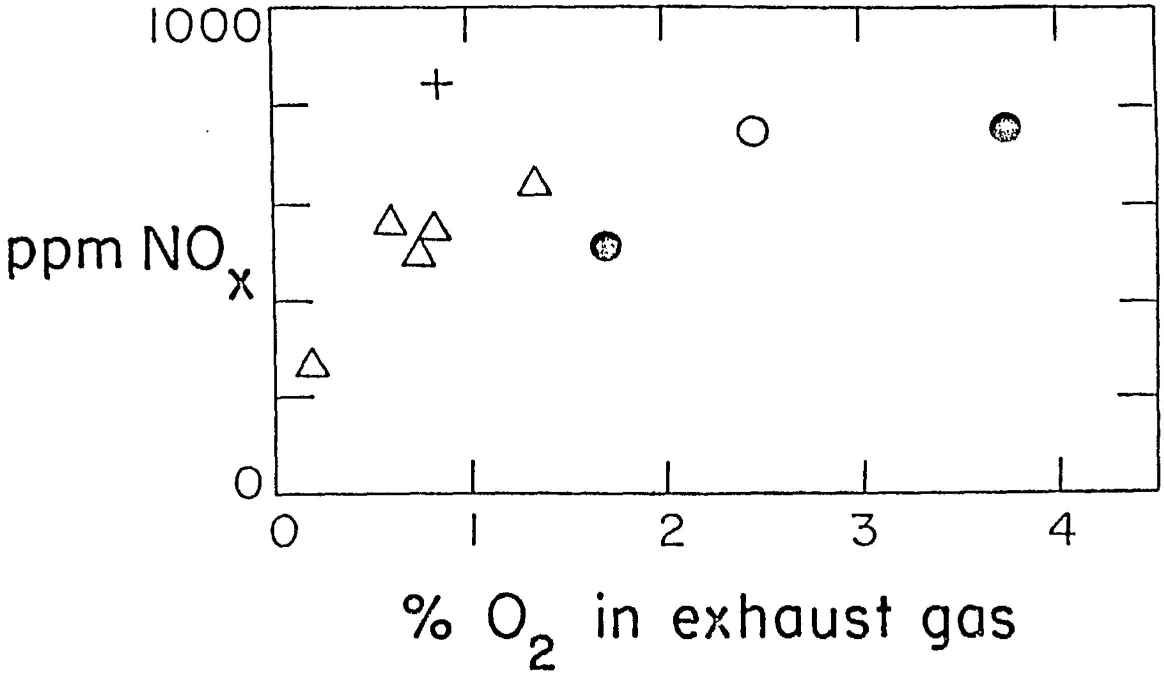

Fig. 14 The NO_x content in the exhaust gases as a function of the oxygen concentration, dry basis. Symbols: key in Fig. 4.

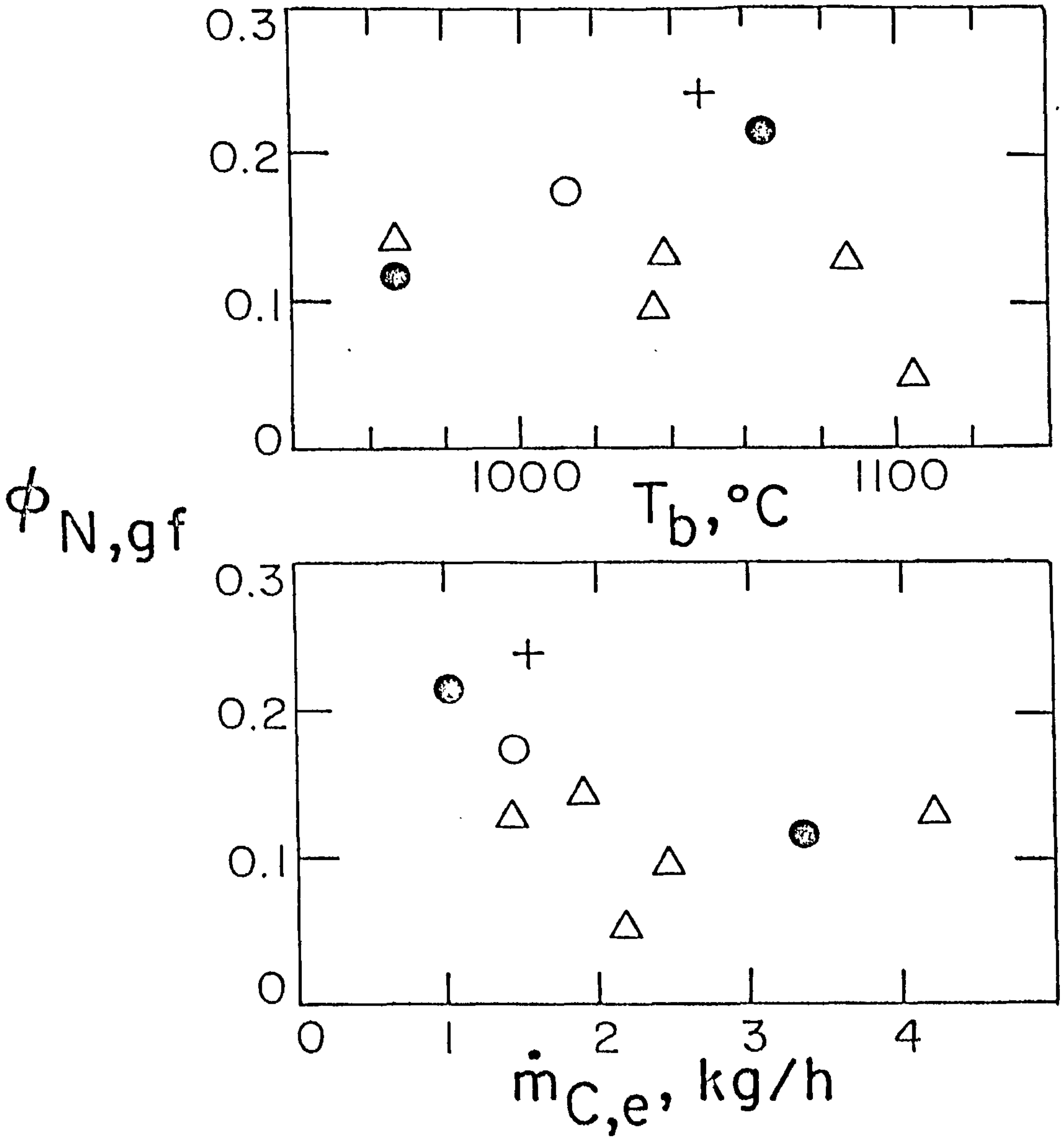

Fig. 15 Fraction of fuel nitrogen converted to NO_x vs bed temperature (top) and elutriated carbon flux (bottom). Symbols: key in Fig. 4.

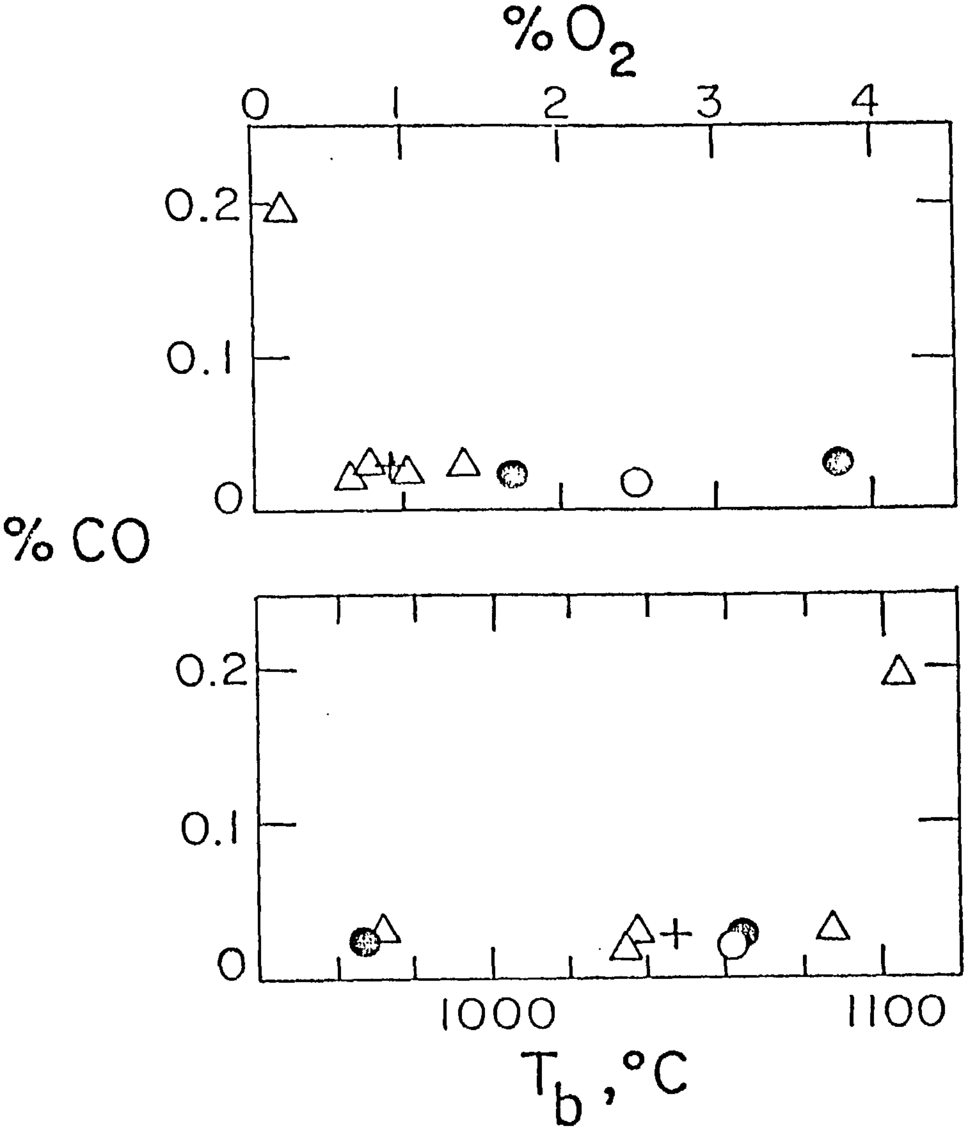

Fig. 16 Carbon monoxide content of the exhaust gases (dry basis) vs the oxygen content (top) and the bed temperature (bottom). Symbols: key in Fig. 4.

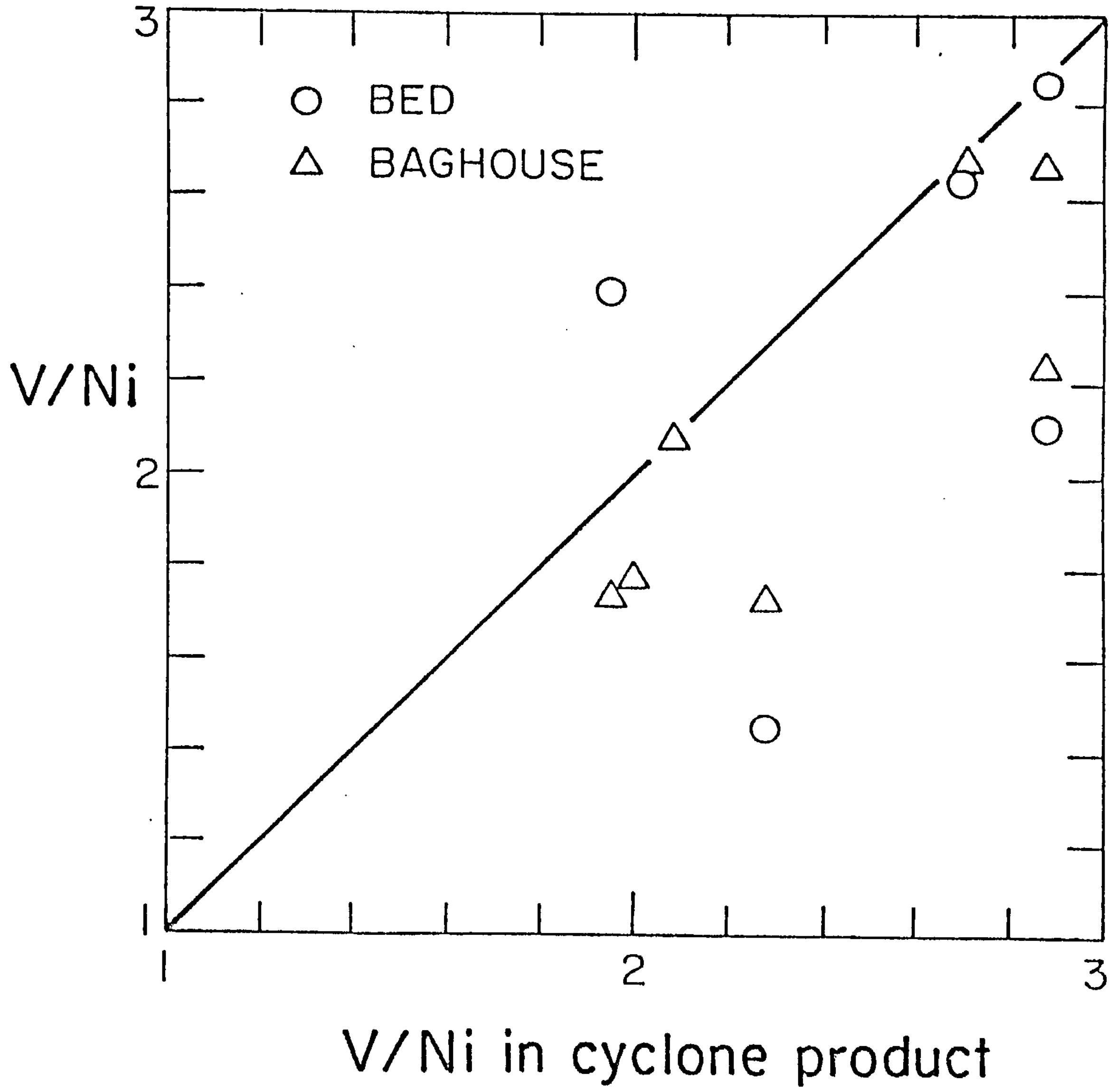

Fig. 17 Ratio of vanadium to nickel in the bed and baghouse products vs the ratio in the cyclone product. Symbols: o, bed; Δ, baghouse.

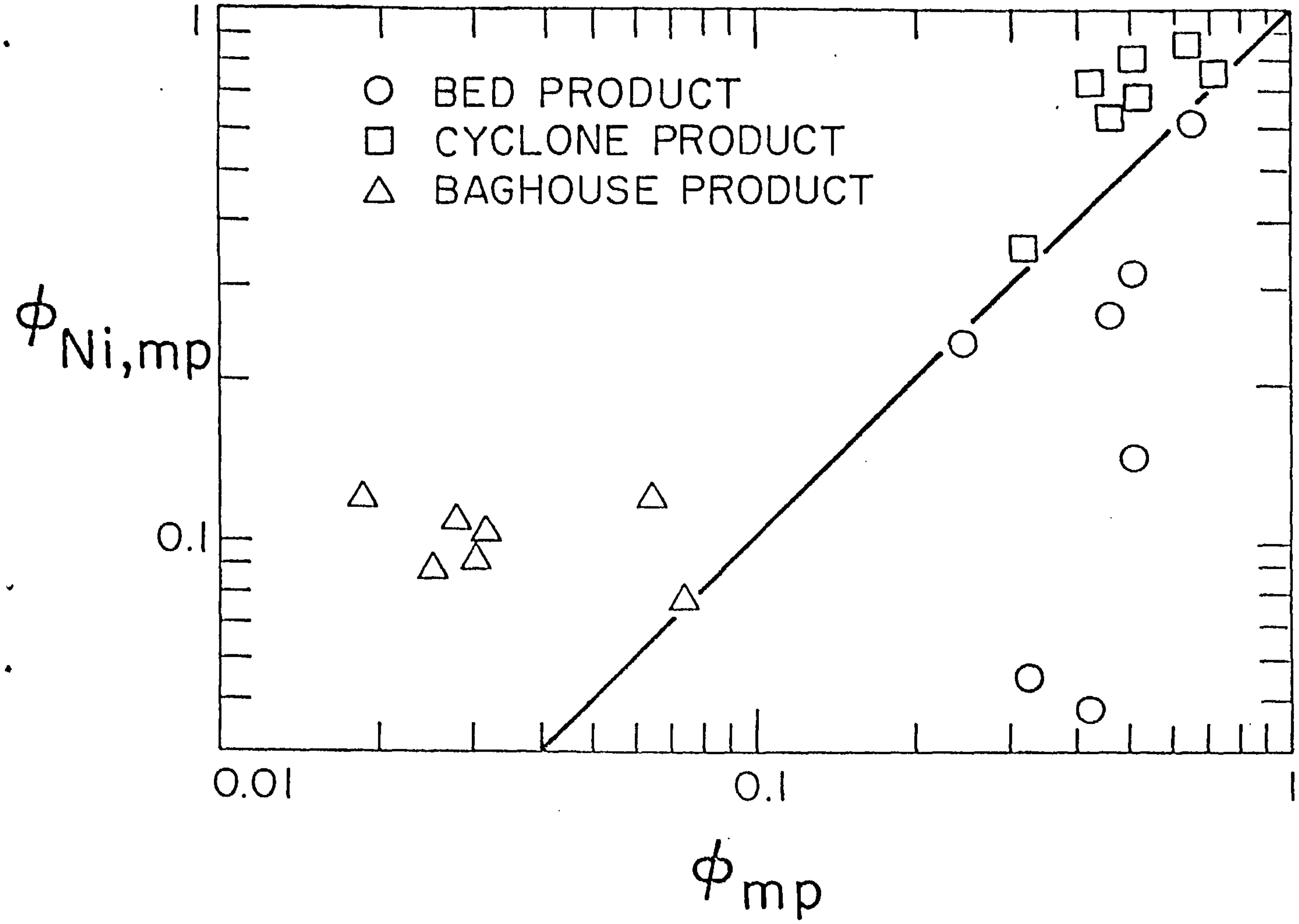

Fig. 18 Fraction of the flux of nickel carried by a given solid product stream vs the fraction of the product mass flux carried by that stream. Symbols: o, bed product; □, cyclone product; Δ, baghouse product.

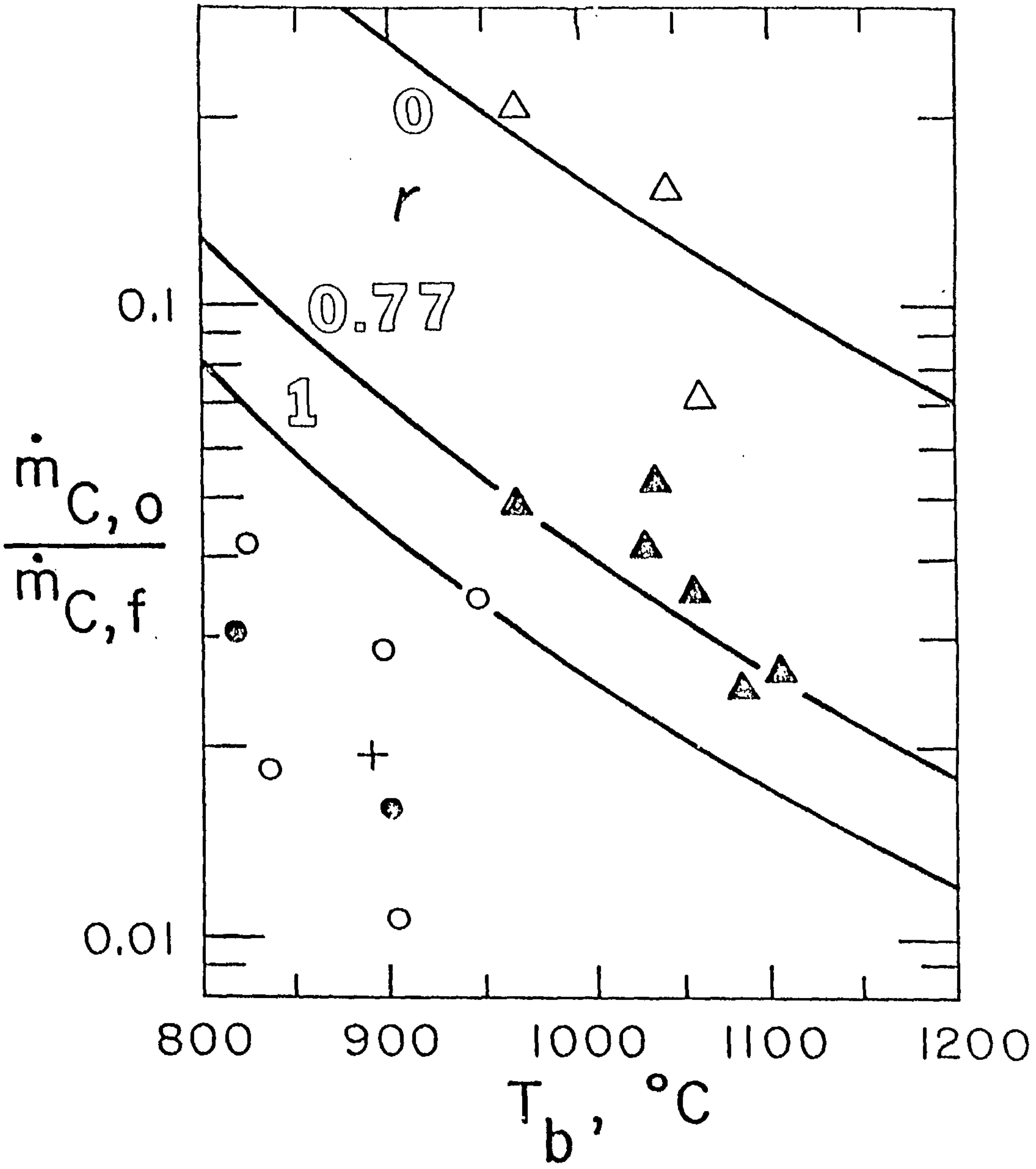

Fig. 19 Fractional overhead carbon loss vs bed temperature, Syncrude coke trials. Curves: prediction of Eq. (2) for $r = 0$, 0.77 and 1. Key to symbols:

△ ▲ present results, AFBC
○ ● + Friedrich, et al (1982), ARFBC
△ $r = 0$ (no recycle)
▲ $r = 0.67$--0.83 (partial recycle of cyclone catch)
○ + $r = 1$ (full recycle of cyclone catch)
● $r = 1$ (full recycle of cyclone catch, and 75% of baghouse catch)
\+ inert bed, no limestone feed, no bed product stream; all other trials were with limestone feed.

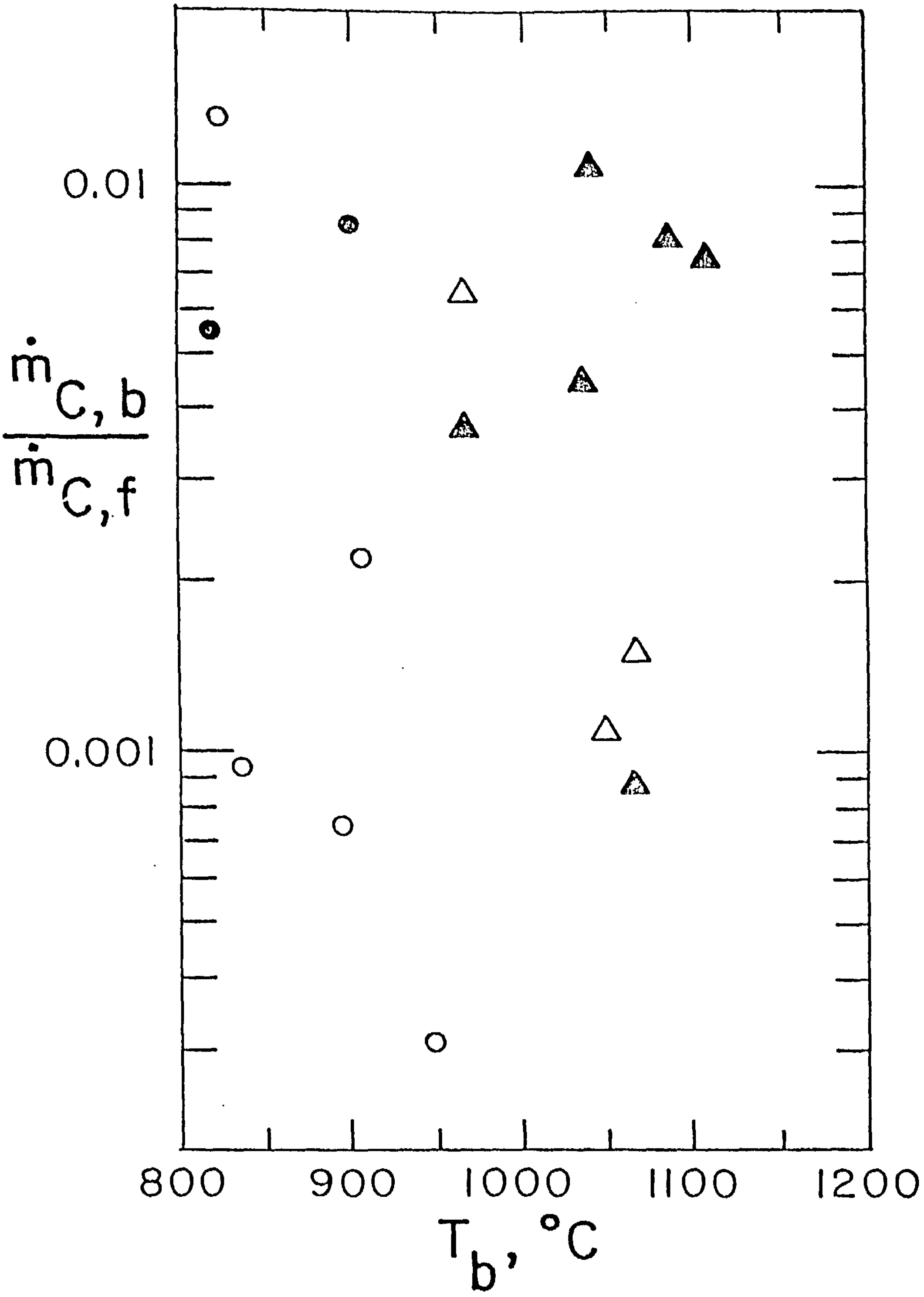

Fig. 20 Fractional bed carbon loss vs bed temperature, Syncrude coke trials. Symbols: key in Fig. 19.

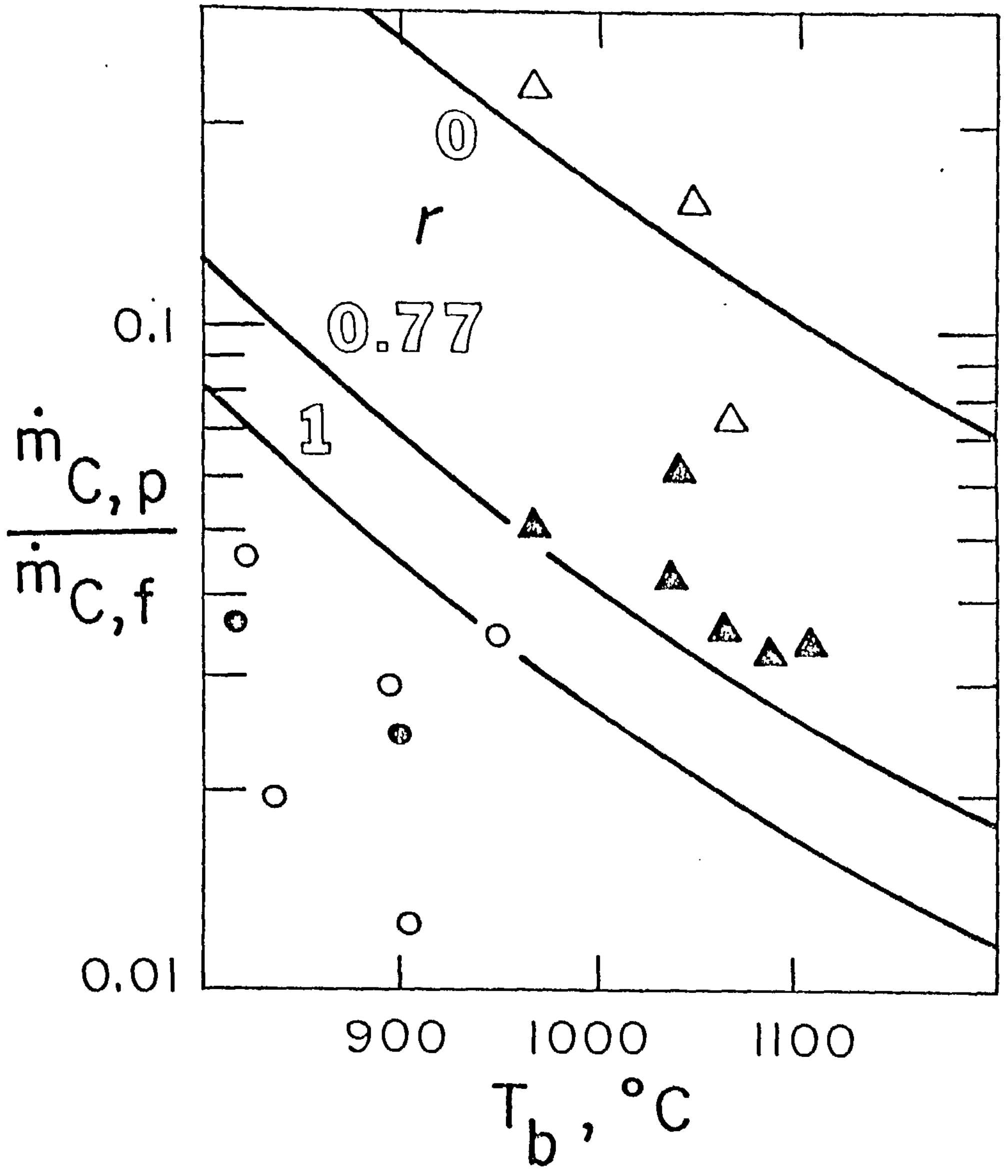

Fig. 21 Total fractional carbon loss vs bed temperature, Syncrude coke trials. Symbols: key in Fig. 19. Curves: prediction of Eq. (2) for overhead carbon loss alone (same as in Fig. 19).

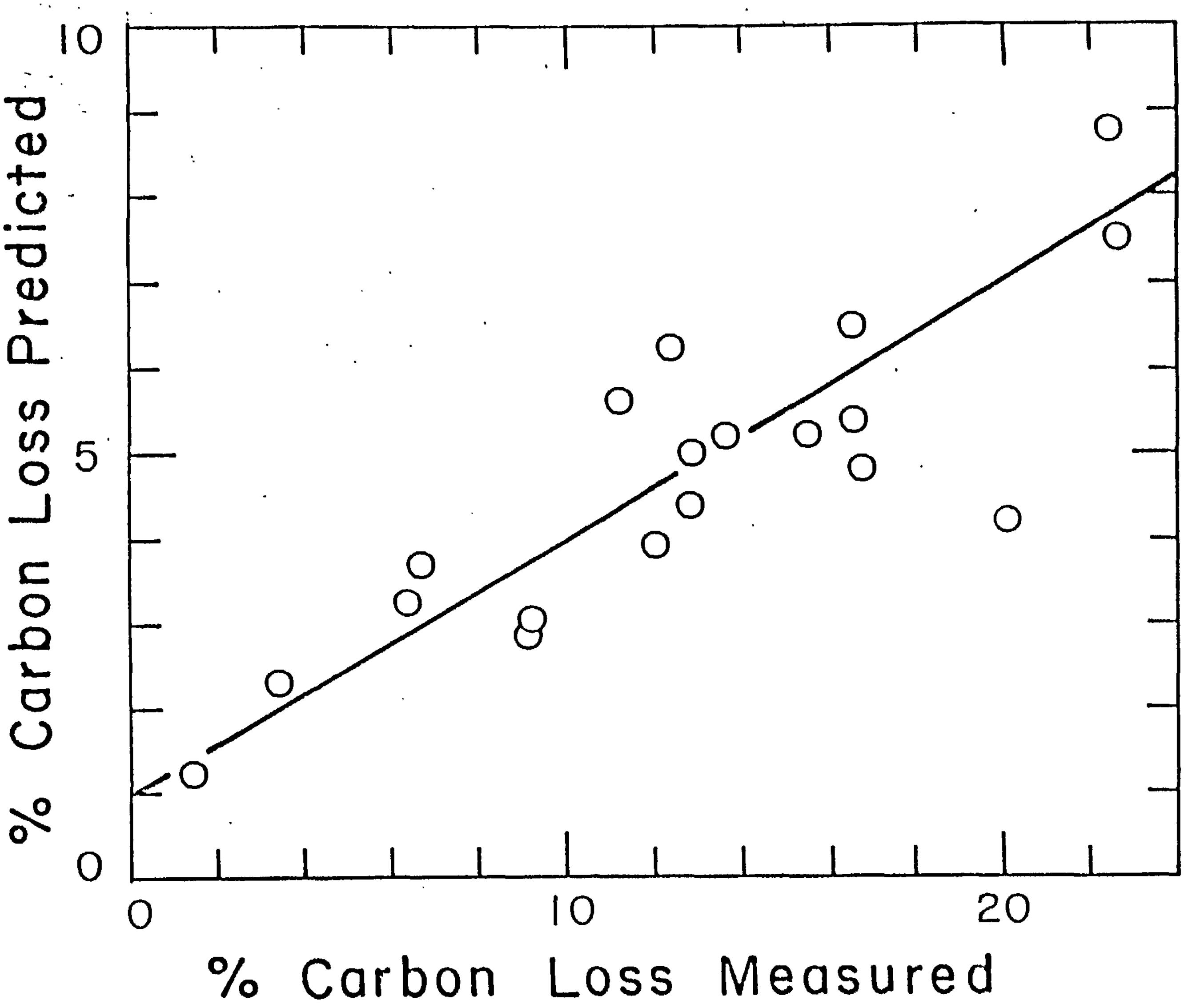

Fig. 22 Overhead carbon loss predicted by Eq. (4) as a function of that measured in the Suncor trials of Anthony, Desai and Friedrich (1982)