

FINAL REPORT

Control of Emissions from Cofiring of Coal and RDF

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Abstract

Research has been conducted toward developing technology for co-firing of coal with municipal solid waste (MSW) in order to reduce emissions of chlorinated organic compounds, particularly polychlorinated dibenzo-p-dioxins and furans (PCDDs and PCDFs). Previous bench- and pilot-scale research has shown that presence of SO₂ can inhibit the PCDD and PCDF formation, and suggested co-firing high-sulfur coal with refuse derived fuel (RDF) to reduce the emissions.

The objective of this research is to identify the effect of process and co-firing options in reducing PCDD and PCDF yield from waste combustion. Two types of municipal waste based fuels were used: a "fluff" refuse-derived fuel (simply referred to as RDF) and a densified refuse derived fuel (dRDF). The coal used was high-sulfur Illinois No. 6 coal. Experiments were conducted in US EPA's recently constructed Multi-Fuel Combustor (MFC), a state-of-the-art facility with fuel handling and combustion release rates representative of large field units. The MFC was fired, at varying rates, with RDF/dRDF and coal, and sampled for PCDD and PCDF. Tests were conducted over a range of process variables such as lime injection, HCl concentration, flue gas temperature, quench, and residence time so that the results are applicable to a wide variety of waste combustors. The data are used for developing a comprehensive statistical model for PCDD and PCDF formation and control.

Phase I tests involved the RDF combustion, resulting in significant PCDD and PCDF yields. Results show that improving the combustion quality can lower PCDD and PCDF formation. Coal co-firing with the RDF caused substantial reduction in yields. Also, no PCDD or PCDF could be detected from the combustion of the Illinois No. 6 coal alone.

Phase II tests utilized the dRDF. A 21-run statistical test matrix was derived and all the tests were completed. The combustion quality was better than that of the "fluff" RDF, and PCDD and PCDF yields from dRDF combustion, though significant, were lower when compared to the RDF. Majority of the formation took place in the temperature range 600 to 300°C, within about 0.5 sec. Coal co-firing reduced PCDD and PCDF formation substantially. Model results also show that coal addition is effective at both high and low HCl levels in the combustor. Therefore, it appears that co-firing coal with waste-derived fuel is a promising technology for PCDD and PCDF prevention. Besides coal co-firing, high-temperature lime injection also appears to be effective in reducing PCDD and PCDF formation.

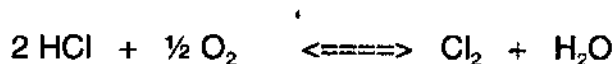
Introduction

Co-firing coal with refuse derived fuel (RDF) is an important component in meeting the objectives of NREL/DOE Municipal Solid Waste Management Program. RDF produces less SO₂ and NO_x emissions compared to coal. However, the yields of chlorinated organics, especially dioxins and furans, are more with RDF than with coal. It is possible that cofiring coal with RDF can combine both these advantages, resulting lower emissions of these pollutants. In fact, effluent sampling from a combined coal/municipal waste plant showed no detectable tetrachlorinated dibenzodioxin (TCDD), nor were noteworthy amounts found on coal fly ash (Kimble and Gross, 1980). Co-firing of coal with refuse-derived fuel (RDF) also showed PCDD and PCDF below detection levels, in spite of increased HCl levels due to the RDF (Ohlsson et al. 1990).

The proposed research examines critical process variables affecting dioxin/furan formation and control. The findings from the test program would provide the ability to make recommendations on the combustion of RDF and waste/coal fuels and to recommend strategies for development and field application of coal-RDF cofiring technology.

Background

Under laboratory conditions simulating municipal waste combustor (MWC) post-furnace environment, experiments with MWC fly ash have shown substantial PCDD and PCDF formation (Stieglitz and Vogg, 1987). A theory has been proposed (Griffin, 1986) and tested (Hagenmaier et al. 1987) that shows formation occurs due to *de novo* synthesis from compounds within the flue gas and fly ash. This synthesis involves the Deacon reaction which occurs over copper (Cu) catalysts:

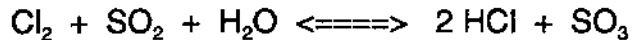


The Cl₂ produced subsequently chlorinates the aromatic ring structures through substitution reactions. The PCDD and PCDF source of chlorine has been confirmed as Cl₂ (Gullett et al. 1990a), and the latter's derivation from primarily the Deacon process has been determined (Gullett et al. 1990b). The carbon source is derived from unburnt, particulate matter (Stieglitz and Vogg, 1987) reacting with O₂ and Cl₂ to form PCDD and PCDF. An alternative theory suggests that the carbon source is derived from high temperature radical reactions during combustion (Ballschmitter et al. 1988) which react at lower temperatures to form PCDD and PCDF (Dickson and Karasek, 1987; Karasek and Dickson, 1987). This theory indicates the catalytic involvement of fly ash constituents in forming biaryl structures from chloroorganic compounds (Dickson and Karasek, 1987; Bruce et al. 1991). Past research has identified HCl and gas-phase precursor concentrations to be dominant variables for higher PCDD and PCDF levels.

A distinct difference in the emissions between coal-fired utility power plants and MWCs is with the levels of sulfur (S) species. While a typical power plant burning a 2% S coal would be expected to have a post-furnace SO₂ concentration of around 1,500 ppm, MWCs experience SO₂ emissions about an order of magnitude less (about 200 ppm). Pilot-scale tests with a MSW fly ash in EPA's laboratory (Raghunathan and Gullett, 1996) have verified that SO₂ as the sulfur species is responsible for the reduced PCDD and PCDF formation, and that substantial inhibition takes place at sulfur-to-chlorine (S/Cl) ratio as low as 0.64.

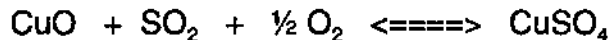
Past studies have established two key mechanisms of interference by the S species:

- (1) Griffin (1986) suggested that the effect of S is to deplete the Cl₂ levels through the gas-phase reaction:



thereby inhibiting the aromatic substitution reactions. Recent work (Raghunathan and Gullett, 1996) appears to confirm this mechanism as a possibility.

- (2) The role of S is to reduce the catalytic activity of the fly ash by reacting the Cu-based Deacon catalyst in the fly ash:



Past work at the US EPA facilities (Gullett et al. 1992) has shown that CuSO₄ is a less active catalyst for the production of Cl₂ through the Deacon process, as well as for the biaryl synthesis step of PCDD and PCDF formation. A U.S. patent (Karasek et al. 1988) claims inhibition of catalytic activity through introduction of S-based compounds (e.g., CS₂, SO₂) and subsequent reduction of PCDD formation.

Lindbauer et al. (1992) have reported that co-firing of coal in a MSW incinerator leads to appreciably lower PCDD and PCDF levels. Recently, Ogawa et al. (1996) compared the effect of adding pure SO₂ with generating SO₂ through coal addition, and found the latter to be more effective. Thus, there are other benefits with coal co-firing than simply being a source of SO₂.

Existing information on effects of process variables and coal co-firing is limited to a narrow set of combustion and operating parameters. This research project examines coal co-firing over a wide range of process conditions and parameters, and evaluates system responses to provide strategies for reducing PCDD and PCDF formation in MSW combustors.

Experimental Setup and Procedures

The newly constructed EPA's Multi-Fuel Combustor (MFC) facility was used for conducting tests for this project. The MFC is rated at 2-million Btu/hr thermal output, which is sufficient to simulate the full range of conditions that might be encountered in practical systems. The MFC is capable of burning a wide variety of solid fuels including municipal solid waste, RDF, biomass, and coal. The modular design of the facility provides flexibility, allowing studies on pollutant emissions and control, for solid fuels with unknown characteristics.

A schematic and a layout view of the MFC facility are shown in Figures 1 and 2, respectively. It consists of a waste feeding system, a coal feeder, a lower combustion chamber containing a stoker, a radiant section, a convective flue gas passage, baghouse, and flue gas cleaning system. The convective section is equipped with cooling coils with high-pressure water circulation. Typical temperature drop across this section is from 600 to 150°C which includes the dioxin formation temperature "window" (200 to 500°C). Residence time/quench across this window is known to be an important parameter and it can be varied in our tests by changing the temperature set point of the cooling water. In addition to the above components, there is a separate fuel preparation system for shredding, screening and mixing of the fuel. A large loading hopper conveys the processed fuel to the fuel silo.

The test program involved two major phases: in the first phase, the waste-derived fuel used was commercial RDF from municipal waste. The as-received RDF did contain some larger pieces and had to be run through the shredder in order to eliminate clogging the feed system. The second phase used a commercial densified refuse-derived fuel (dRDF), again from municipal waste. In both phases, the coal used was an Illinois #6 coal, donated by Monterey Coal Company, Carlinville, IL, for this project. The coal was ground and classified to an average size of about 1 mm. The coal was fed using a screw feeder and enters the burner at the same location as the RDF/dRDF. Analyses of the dRDF and coal used are shown in Tables I and II, respectively.

The convective section and the duct are equipped with several ports for flue gas sampling and temperature measurements, as indicated in Figure 2. For most of the runs, flue gas was sampled from two locations (A and B in the figure) for chlorinated organics according to EPA Method 23 and analyzed for total dioxins and furans, as well as congener distribution. The cooling coil originally present in location B was removed for this project, to accommodate dioxin sampling. For selected runs, dioxin samples were drawn from an additional sampling port, just before the convective section (location C). Before and after running Method 23 trains, a velocity traverse of the duct was carried out to measure the flue gas flow rate. Flue gas was also sampled through continuous emission monitors (CEMs) for recording the O₂, CO₂ and CO gas composition. In addition, hydrogen chloride (HCl) and sulfur dioxide (SO₂) concentrations were measured on-line separately.

Prior to a run, the MFC was fired with natural gas to maintain the temperatures in the system. Then, the RDF/dRDF was fed continuously and the system was allowed to reach temperature equilibrium. For coal co-fired tests, the coal was introduced and again the temperatures were allowed to equilibrate. When the operation became steady, the flue gas was sampled for PCDD and PCDF for about two hours.

In Phase I tests, which involved the "fluff" RDF, the feed and burn could not be controlled sufficiently and the temperatures were lower than what is observed in typical waste combustor operation. As a result, the flue gas O₂ and CO levels were higher than desired. Therefore, only a few tests were run with the RDF. To alleviate this problem, a dRDF, which is a densified (pelletized) refuse derived fuel, was acquired from a commercial facility and used for subsequent testing (Phase II). The combustor operation was much improved with more uniform fuel feed and lower CO levels.

For Phase I tests with the "fluff" RDF, the run conditions are summarized in Table III. Under Phase II, which used the dRDF, experiments conducted under this project were derived statistically and the test matrix is shown in Table IV. During each test, the fuel feed rate is adjusted, whenever necessary, to maintain a constant flue gas temperature. Nearly the same firing rate is maintained between tests, again, by matching the flue gas temperature reading. For low fuel feed runs, natural gas is co-fired to compensate for the decrease in heat release and maintain similar temperature ranges between runs. Quench is varied by varying the temperature set point of the cooling water used in the convective section of the furnace. For runs with HCl addition, there was about a 100 ppm increase in HCl concentration. The sorbent used is a commercial hydrated lime, fed as a slurry at a Ca/Cl ratio of about 1.5. The sorbent injection temperature was approximately 700°C.

PCDD and PCDF samples (Method 23) were analyzed in EPA's in-house Organics Support Laboratory (OSL). Analysis was conducted through high resolution gas chromatography/low resolution mass spectrometry (HRGC/LRMS), using a Hewlett-Packard 5890/5970 Gas Chromatography/Mass Selective Detector (GC/MSD). The methodology is a slight adaptation of EPA Method 23 (1991) and RCRA Method 8280 (1986). Isotopically labeled internal standards for each congener class are incorporated during the extraction and clean up phases of the analytical procedures to enhance analytical accuracy. An internal standard was used that consisted of a ¹³C₁₂-labeled congener from each tetra-octa PCDD and PCDF (except for octa-CDF). The recovery standard ⁶C₁₂-labeled TCDD is added before injection on the GC. The recovery must be within 40-120% to be acceptable. Recently, the OSL has expanded its capability to include quantification of mono-tri PCDD and PCDF congeners as well. Thus, the results obtained are levels of each mono-octa PCDD and PCDF congener in the sample.

Results and Discussion

Phase I tests with the "fluff" RDF

The run conditions and sampling data are provided in Table III. The reported values have not been corrected to 7% O₂. For the trial RDF burn (run 1), the temperatures were lower, resulting in high CO formation. Runs 2 and 4 involved better combustion conditions, although there were CO excursions exceeding 2000 ppm. Run 3 was a natural gas blank in between runs 2 and 4, with no RDF or coal feed. Run 5 was a coal baseline and run 6 is the coal-RDF co-fired test. Results from the above tests are shown in Figure 3 as tetra-octa total PCDD+PCDF yield.

Substantial levels of PCDD and PCDF are measured at both sampling locations from the RDF. In fact, the difference in yields between the two locations is small. Thus, much of the formation takes place in-flight, within seconds from the burner. It is clear that effective control should discourage this formation, before the flue gas and particles reach the particulate control device. Combustion quality appears to play an important role in PCDD and PCDF formation: run 1 (high CO and lower temperature) yields are much higher than those from run 2 or run 4. Given the variations in the run conditions and the nature of dioxin formation, difference between the two RDF baseline run (runs 2 and 4) yields is small, rendering credibility to the data obtained. Also, as with field units, yields of PCDF are higher than those of PCDD in these tests. However, the CO levels in our RDF baseline tests are higher than in typical municipal waste combustors).

Contrary to the RDF, no PCDD or PCDF was detected from coal burning (run 5). Even the natural gas blank test (run 3) yielded dioxins, although at much lower levels compared to RDF. Although the system was cleaned to prior to each test, some particle deposition on the system walls from earlier testing is inevitable, which could cause low yields even with natural gas. However, coal baseline test showed no such residual or hysteresis effect. It appears that flue gas from coal burning, presumably SO₂, strongly inhibits formation.

The addition of coal to RDF in the co-fired test provided better burn conditions -- increased temperatures and lower CO. In this test, the resulting sulfur-to-chlorine (S/Cl) ratio was about 1.5. Under these conditions, the PCDD and PCDF yields decreased sharply from the RDF baseline levels. Past work at the EPA facilities (Raghunathan and Gullett, 1996) had suggested a S/Cl ratio of above 1.2 for effective dioxin emission control. Thus, Phase I tests indicate that co-firing RDF with coal is an effective option for MWCs for preventing PCDD and PCDF formation.

Phase II tests with the dRDF

For each test, temperature data at various ports as well as the flue gas

composition data were stored in the computer. Run averages of these data are calculated for the duration of dioxin sampling so that these values correspond to the measured dioxin yields. With the total flue gas flow rate known from the velocity traverse data, the average flue gas temperature profile data are used to determine the flue gas residence times at various locations in the MFC. In the temperature profiles, it is arbitrarily set that the residence time $t=0$ at 650°C . The choice of 650°C stems from the fact that most of dioxin formation is known to take place below this temperature. In this project, for three runs, dioxin levels were measured for the high-temperature ($\sim 600^{\circ}\text{C}$) dioxin sampling port (Port D), and the yields were relatively small.

A summary of test parameters, gas compositions, and the measured dioxin yields for the tests under this project are given in Table V. Note that the values are not corrected to 7% O_2 . The PCDD and PCDF results shown in the table are the sum of tetra-octa congeners only; mono-tri PCDD and PCDF are not subject to regulation.

The gas composition data shows low CO levels from dRDF burning, indicating good combustion quality. Thus, the experimental data may represent actual waste combustion processes. Furthermore, of the total PCDD and PCDF (tetra-octa) measured, approximately 65% lies with the PCDF congeners. Typical MSW combustion processes are known to yield more PCDF than PCDD. Comparison of Tables III and V also indicate that, in general, yields from dRDF combustion are lower compared to RDF combustion. The possible reasons are that, with the former, the HCl concentration in the flue gas is lower and the combustion quality is better (lower CO).

For run CRDF-9, dioxin levels were measured at three different sampling ports and the results are shown in Figure 4. The figure shows the total PCDD and PCDF yields for tetra-octa as well as for mono-octa congeners. The PCDD and PCDF levels measured at the high-temperature port are relatively low. Majority of the formation takes place between Ports D and B, in less than 0.5 sec. An examination of the temperature profile, shown in the same figure, indicates that in this region, the temperature decreases sharply. A more gradual temperature decline would result in larger residence times in this temperature window, allowing more PCDD and PCDF formation. After Port B, the change in PCDD and PCDF levels is small. In fact, the yield at Port A is lower than that in Port B, although Port A is much further downstream. This may be due to sampling bias at Port B because of the presence of the cooling coils; or some PCDD and PCDF destruction may be occurring between Ports B and A. The figure also shows that the yields of mono-tetra PCDD and PCDF are significant, and it is possible that under different process conditions some of them might shift to the toxic, higher chlorinated congeners.

An average analysis of all the experimental data has been performed. The data are divided into three groups, dRDF alone, dRDF with coal co-firing, and dRDF

with sorbent injection, although within a group other parameters such as HCl concentration and quench may vary. For each group, average PCDD and PCDF yield is computed for each congener class. Results are plotted for mono-octa PCDD and PCDF congeners in Figures 5 and 6, respectively. Both coal co-firing and sorbent injection decrease PCDD and PCDF formation significantly; the congener pattern is similar to that of the base dRDF case, and therefore, the reduction is not congener-specific.

However, for the more toxic tetra-octa congeners, coal co-firing appears to be more effective. The total tetra-octa PCDD and PCDF yield for the three groups is plotted in Figure 7. The results clearly indicate that coal-dRDF co-firing reduces PCDD and PCDF formation and is slightly superior to calcium-based sorbent injection.

Experimental results have been analyzed statistically for Port A and Port B data separately. The model results for both cases are similar and the model R^2 for the data for each port is 0.76. Among the five exogenous variables (COAL, RDF, QUENCH, SORBENT and HCL, see Table III), four 2-factor interactions involving all five variables were found to be significant: COAL-HCL, RDF-QUENCH, QUENCH-SORBENT, and SORBENT-HCL. Thus, model predictions for coal co-firing are available. Model predictions are shown in Figures 8 and 9 for Port A and Port B data, respectively. The model predicts that increase in HCl concentration increases the PCDD and PCDF yield for dRDF combustion. More importantly, at both low and high HCl levels, the model indicates that coal co-firing reduces PCDD and PCDF formation significantly.

Conclusions and Recommendations

Commercial refuse-derived fuel (RDF) and densified (pelletized) refuse-derived fuel (dRDF) were combusted in a 2-MM Btu/hr stoker combustor. Majority of the PCDD and PCDF formation took place between 600 and 300°C within about 0.5 sec.

Improving the combustion quality appears to lower PCDD and PCDF yields.

Co-firing Illinois No. 6 coal with both the RDF and dRDF reduced PCDD and PCDF formation substantially. This reduction appears to be uniform across the entire congener range.

Hydrated lime sorbent also decreases PCDD and PCDF formation, but coal co-firing was slightly more effective.

Statistical model of the data indicate that PCDD and PCDF yield increases with HCl. Coal co-firing reduces PCDD and PCDF formation at both low and high HCl levels.

Co-firing coal with waste-derived fuel is a candidate technology for reducing PCDD and PCDF emissions in some commercial waste burning facilities.

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Disclaimer Statement

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Table I. Analyses of the densified refuse-derived fuel (dRDF) used (as-received)

PROXIMATE ANALYSIS (%)

Moisture	7.83
Ash	8.71
Volatile matter	70.62
Fixed Carbon	12.84

	100.00

ULTIMATE ANALYSIS (%)

Moisture	7.83
Carbon	41.70
Hydrogen	5.58
Nitrogen	0.80
Sulfur	0.09
Ash	8.71
Oxygen (diff.)	35.29

	100.00

Chlorine	0.14
Calcium	1.35
Copper	0.002
Btu/lb	7,059

Table II. Analyses of the Illinois #6 coal used (as-received after sizing)

PROXIMATE ANALYSIS (%)

Moisture	14.96
Ash	8.32
Volatile matter	33.51
Fixed Carbon	43.21

	100.00

ULTIMATE ANALYSIS (%)

Moisture	14.96
Carbon	60.25
Hydrogen	4.22
Nitrogen	1.09
Sulfur	3.36
Ash	8.32
Oxygen (diff.)	7.80

	100.00

Chlorine 0.09

Btu/lb 10,866

Table III. Multi-Fuel Combustor Test Conditions for Phase I tests with the "fluff" RDF

Run No	fuel	description	flue gas conditions						conv section		pre-baghouse	
			O ₂ %	CO ₂ %	CO ppm	HCl ppm	SO ₂ ppm	T _{flue} °C	T _s °C	PCDD+F ng/dscm	T _s °C	PCDD+F ng/dscm
1	RDF	trial burn	16.5	3.6	1345	n.m.	n.m.	554	250	1253	134	1340
2	RDF	baseline	14.8	5.3	201	n.m.	n.m.	795	302	716	153	798
3	natural gas	blank	13.7	2.7	3.2	n.m.	n.m.	766	260	46	117	95
4	RDF	baseline	12.8	6.2	690	n.m.	n.m.	691	239	497	124	630
5	coal	baseline	17.8	2.3	86	n.m.	n.m.	831	285	n.d.	151	n.d.
6	RDF+coal	co-fired	17.1	3.9	41	321	492	861	341	180	180	26

T_{flue} flue gas temperature (at location FG1, Figure 2)

T_s sampling temperature

n.m. not measured

n.d. none detected

Table IV. Multi-Fuel Combustor test matrix for Phase II tests with the dRDF

Run	Coal feed	dRDF feed	Quench	Sorbent feed	Added HCl	Run ID	Sampling locations
1	None	Low	Low	None	None	CRDF-12 CRDF-18	A,B,D A,B
2	None	Low	Low	None	Yes	CRDF-19	A,B
3	None	Low	Low	Yes	None	CRDF-30	A,B
4	None	Low	Low	Yes	Yes	CRDF-35	A,B
5	None	Low	High	None	None	CRDF-20	A,B
6	None	Low	High	None	Yes	CRDF-21 CRDF-23	A,B A,B
7	None	Low	High	Yes	None	CRDF-29	A,B
8	None	Low	High	Yes	Yes	CRDF-36	A,B
9	None	High	Low	None	None	CRDF-09 CRDF-13	A,B,D A,B
10	None	High	Low	None	Yes	CRDF-14	A,B
11	None	High	Low	None	None	CRDF-31	A,B
12	None	High	Low	Yes	Yes	CRDF-32	A,B
13	None	High	High	None	None	CRDF-07	A,B
14	None	High	High	None	Yes	CRDF-15	A,B
15	None	High	High	Yes	None	CRDF-28	A,B
16	None	High	High	Yes	Yes	CRDF-34	A,B
17	High	High	Low	None	None	CRDF-24	A,B
18	High	Low	Low	None	None	CRDF-26	A,B
19	High	High	High	None	None	CRDF-08 CRDF-27	A,B A,B
20	High	High	Low	Yes	None	CRDF-37	A,B
21	High	High	Low	None	Yes	CRDF-25	A,B
	High	Medium	High	None	None	CRDF-11	A,B,D,A
Blank*	None	None	Low	None	None	CRDF-10	A,B
Blank*	None	None	High	None	None	CRDF-16	A
Blank*	None	None	---	None	None	CRDF-16	A
Blank*	None	None	High	None	High	CRDF-22	A

*In Blank tests, the combustor was fired with natural gas

Table V. Summary of test conditions and results for the Phase II MFC tests

Run	Flue gas composition					Port B			Port A		
	O ₂ %	CO ₂ %	CO ppm	HCl ppm	SO ₂ ppm	T _{samp} °C	t _R * sec	4-8 D+F ng/dscm	T _{samp} °C	t _R * sec	4-8 D+F ng/dscm
CRDF-07	14.4	6.9	10	78	0	336	0.41	605	154	1.78	513
CRDF-08	16.9	4.8	31	95	427	334	1.07	86	160	2.42	57
CRDF-09	13.4	6.2	23	73	16	317	1.89	302	171	3.16	187
CRDF-11	9.3	9.6	80	114	136	318	0.68	104	146	2.18	28
CRDF-12	11.5	7.0	6	44	8	296	1.23	31	152	3.61	21
CRDF-13	12.8	7.1	9	65	11	321	1.94	86	180	3.69	34
CRDF-14	13.3	6.8	28	146	1	328	1.81	1910	176	3.66	1369
CRDF-15	14.2	6.4	7	192	0	335	0.51	216	163	2.20	191
CRDF-18	13.7	4.4	1	62	0	n.a.	n.a.	9	n.a.	n.a.	3
CRDF-19	13.7	4.3	0	224	0	n.a.	n.a.	20	n.a.	n.a.	1
CRDF-20	13.5	4.3	1	28	0	365	0.43	24	155	2.04	4
CRDF-21	12.6	5.1	1	209	0	380	0.41	85	172	1.94	44
CRDF-23	11.6	5.7	7	200	0	339	1.91	271	178	3.41	168
CRDF-24	12.6	7.1	97	151	172	349	1.58	32	186	3.06	29
CRDF-25	12.7	6.9	31	193	148	370	0.86	14	196	2.30	15
CRDF-26	13.7	4.5	2	21	159	n.a.	n.a.	5	n.a.	n.a.	10
CRDF-27	12.8	6.7	2	71	170	299	1.28	2	150	2.91	4
CRDF-28	12.8	6.8	6	52	4	378	0.39	96	178	1.72	66
CRDF-29	12.1	6.2	0	21	0	380	0.37	8	179	1.66	4
CRDF-30	13.8	4.8	7	11	0	374	0.62	19	192	1.93	14
CRDF-31	12.2	7.6	9	56	17	344	0.73	7	173	2.32	8
CRDF-32	12.9	6.9	3	149	0	350	0.47	2	180	1.97	0
CRDF-34	12.6	7.2	14	155	0	347	0.72	79	178	1.94	61
CRDF-35	12.7	4.9	0	170	0	329	0.72	244	180	2.14	60
CRDF-36	12.7	5.4	3	153	0	329	0.41	35	168	1.76	77
CRDF-37	11.0	8.1	14	73	139	323	0.43	28	161	1.90	4

* Residence time t_R based on t=0 at 650°C; T_{samp}=Sampling port temperature; 4-8 D+F= tetra-octa PCDD+PCDF

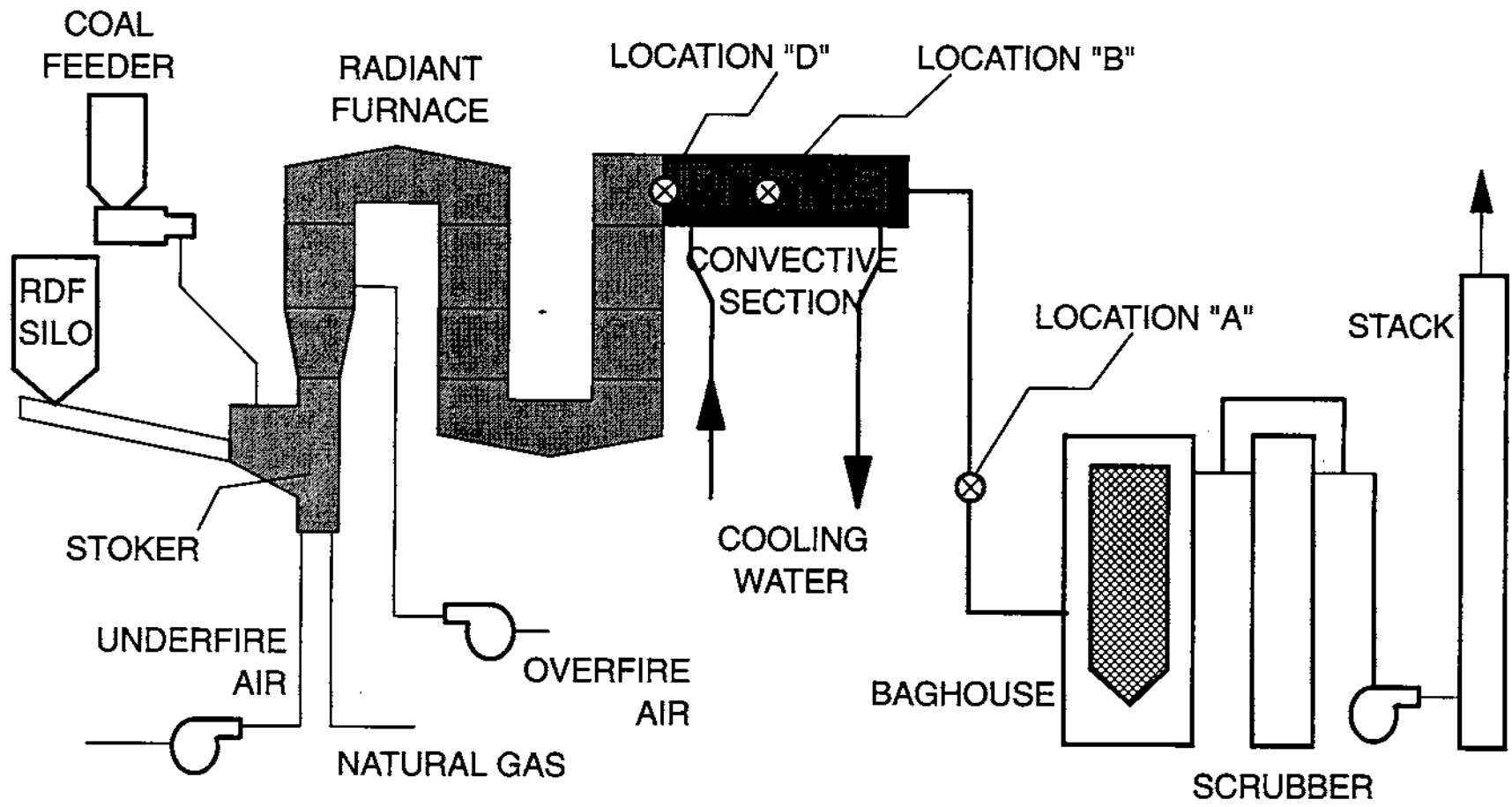


Figure 1. Schematic of the Multi-Fuel Combustor (MFC)

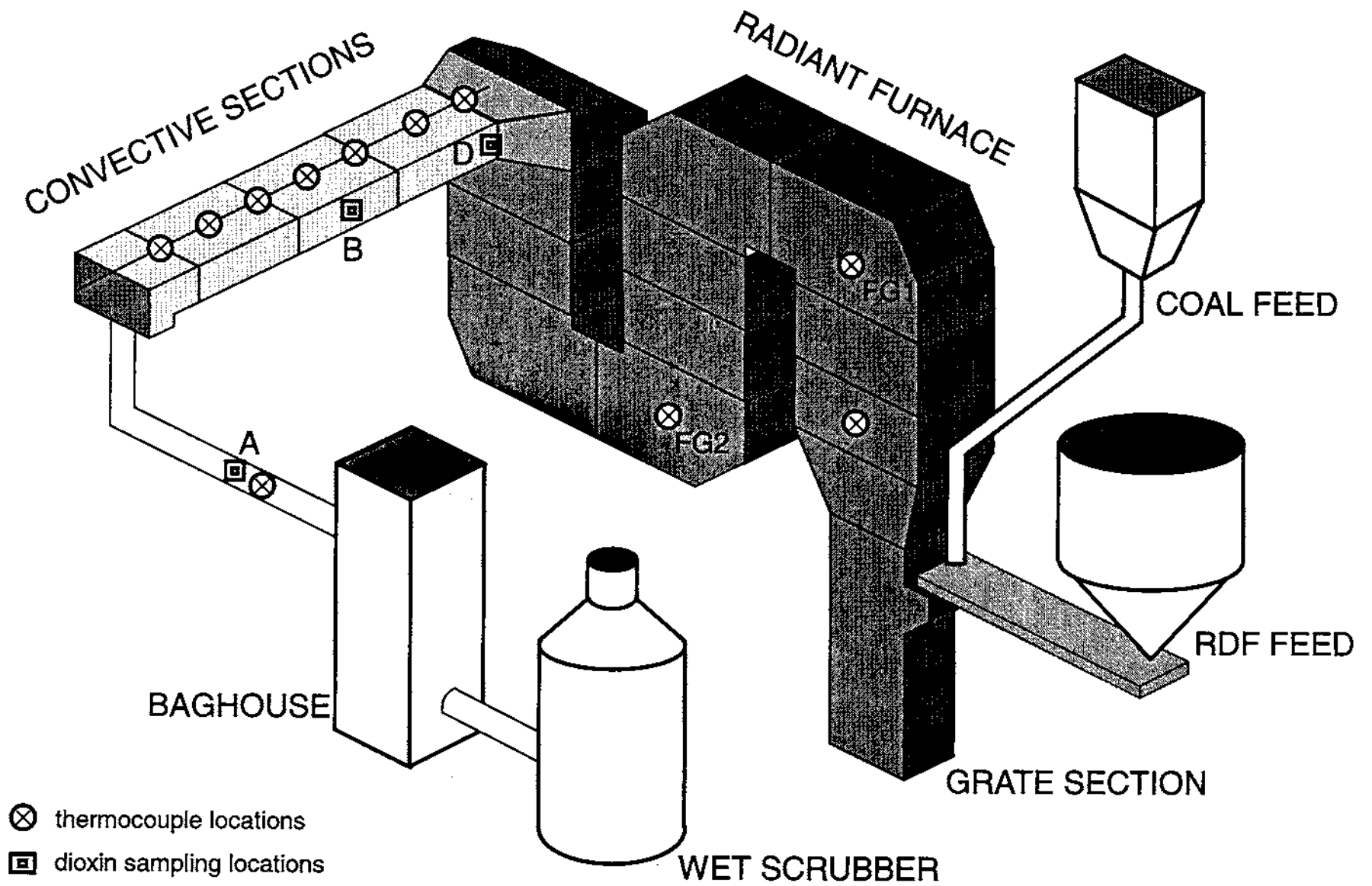


Figure 2. A view of the Multi-Fuel Combustor

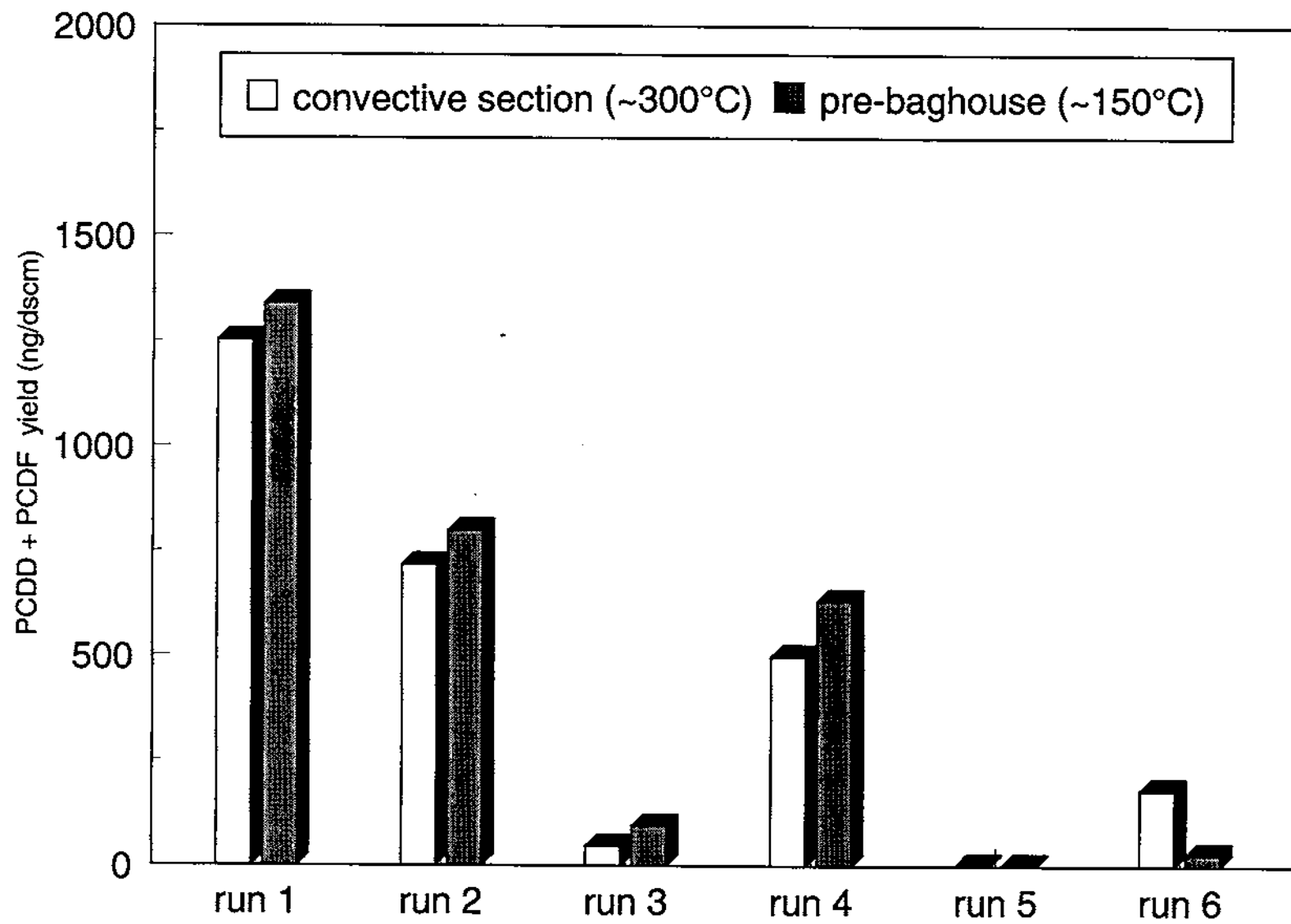


Figure 3. Total PCDD and PCDF (tetra-octa) yields from Phase I "fluff" RDF tests

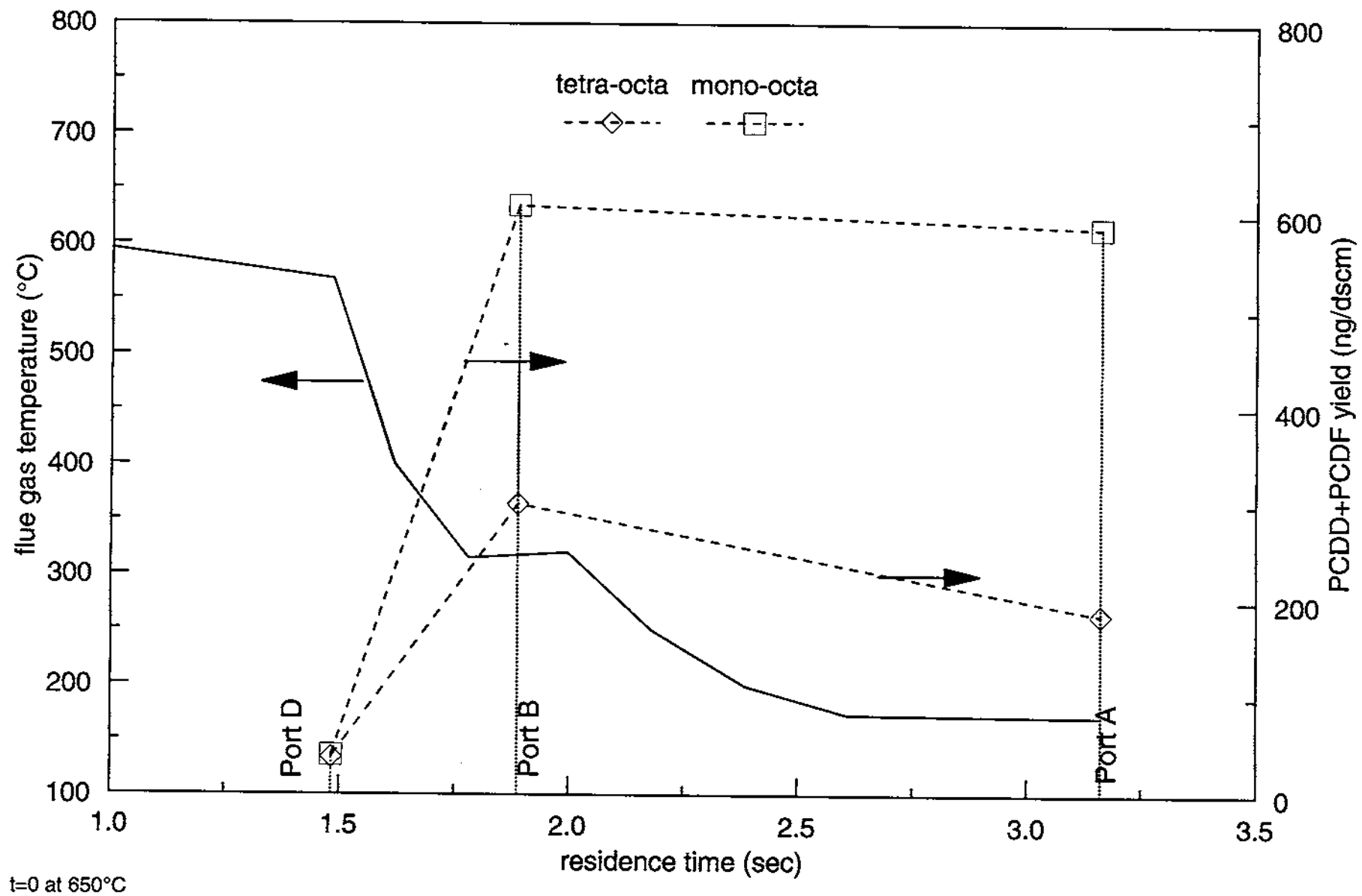


Figure 4. PCDD and PCDF yields from dRDF combustion measured at the three sampling ports

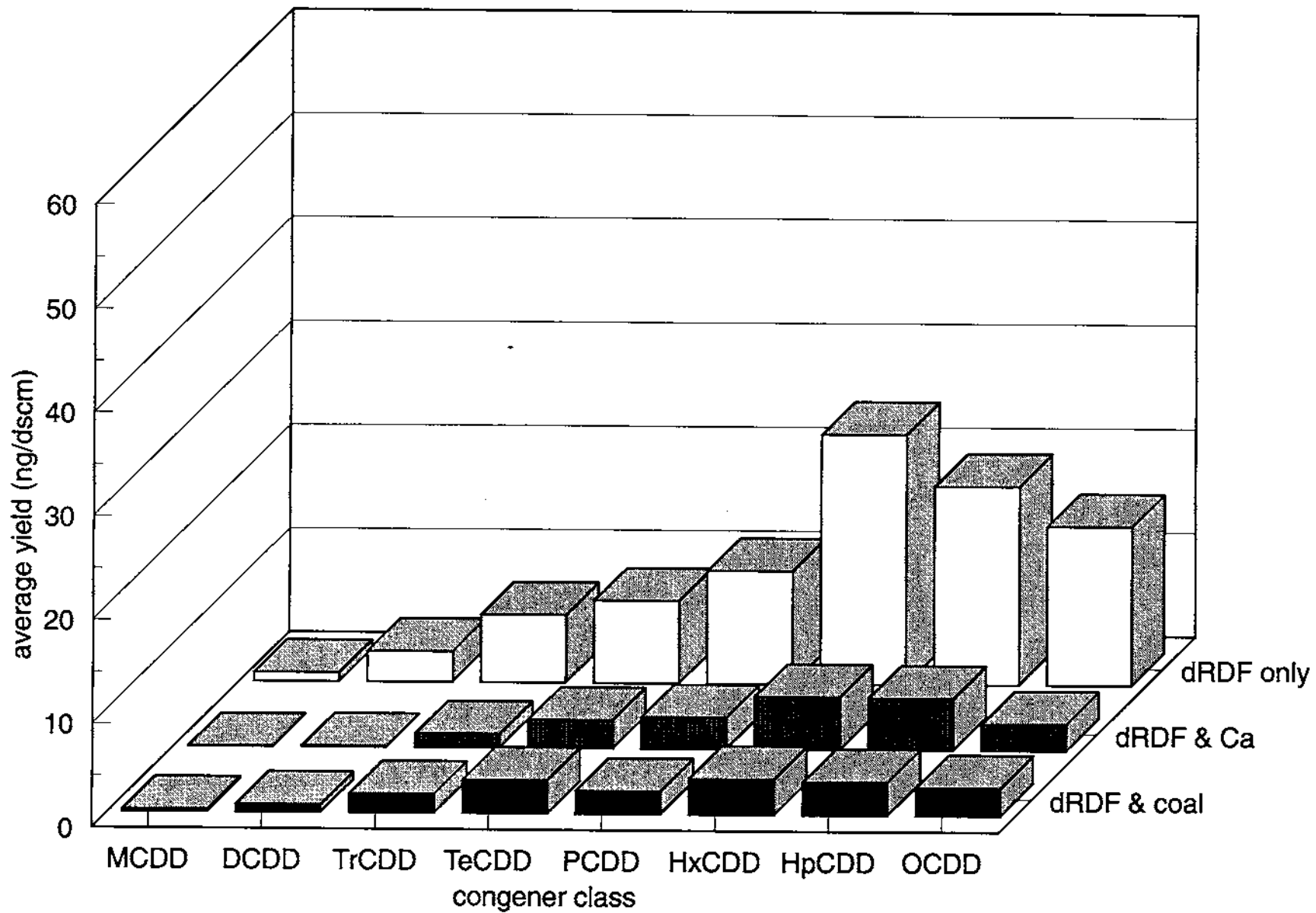


Figure 5. Effects of coal co-firing and sorbent injection on PCDD congener yield from dRDF combustion

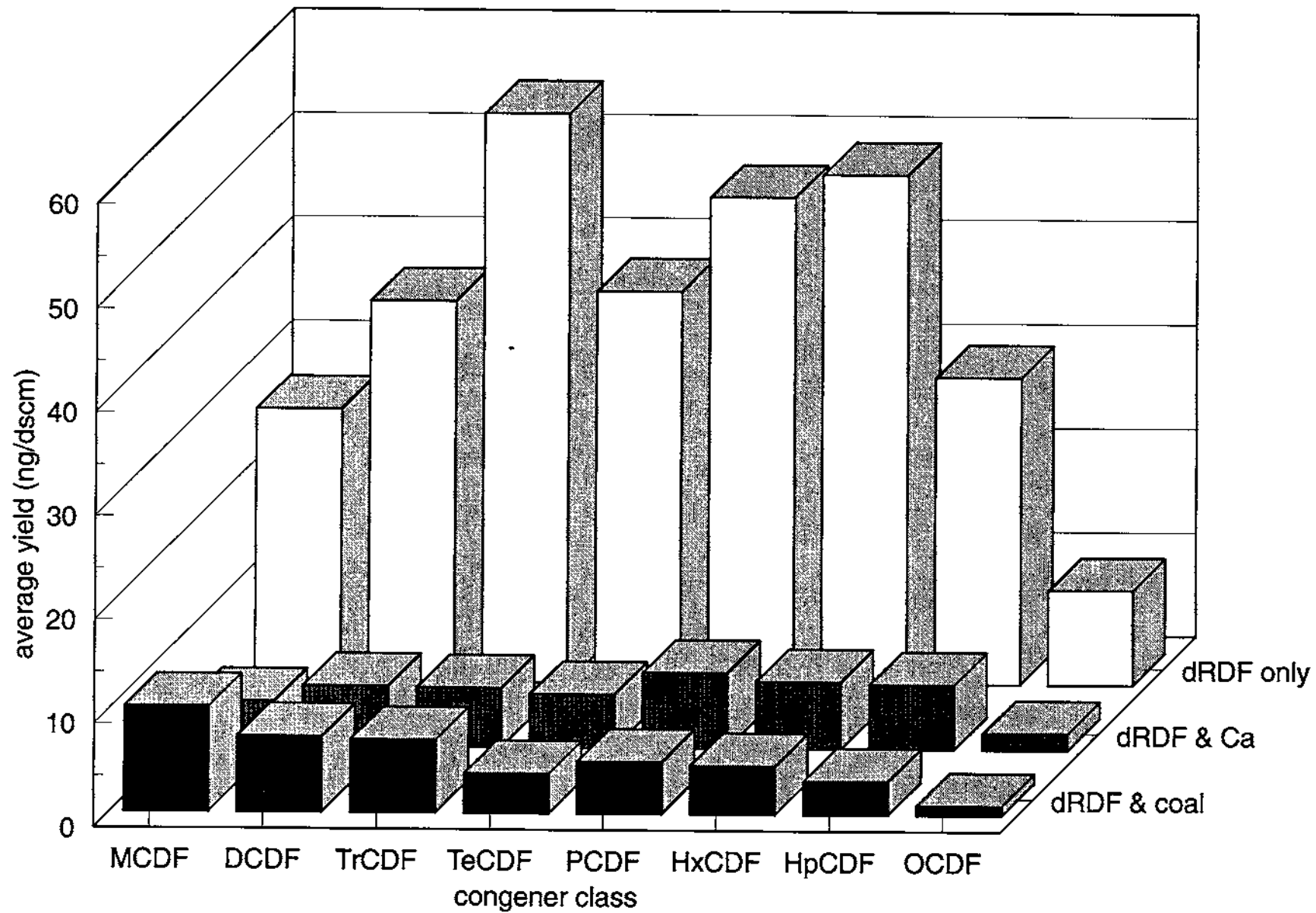


Figure 6. Effects of coal co-firing and sorbent injection on PCDF congener yield from dRDF combustion

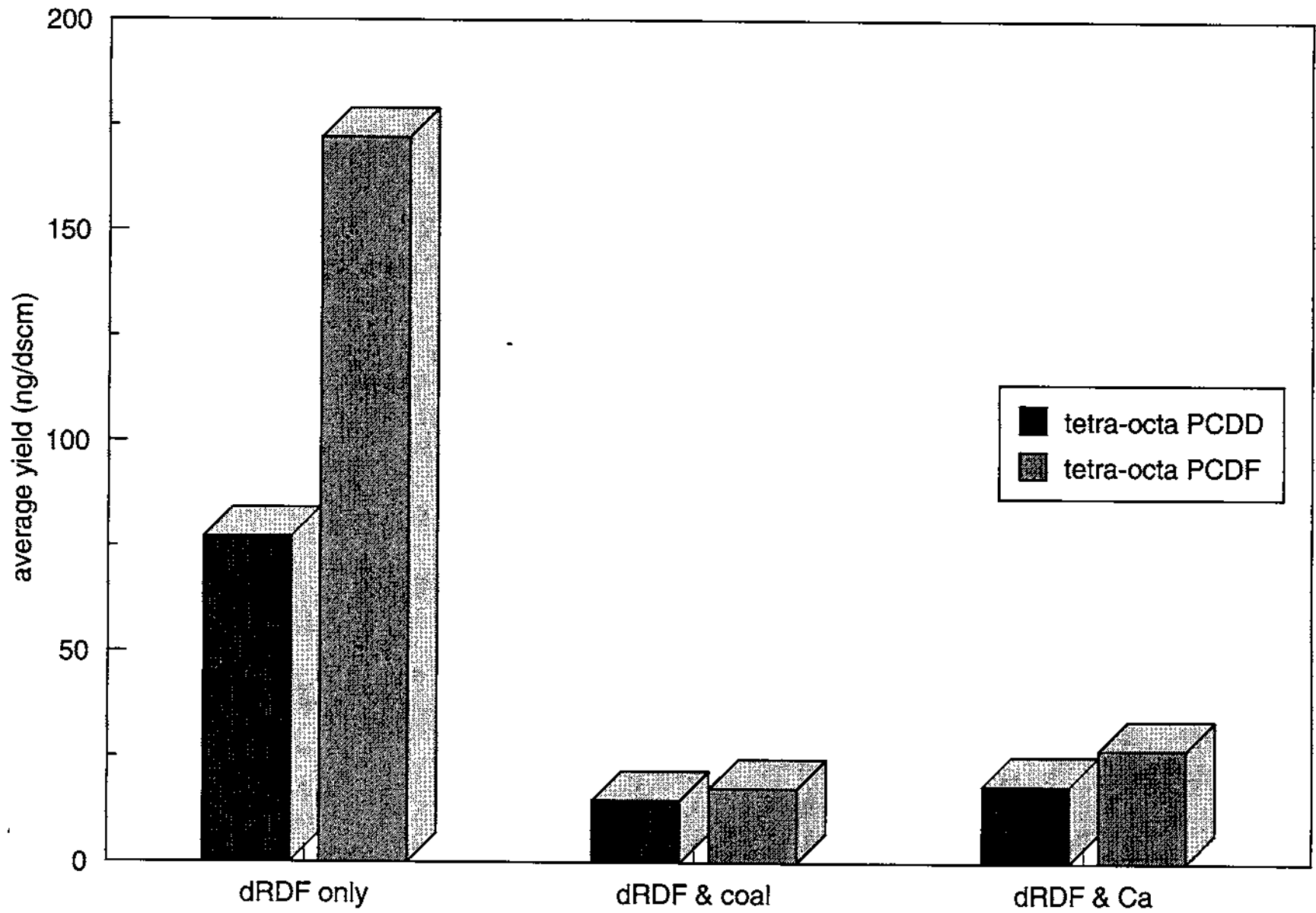


Figure 7. Effects of coal co-firing and sorbent injection on total PCDD and PCDF yield from dRDF combustion

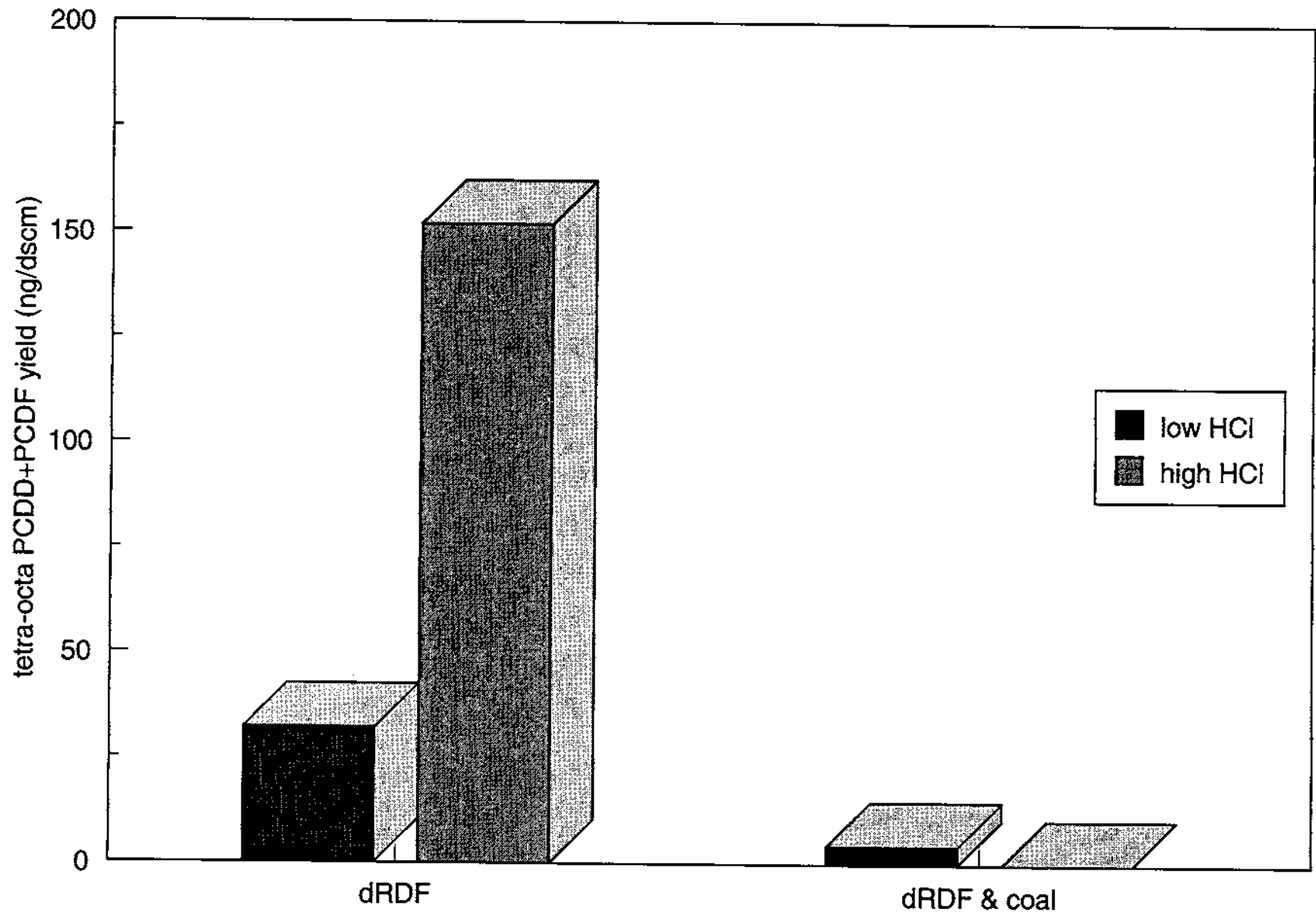


Figure 8. Effect of coal co-firing on PCDD+PCDF yield predicted by the model for Port A (Phase II tests)

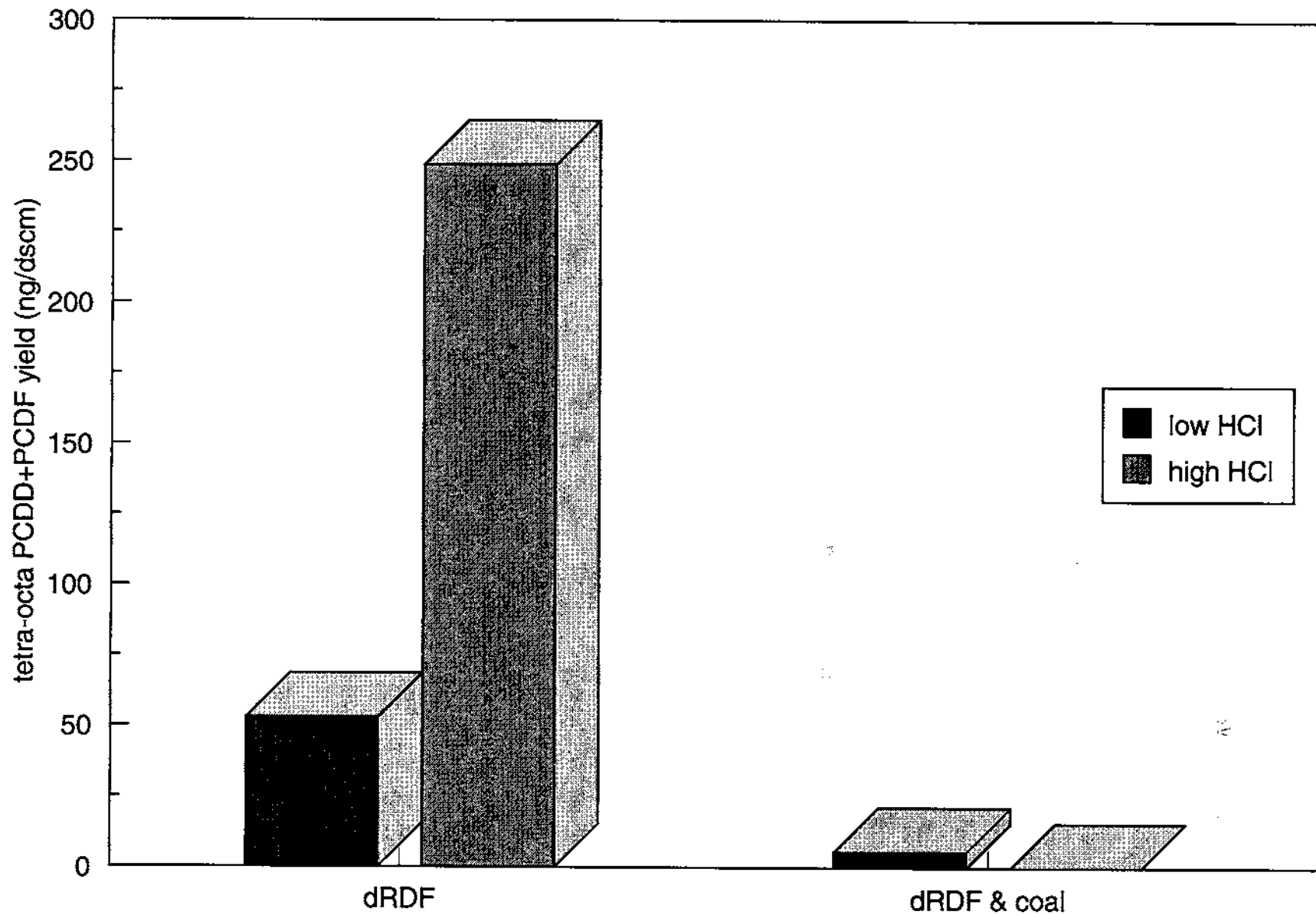


Figure 9. Effect of coal co-firing on PCDD+PCDF yield predicted by the model for Port B (Phase II tests)