Tests of a Prototype of the CLAS Combustion Precursor Sensing System[1]

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1.0 Introduction

The CEBAF Large Acceptance Spectrometer (CLAS) consists of a six-coil toroidal magnet surrounded by components of four types of detector systems in a quasi-spherical arrangement. In order to achieve the highest acceptance, the target region is almost completely enclosed by detectors to a radial depth of up to 6 meters; half of the total volume is taken up by active detector components. By the nature of its design, cables originate over a large volume of space and often run through completely inaccessible paths before arriving at the electronics nearby. The spectrometer is highly segmented in order to handle high luminosity, which means that there are many detection channels and therefore many cables. A significant number of cables are associated with the phototube-based detectors which make up the trigger; for each of these cables there is also a delay cable more than four times as long as the trigger cable. Much of the electronics to which the cables are attached are fast, high-current devices requiring significant cooling to operate.

These intrinsic features of the spectrometer create a rather special fire protection situation.

The total inventory of plastics is approximately 340 cubic meters, of which 90% is from cables. In terms of fuel this vastly outweighs the 1000 cubic feet of flammable gas (diluted with inert gas) present; in addition, the cables are coupled to electronics whose total potential power consumption exceeds half a megawatt. (Further, the DC power supply consumption in the end station for all the normal and superconducting magnets totals to another half megawatt.) The most likely fire scenario during the times when no-one is present in the end station is that some component of the electronics fails, igniting cables which propagate the fire to other cables and fuel sources. Even if the ignition source is due to human inattention (such as hot weld splatter or sparks from metal grinding activity) rather than electronic failure, the largest fuel source is the plastics in the cable jacketing and also in some of the detector systems. For this reason, the cable plant is a major concern of the fire protection system.

Conventional fire protection systems are primarily designed to protect buildings and not the contents of buildings. In a scientific installation such as the CLAS, a very substantial amount of damage has already been done by the time one of the end station dry-pipe sprinkler heads has deployed. Not only does this require an existing large fire to begin with, but the presence of large amounts of water in a densely-packed electronics area is by itself

1. The proposed acronym for this system is “COMPRESS,” for COMbustion PREcursor Sensing System.

enough to produce significant damage to the electronics, and it presents other hazards as well. A significant amount of downtime and repair would be required to restore the spectrometer to a functioning condition for the smallest imaginable fire of this type.

Systems to detect fire conditions at a much earlier stage have been developed. The VESDA ('Very Early Smoke Detection Apparatus') system is a commercial product employed by CEBAF in the experimental halls. At present, this system provides an alarm and arms the sprinkler system. The city fire department is not automatically notified, and no sprinklers operate unless enough heat is present to melt the head. In addition, if the sprinkler head melts but the VESDA system for some reason does not alarm, no water comes out of the sprinkler. This arrangement is referred to as a "dual pre-action" system. This system satisfies all applicable codes, and currently plays an important role in establishing fire insurance premiums and satisfying DOE requirements.

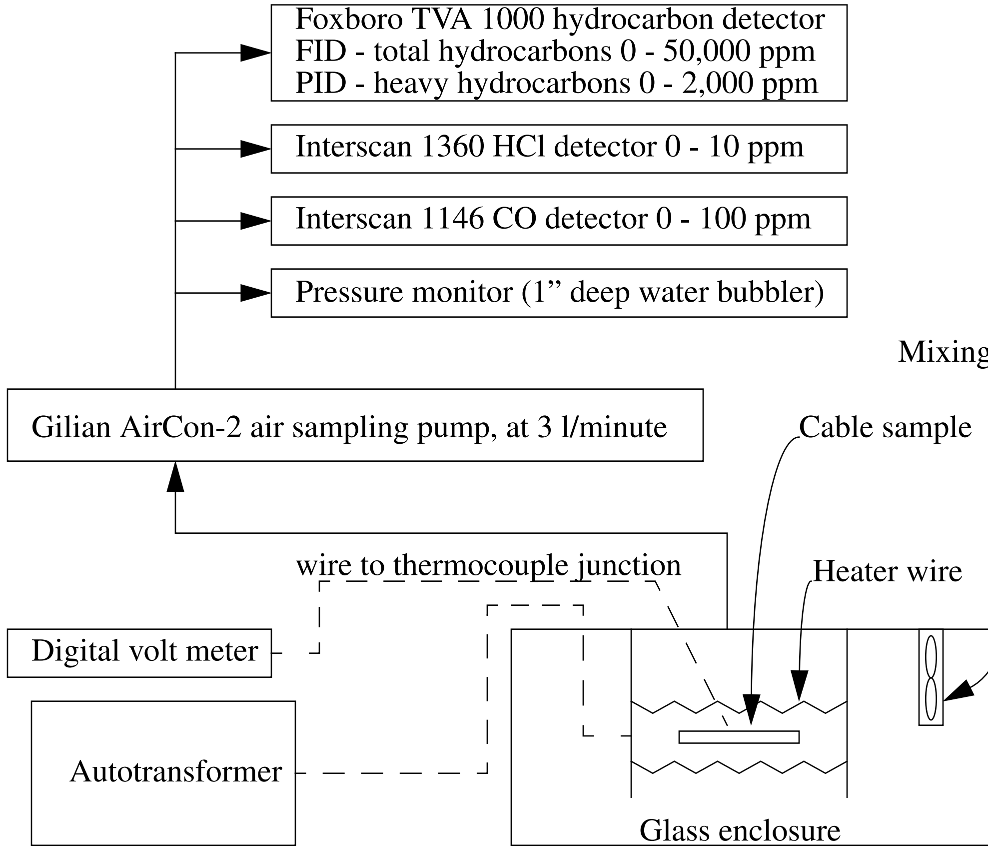
While recent experience with the VESDA system has been reasonably positive, it has in principle, several potential drawbacks. This system employs sensitive smoke and aerosol detection technology. There is a significant variation in the sensitivity of this technology to fires from different fuels; some fuels at a given temperature and power output emit much more smoke than others. A second limitation is that this system is optimized to satisfy the commercial market as a whole; a more focused and sensitive system can be developed if the fuel is known in advance, such as the cable inventory in an installation such as the CLAS. Finally, a dedicated alternate system could provide a level of redundancy to the fire protection scheme to guard against undetected failures of the VESDA system (caused by, e.g, radiation damage to the sensor heads). (Redundant systems are commonly employed when the cost of a failure is very great, such as the dual personnel safety system at CEBAF which protects personnel against accidental radiation exposure.)

Such a dedicated system has been developed at Fermi National Accelerator Laboratory based on a completely different technology. This system is based on detection of gases emitted from a particular fuel when it is heated, in this case cable jacketing. This method is complementary to the VESDA system (which is also employed at Fermilab in the same installation) in that some cable jackets give off gases when heated but very little smoke. The sensitivity of the method for a given installation is only limited by the sensitivity of gas detectors (which is a very mature technology), airflow and diffusion patterns, and the ambient concentration of the gases of interest in the space monitored.

This report describes tests of a prototype of this kind of system which could be used in the CLAS. This prototype is based on gas sampling using a calibrated sampling pump, unlike the Fermilab system which employs diffusion-based sensors. The measurements described in the following were intended to 1) establish ambient levels of the gases of interest in areas similar to those of the CLAS electronics rooms in the end station, and 2) reproduce and characterize the observation of the emission of carbon monoxide (CO), hydrocarbon gases, and hydrogen chloride (HCl) gas from heated cable jackets, using a pump-based sampling system.

2.0 Experimental Method

FIGURE 1. Diagram of the experimental apparatus.



2.1 Experimental Apparatus

A glass enclosure was fitted with a mixing fan, a support for heater coils, a support for a cable sample, and electrical connections for the heater coils. An autotransformer was used to set the voltage across the heater wire. There were four heater wires in series positioned parallel to the cable sample on four sides surrounding the sample. The distance between the heater wires and the cable sample was about 1”. The heater wires were about 3” in length and the cable sample was 2” in length. A calibrated sampling pump removed air at a rate of approximately three liters per minute from the area above the cable sample. Three gas detectors were connected to the output of the sampling pump, in addition to a water bubbler which maintained the output pressure at 1” of water. The mixing fan provided a rapid dispersion of gases throughout the volume of the enclosure. A thermocouple junction was inserted into a small slit in the cable jacket to measure the jacket temperature. The junction was connected to a digital voltmeter.

Two of the gas detectors, for CO and HCl, are based on electrochemical technology. The third detector, the Foxboro TVA, contained two independent gas detectors. One was based on flame ionization detection (FID), the other was based on photo-ionization detection (PID). The FID measures the total concentration of hydrocarbon gases (basically counting H-C bonds). The PID measures the hydrocarbon gases which can be ionized by a 10.6 eV light source; these are the heavier hydrocarbons, in particular, heavier than ethane. The purpose of using this particular detector was to see if an ethane-blind detector would give a useful signal; it is expected that there will be some ambient level of ethane in the end station since the drift chambers use this gas in combination with argon.

2.2 Experimental Procedure

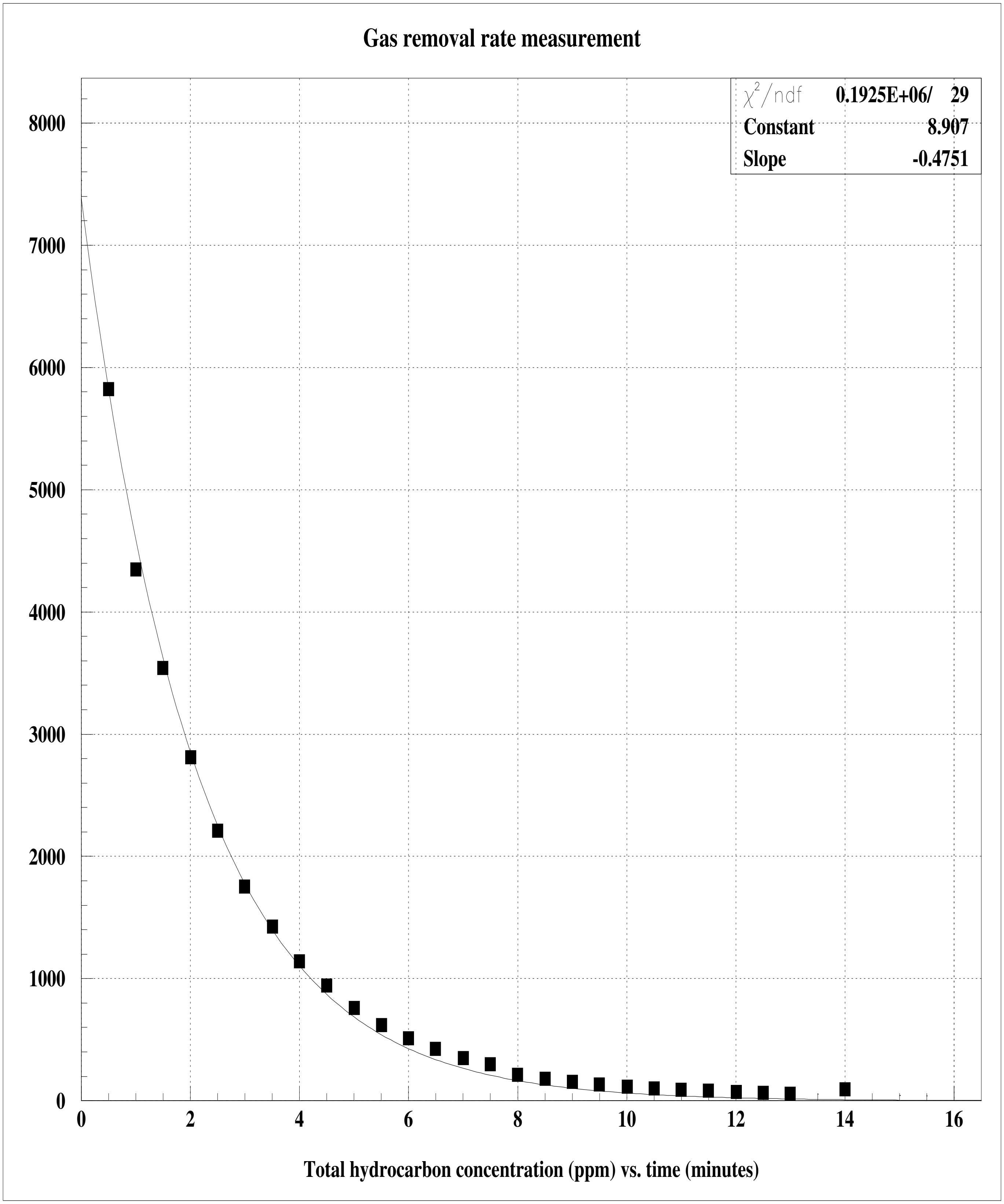
Background levels of the measured gases were obtained at a variety of locations which were expected to be relevant to the final system. Results are reported in the following section.

Calibration of the gas detectors had been performed by the company from which the detectors were rented, just before they were used for these measurements. Qualitative testing of the gas detectors was performed by exposing them to the fuel from a butane lighter, and by lighting a small sample of polyethylene in front of the intake. The first test elicited a very large response from the hydrocarbon detector, and the second produced a response from the carbon monoxide detector. The hydrogen chloride detector did not respond to any simple test, but did give a reasonable indication during the cable heating tests.

For the cable heating tests, all detectors were turned on and allowed to warm up for 15 - 30 minutes. The electrochemical detectors were re-zeroed before each measurement (these exhibited some zero drift). A cable sample was mounted in the center of the heater wire arrangement. Background levels were recorded every minute for several minutes before beginning each trial. The autotransformer was then turned up to a fixed value, and the temperature of the jacket, gas concentrations, and the time were recorded once per minute in a lab notebook. Some experimentation was required to determine a useful operating range of the autotransformer for each heater wire used (several heater wires broke and were replaced). The air temperature in the enclosure was recorded for a few trials, and the humidity and temperature of the outside air was recorded for all trials. The temperature ranged from 68-78 degrees F and the humidity was typically 30%.

One different type of measurement was performed to determine the actual gas removal rate. A quantity of an argon-ethane mixture was introduced into the glass enclosure (approximately 500 cc of 37% ethane, 63% argon) and the output of the FID (which measures ethane) was recorded. The results are shown in Fig. 2. The time constant was determined to be 2.1 minutes. In a model where only gas pumping removes gas, this time constant (for a 10 gallon enclosure) implies a leak rate of 18 liters per minute. Thus the gas pump (at a measured rate of 3 liters per minute) was not the primary means by which the gas in the enclosure was being diluted. The mixing fan blew air past a number of openings which probably contributed to the gas removal rate. In addition, convection of the heated air from the chamber through these openings undoubtedly contributed to gas removal. Finally, diffusion also effectively removes gas from the volume. In a model where convective gas transport is responsible for dilution, the measurement in Fig. 2 gives a rate of removal for all the gases measured. However, to the extent that diffusion is responsible for this removal, the gas removal rate measured is an overestimate for the other gases since the diffusion rate is proportional to the square root of the mass of the gas, and ethane is lighter than all the other gases.

FIGURE 2. Measurement of the gas removal rate of the glass enclosure.



3.0 Background Measurements

The ambient levels of the three types of gases in question were measured in areas which were expected to be representative of the endstation and/or areas dense in electronics and cables. Essentially very little background was found anywhere. Table 1 shows the numbers which were measured.

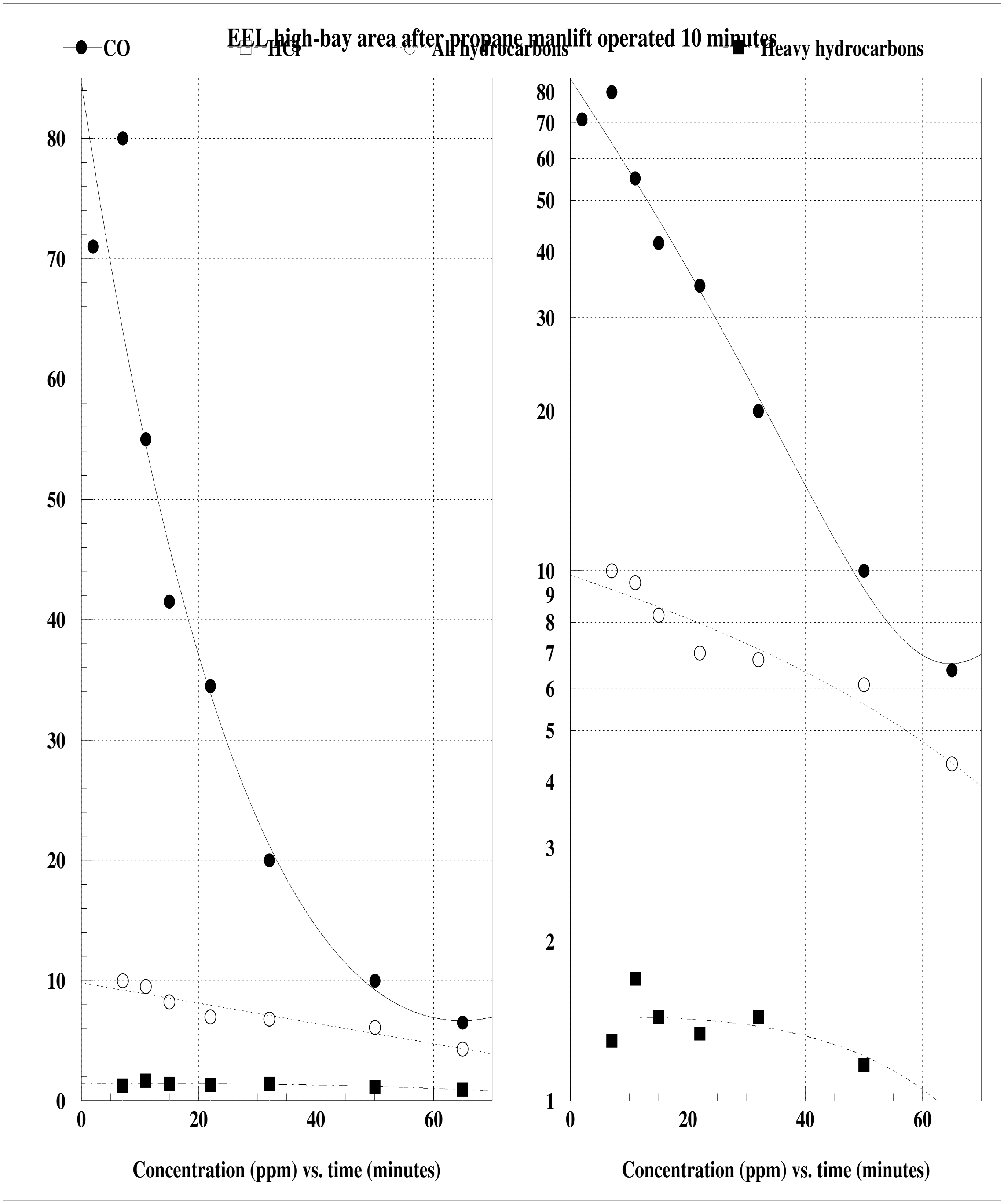
TABLE 1. Ambient levels of gases in areas of interest (ALL UNITS ARE PPM).

Location	CO	HCl	All Hydrocarbons	Heavy Hydrocarbons
CEBAF Center L212 - computer room area	0.8	0.0	0.3-0.4	-0.03
CEBAF Center L220 - computer center UPS battery/transformer room	0.8	0.0	0.1-0.2	-0.04
CEBAF Center B129 (office space)	0.7	0.0	0.0-0.1	-0.01
Test Lab High-Bay Area - cosmic ray test electronics and cables	0.8	0.0	0.2	0.00
EEL High-Bay Area	1.0	0.0	1.0	0.06
End Station B (some welding)	0.9	0.0	5.6	0.02
Hall B Counting House electronics area	0.5	0.0	0.8	0.0
Hall C Counting House electronics area	0.9	0.0	1.1	0.0
Hall C Counting House personnel area	1.0	0.0	0.8	-0.01
EEL High-Bay Area after propane manlift operated for ~10 minutes	80	0.0	10	1.3

The last entry in the table occurred while a propane-powered manlift operated in the EEL High-Bay Area for about ten minutes. A plot of the concentrations measured for about an hour afterwards is shown in Fig. 3 on a linear and logarithmic scale.

At least three comments can be made about this plot. First, this is relevant for a fire protection system since operation of a propane manlift in the area being monitored would produce artificially elevated levels of most of these gases and trigger a false alarm. Second, the time constant for a relatively large volume room is seen to be greater than 20 minutes for the carbon monoxide. This is a crude measurement since this room does not have good mixing and there were probably large concentration gradients in the room. Third, the apparent time constants for the three types of gas are quite different. This is not easily explained by diffusion rate differences, which should be different by only 25% for CO and for propane (CO should diffuse faster, qualitatively consistent with the plot). This is relevant to this study since its conclusions rely on an extrapolation using a gas removal rate measured with ethane only. No simple explanation of this data can really be proven since this is not a controlled measurement.

FIGURE 3. Sample of a large-volume room test following heavy equipment activity.



4.0 Extrapolation from the Test Enclosure to Larger Rooms

The data which follow were obtained in a 10 gallon glass enclosure which had a measured effective leak rate (due to direct or indirect pumping, or diffusion). Under certain simple assumptions these measurements can be extrapolated to larger rooms.

The concentration in any enclosure at time $t+\Delta t$ can be approximately related to the concentration at time t (for sufficiently small Δt) by the following equation:

$$C(t+\Delta t)V \cong C(t)V - C(t)R^r\Delta t + C(t)R^e(t)\Delta t \qquad (1)$$

In this equation C is the total gas concentration (in, e.g., mg/L), V is the enclosure volume, R^r is the removal rate (volume/time) of gas (presumed constant), and $R^e(t)$ is the emission rate of gas from a heated cable (presumed to depend on time). The leftmost term is the total mass of gas present in the enclosure at time $t+\Delta t$; the next term is the total mass of gas present at time t; the next term is the mass of gas removed from the volume in time Δt, and the last term is the mass of gas emitted by the heated cable in time Δt. Any ambient (constant) level of gas is present on both sides of the equation, and therefore drops out. Forming the combination $\frac{C(t+\Delta t)-C(t)}{\Delta t}$ and taking the limit as $\Delta t \to 0$ yields

$$\frac{dC(t)}{dt} = C(t)\frac{R^e(t)}{V} - C(t)\frac{R^r}{V} \qquad (2)$$

which may be rearranged to read (for $C(t) \neq 0$)

$$R^e(t) = V\frac{1}{C(t)}\frac{dC(t)}{dt} + R^r \qquad (3)$$

This relates the rate of emission of gas to the fractional concentration change and to the pumpout rate. Equation (3) may be directly integrated to yield:

$$C(t) = C_0 \exp\left[-\frac{R^r}{V}t\right] \cdot \exp\left[\frac{1}{V}\int_0^t R^e(t)dt\right] \qquad (4)$$

This equation can be checked for consistency: if the rate of gas emission from the cable $R^e(t) = 0$ then any initial concentration decreases exponentially to zero (as was seen in Fig. 2). For $R^e(t) = const = R^r$, $C(t) = C_0$ (no net concentration change when the pumpout rate equals the emission rate). For a gas emission rate which increases with time, the accumulated concentration rises even faster than a pure exponential. The pumpout time constant for the volume is:

$$\tau^r \equiv \tau = V/R^r \qquad (5)$$

Equations (3) - (5) may be used directly to relate the gas concentration time development in the test enclosure (denoted "*te*") to that of the electronics rooms (denoted "*er*") which are being monitored, given an assumed pumpout rate for the electronics rooms. For identical heating conditions the gas emission rate in the test enclosure is the same as it is in the electronics room ($R^e_{er}(t) = R^e_{te}(t)$). Using this, the concentration as a function of time in the electronics rooms is given by:

$$C_{er}(t) = C_{0er}\exp[-t/\tau_{er}] \cdot \exp\left[\frac{1}{V_{er}}\int_0^t R^e_{er}(t)dt\right]$$

$$= C_{0er}\exp[-t/\tau_{er}] \cdot \exp\left[\frac{1}{V_{er}}\int_0^t R^e_{te}(t)dt\right]$$

Using equation (3) for $R^e_{te}(t)$, performing one integration, and simplifying,

$$C_{er}(t) = C_{0er}\exp[(1/\tau_{te} - 1/\tau_{er}) \cdot t] \cdot \exp\left[\frac{1}{V_{er}}\int_0^t \frac{1}{C_{te}(t)}\frac{dC_{te}(t)}{dt}dt\right]$$

Evaluating the integral and simplifying produces the expression

$$C_{er}(t) = \frac{C_{0er}}{C_{0te}}C_{te}(t)\exp[(1/\tau_{te} - 1/\tau_{er}) \cdot t]$$

Recognizing that for the same mass of gas produced, $C_{0er}/C_{0te} = V_{te}/V_{er}$, and allowing for the possibility of pre-existing background levels of gas b_{te} and b_{er}, the final result is:

$$\boxed{C_{er}(t) = \{C_{te}(t) - b_{te}\} \cdot \frac{V_{te}}{V_{er}} \cdot \exp[(1/\tau_{te} - 1/\tau_{er}) \cdot t] + b_{er} \qquad (6)}$$

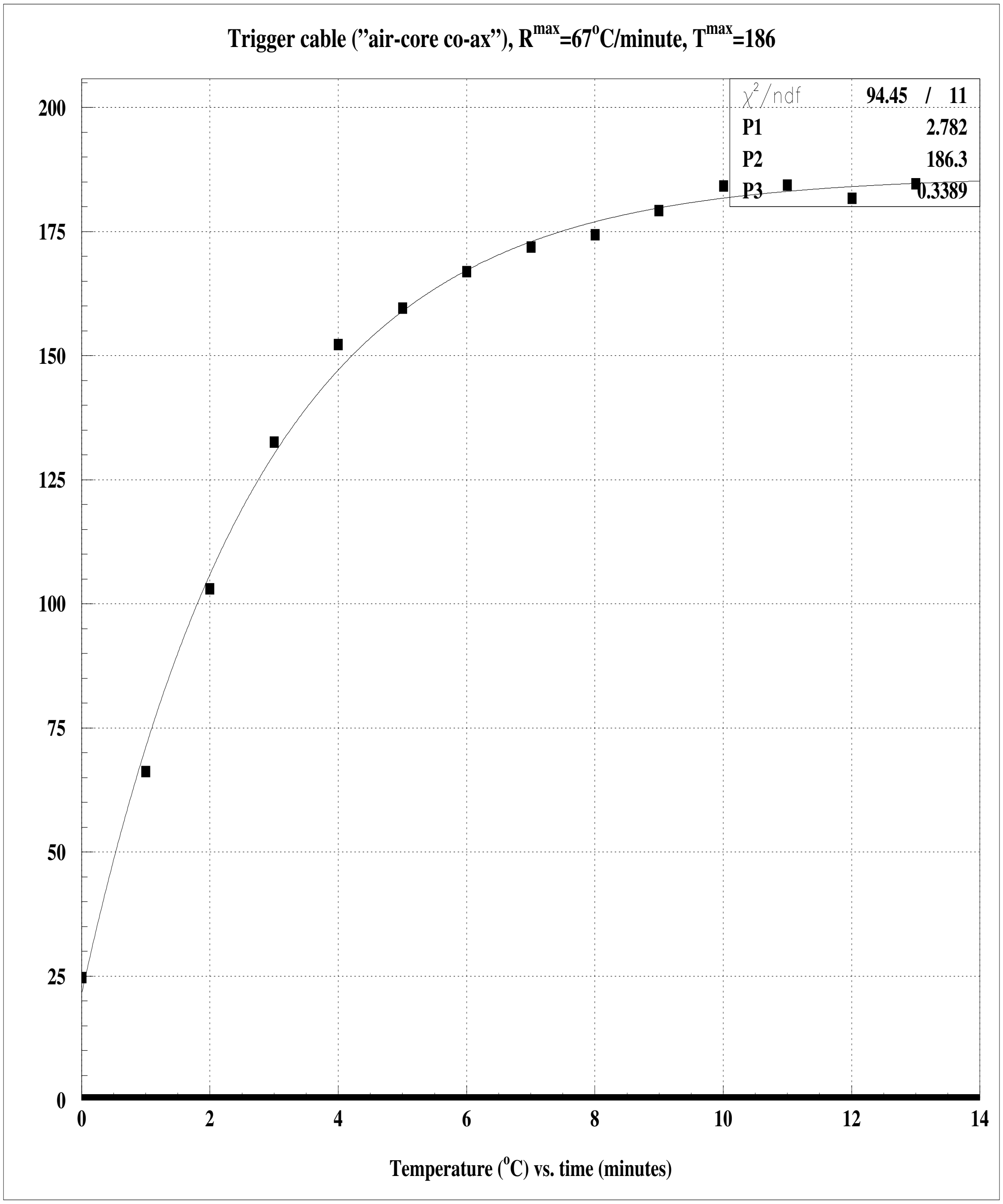
This shows explicitly the three factors influencing the extrapolation: the ratio of the volume of the test enclosure to the electronics room; the leak time constant for the test enclosure; and the leak time constant for the electronics room.

5.0 Cable Heating Tests

5.1 Heating Rate Measurement

The temperature rise of the cable jackets was measured as a function of time. In all tests this consisted of a rise with time which was approximately an exponential approach to an equilibrium value. A sample of this function is shown in Fig. 4.

FIGURE 4. A typical temperature rise curve for the cable heating measurement.



Plots of this function will not be shown for each set of data which follows; rather, the fitted parameters R^{max} and T^{max} are given in the title. T^{max} is the plateau value of the temperature from the fit, and R^{max} is the rate of maximum temperature rise given by T^{max} divided by the fitted time constant. These give a crude idea of the power being deposited in the cable jacket. These parameters depend on the details of the heater wire geometry as well as the cable type and voltage across the heater wire. In the first set of six measurements where the same heater wire and cable sample type were used but a variety of autotransformer settings was used, the time constant (from the exponential fit) for the heating was

3.5 +/- 0.5 minutes for all six measurements, and the maximum temperature (from the exponential fit) increased monotonically with the autotransformer setting. (Over all twelve cable trials, the average time constant was 3.2 +/- 1.1 minutes, a somewhat greater range since several different heater wire configurations were employed.) Therefore the maximum temperature is probably the best parameter to use to estimate relative power deposit, and it is most accurate when the comparison is between two identical cable samples with identical heater configurations.

One complication with all heating trials except for the RG58 cables was that the jacket dripped off after some temperature was reached. This resulted in a visibly decreased signal in some cases, and a less accurate measurement of the jacket temperature in some cases. In a real situation the same problem may happen - if the cable is suspended from a connector the heated jacket may drip off and produce less of a gas signature than if the cable is lying on a supporting surface.

An estimate may be made of the power actually deposited in the cable. The cable jacket temperature was measured to be at a much higher temperature than the temperature of the air in the enclosure, therefore the power deposited in the cable sample can be considered to be from radiation only. A current of 5.4 amperes was measured at a voltage of 140 volts (the autotransformer output voltage for some tests), indicating a total power dissipation of about 760 watts. Based on the length of the heating wires and the distance between the heating wire and the cable, a crude estimate of the fraction of this power deposited in the wire is 4%. From these numbers it is expected that about 30 watts are absorbed by the cable. This gives an order-of-magnitude estimate for comparison with possible ignition scenarios.

5.2 Heating Rate Variation - Trigger Cables

The largest volume of cable in the endstation will be coaxial cable, with a PVC jacket and a polyethylene dielectric. One representative cable of this type is the trigger cable, which is similar to Belden 9913 in construction (popularly called “air-core” co-axial cable). The following six figures show the gas concentrations for all four types of gas on linear and logarithmic scales, and show the extrapolation to the 100,000 liter room volume with an assumed 20 minute leak time constant. (The horizontal and vertical scales have the same range for all of the following twelve figures, to facilitate comparison; the extrapolation shown stops at the same point in time as the measured data.) Figures 5 through 10 are in order of maximum to minimum power deposit as indicated by the parameter T^{max} and also by the autotransformer setting; each of these is for trigger cable, and all used the same heater wire and geometry.

A clear feature of these six trials is that for sufficient T^{max}, there is a *threshold* above which the gas emission markedly increases for all four gas types. This was actually observed for every cable type, the actual value of the threshold depending to a small extent on which cable type is being heated. For the trigger cable, the threshold value is about 150 ^{o}C as seen in figures 5 through 8. Figures 9 and 10 show lower power trials, where the value of T^{max} is less than the threshold temperature. When this is the case, the *shape* of the gas emission curve is different for the different gases, the extreme case of which is seen in Fig. 10 where no carbon monoxide is observed at all for T^{max} = 76 ^{o}C. When T^{max} is well above the threshold value, the shape of the gas emission curves of the different gases are fairly similar.

FIGURE 5. Trigger cable for an autotransformer setting of 75% (of 110 volts).

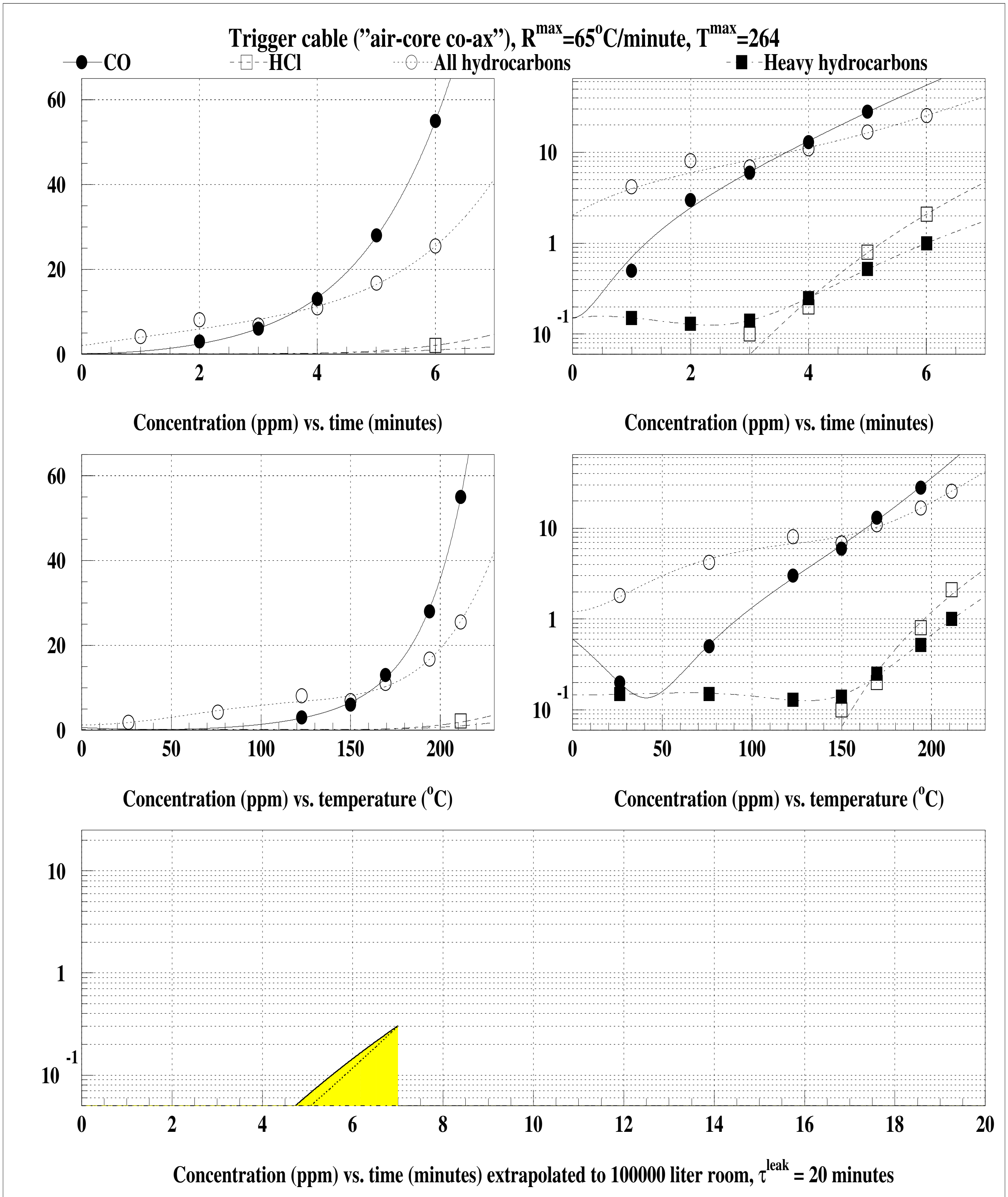


FIGURE 6. Trigger cable for an autotransformer setting of 70% (of 110 volts).

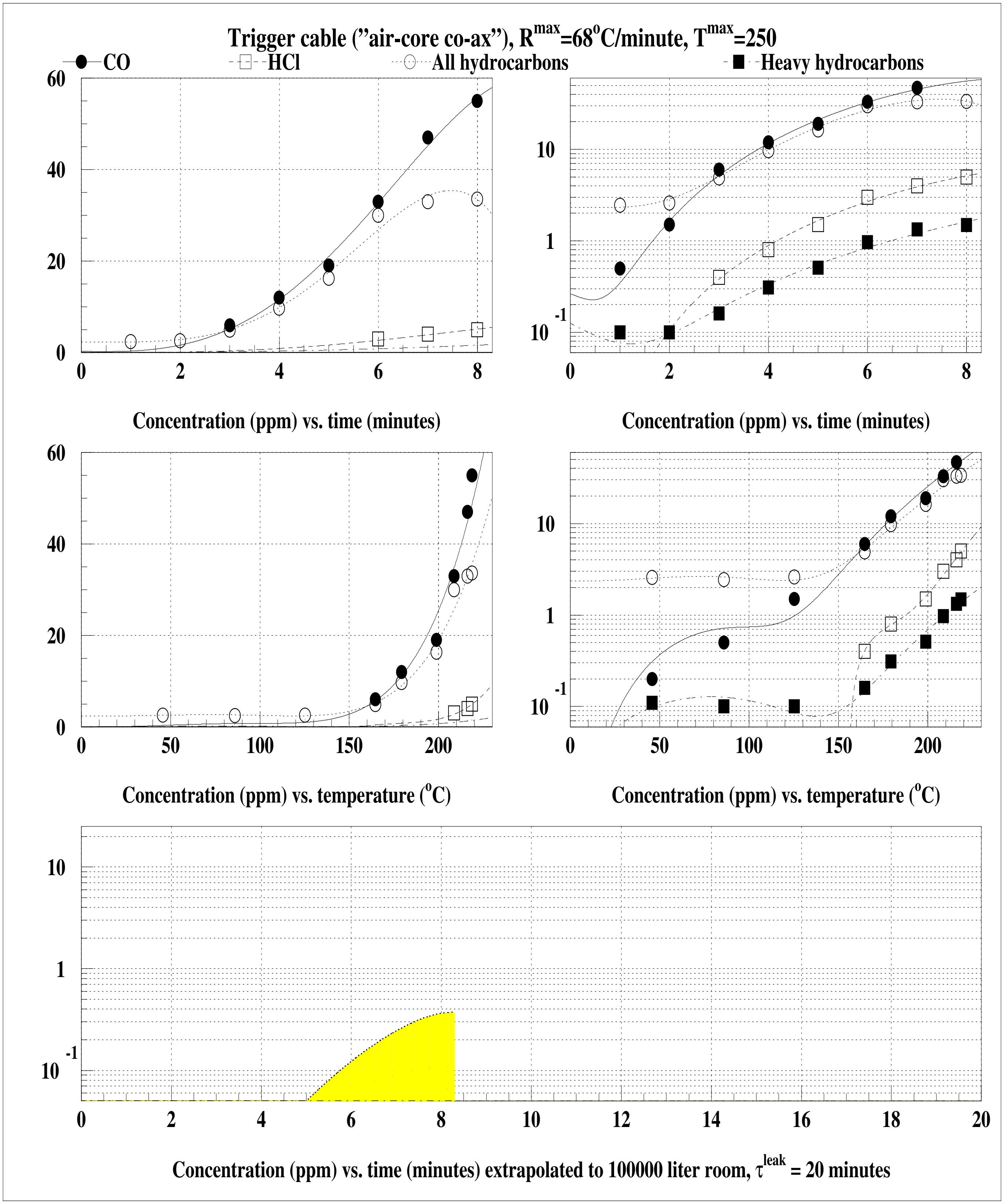


FIGURE 7. Trigger cable for an autotransformer setting of 65% (of 110 volts).

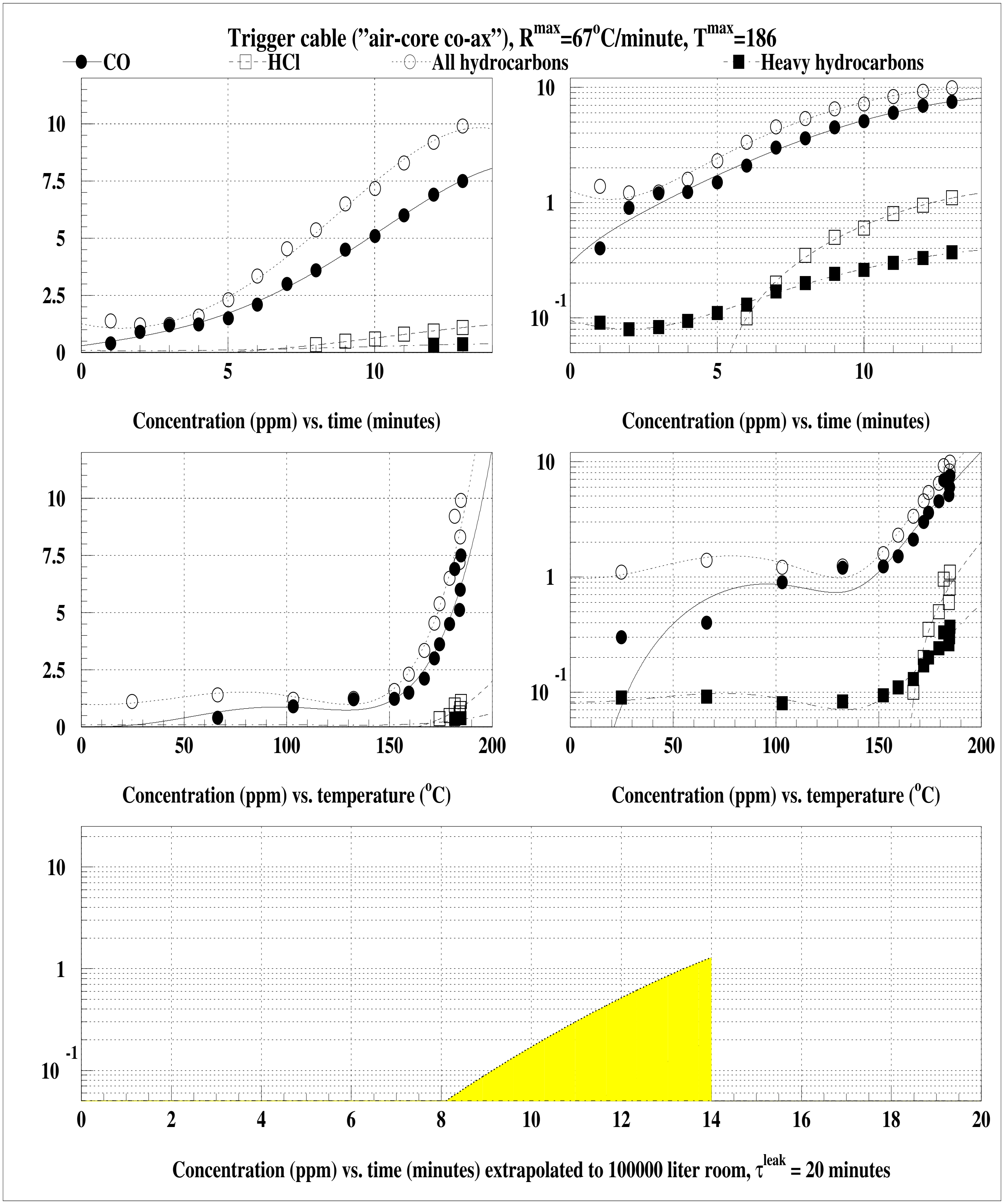


FIGURE 8. Trigger cable for an autotransformer setting of 70% (of 110 volts).

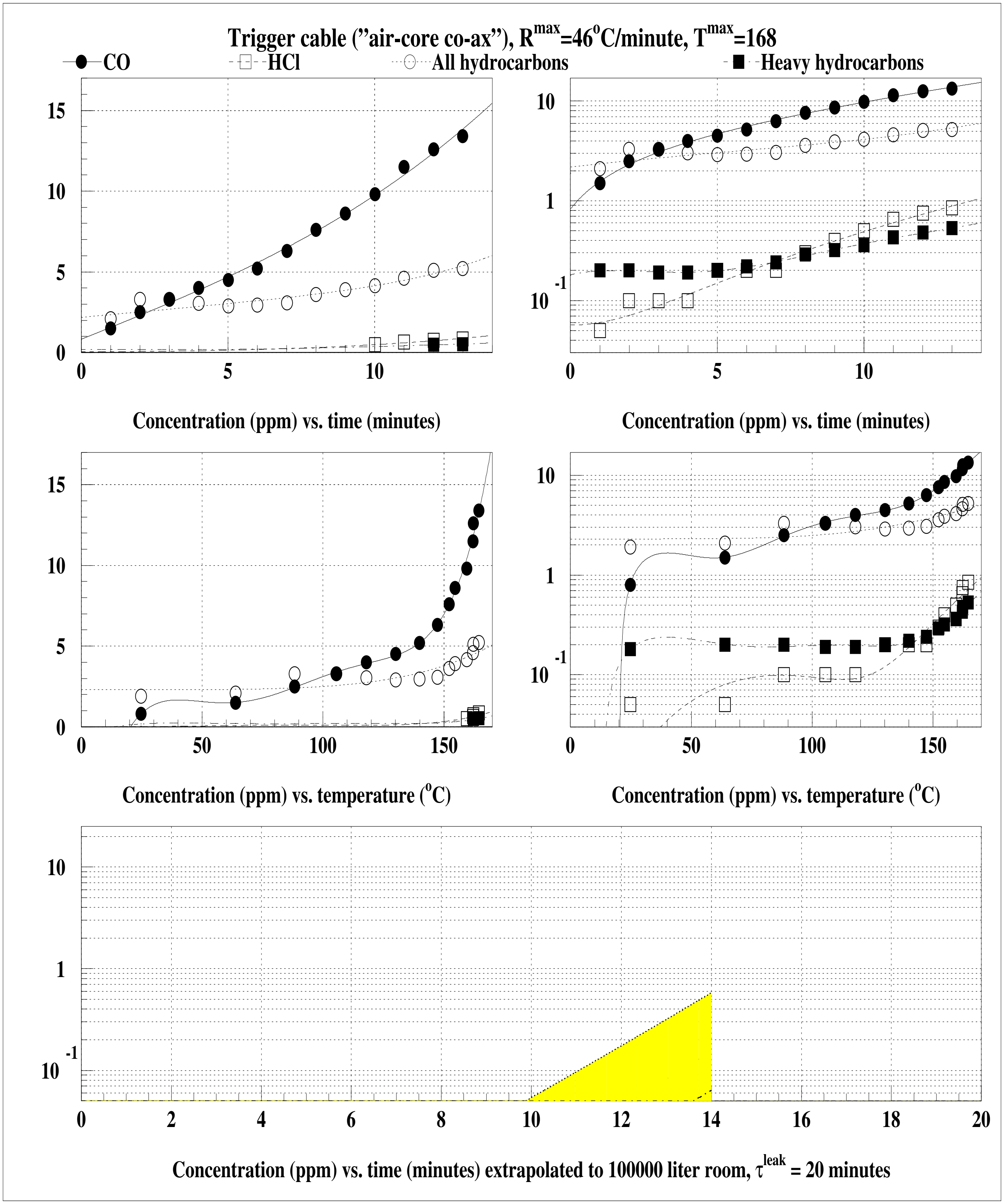


FIGURE 9. Trigger cable for an autotransformer setting of 50% (of 110 volts).

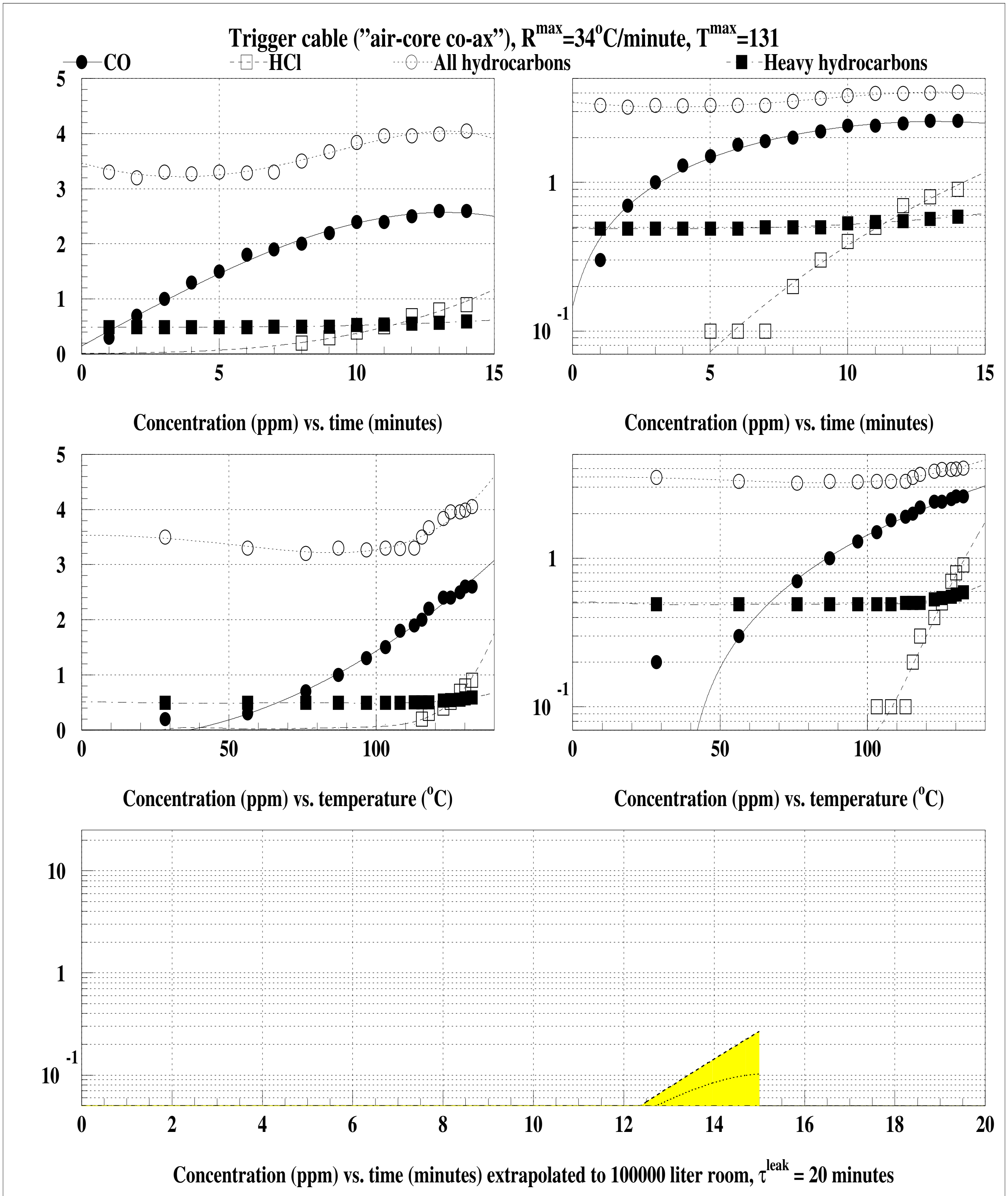
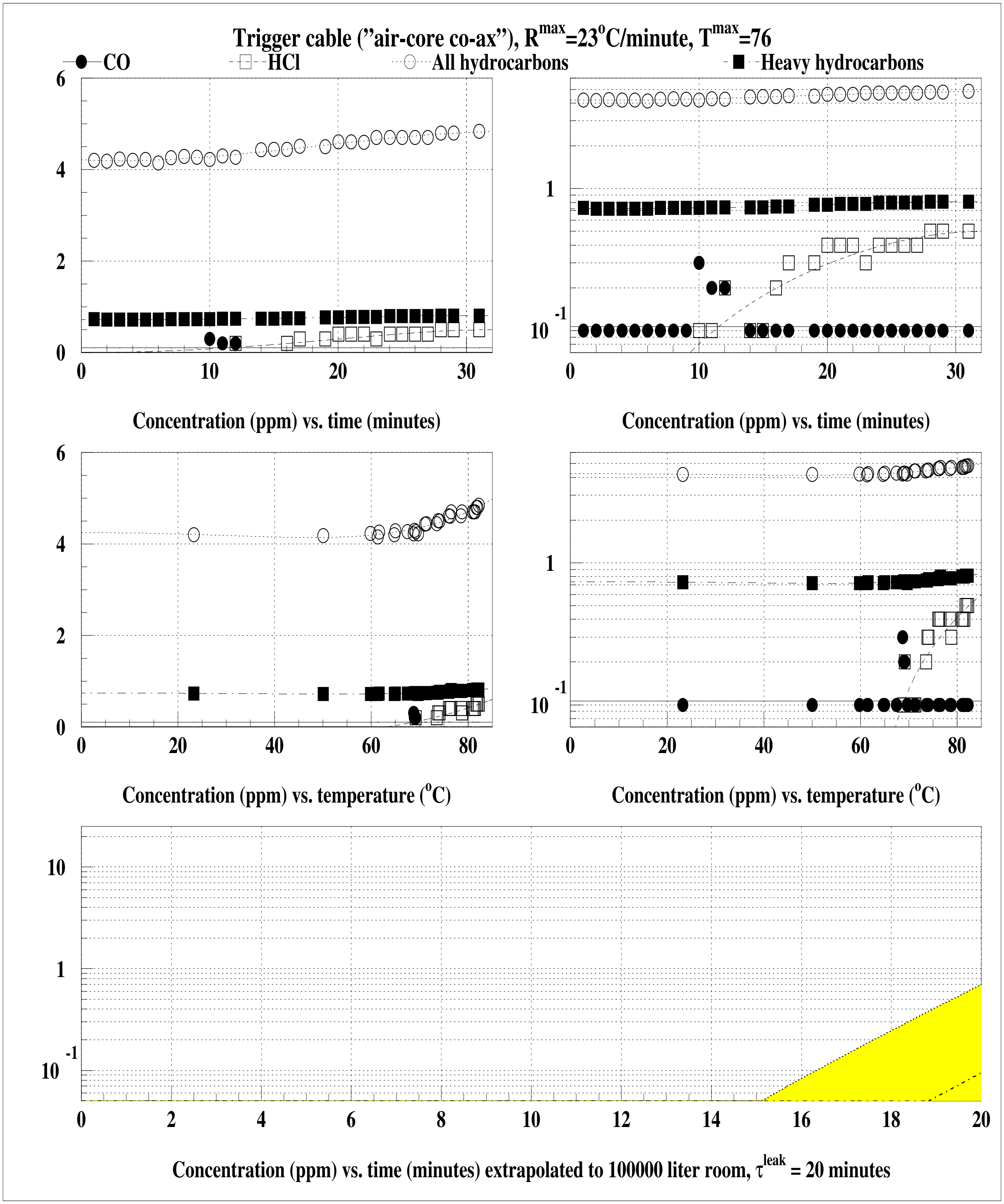


FIGURE 10. Trigger cable for an autotransformer setting of 40% (of 110 volts).



6.0 Drift Chamber Low Voltage Cables (and HCl Transport Test)

The drift chamber “low-voltage cables” provide power for the electronics directly mounted on the drift chambers in a location which is completely inaccessible when the chambers are installed. These cables, unlike the trigger, signal, and high-voltage cables, actually carry a significant current (up to 2.5 amps at 7.5 volts), and there are several hundred of them in the system. While each signal line and signal return line are individually fused, in the unlikely event of a failure (e.g. someone accidentally replaces fuses with the wrong rating and a preamp shorts, etc.) there is a significant amount of power available to dissipate in the cable.

The plots in Fig. 11 and Fig. 12 show the results for the heating tests of the low-voltage cables. The drop at minute 7 in Fig. 11 is due to the jacket dripping off.

Hydrogen chloride gas is known to be difficult to transport through tubing. Various sources have cited significant attenuation of HCl gas in sampling tubes, due to such processes as condensation, absorption into moisture residing in contamination on the tube walls, and reacting with the tube material. Thus the transport problem has been characterized as depending on the tubing material and on humidity; even chemically inert tubing does not solve the problem. (A best guess is that clean, large-diameter, chemically inert tubing in a low-humidity environment will achieve the best results.) In an effort to estimate how big this effect is, the length of Tygon tubing going to the HCl detector was varied during the measurement. Between minute 8 and minute 9 in Fig. 12 the entire gas sampling system was disconnected from the glass enclosure, and the HCl detector was directly connected to the enclosure. This reduced the length of the sampling tube from approximately 66” to approximately 26”. As may be seen, the gas concentration was not observed to change significantly. It would have been expected to increase with a 30 second time constant. At minute 11 on Fig. 12 the entire tubing system was restored to its former routing. While small shifts are seen between these points, no large effect was seen. The ambient relative humidity for this measurement was 32%, and the temperature of the ambient air was 76 ^{o}F. Although the air temperature in the enclosure was not measured for this trial, it was measured for previous trials; in comparing these it is likely that the air temperature was well in excess of 135 ^{o}F inside the enclosure and therefore the relative humidity of the air passing through the sampling tube was probably much less than the 32% mentioned above. While no conclusion can be drawn about the humidity dependence of the HCl transport, it appears that no dramatic absorption is occurring in the Tygon tubing. (See next section for another HCl transport test.)

FIGURE 11. Drift chamber low-voltage heating tests.

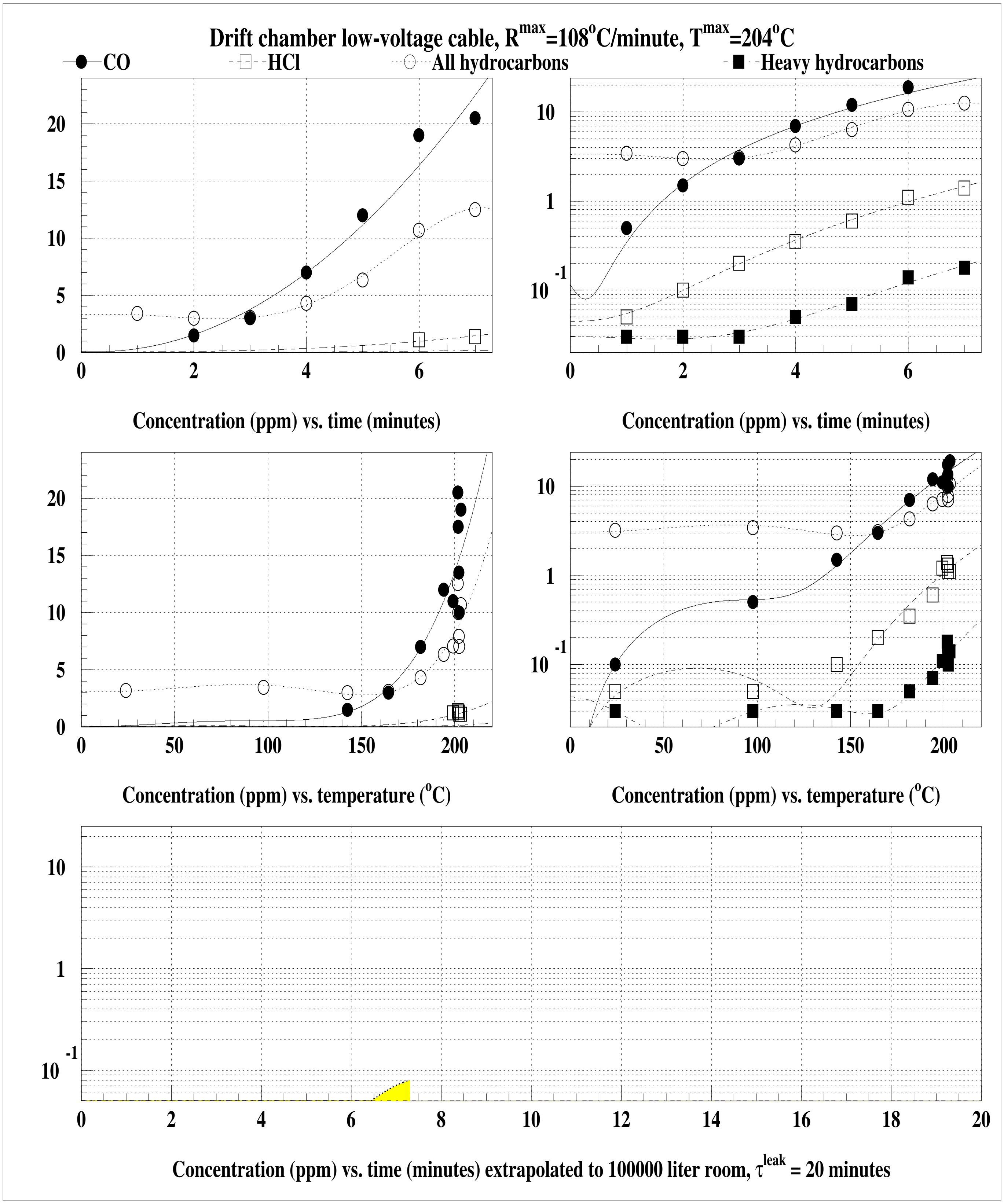
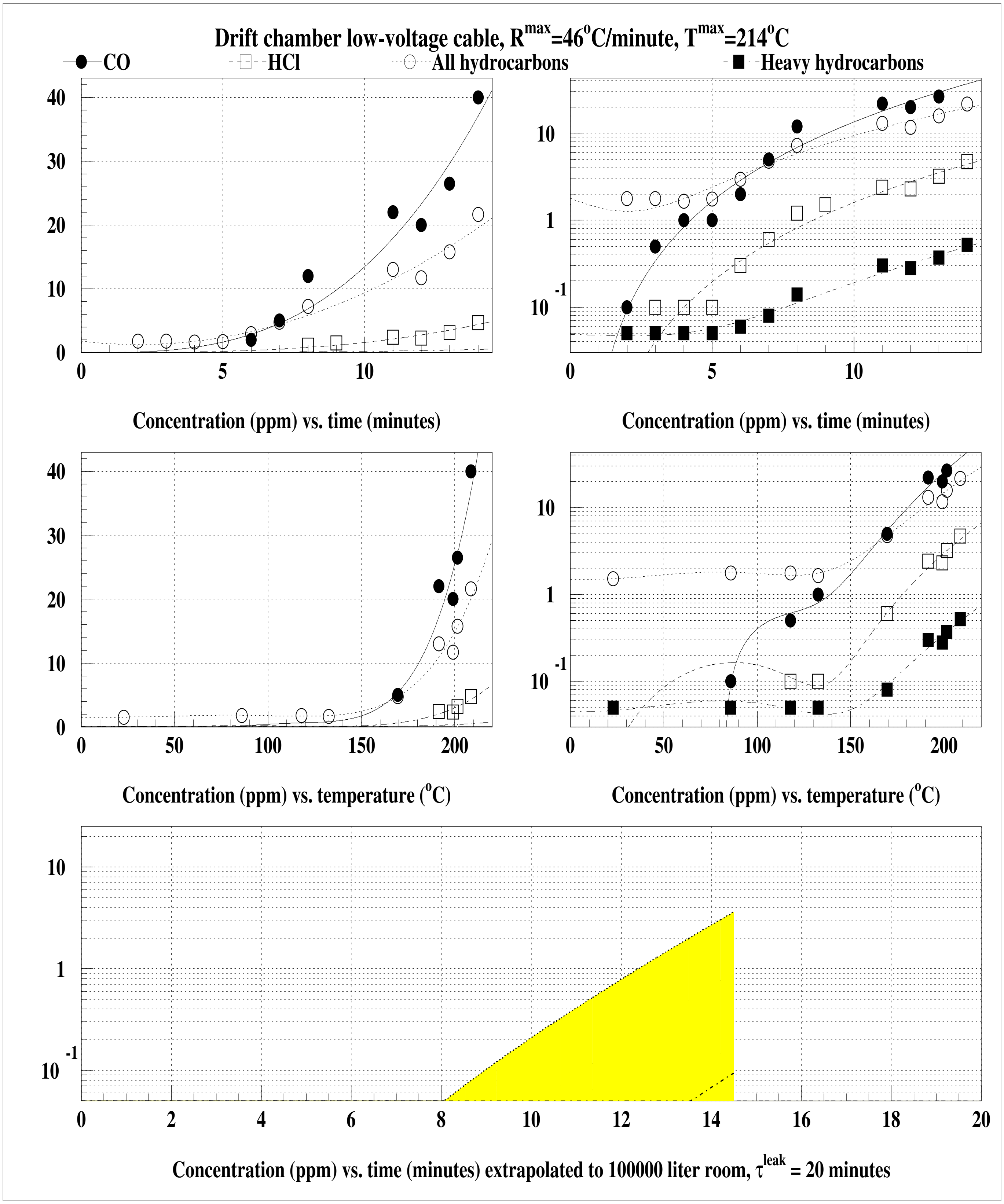


FIGURE 12. Drift chamber low-voltage cable heating tests, with HCl transport test.



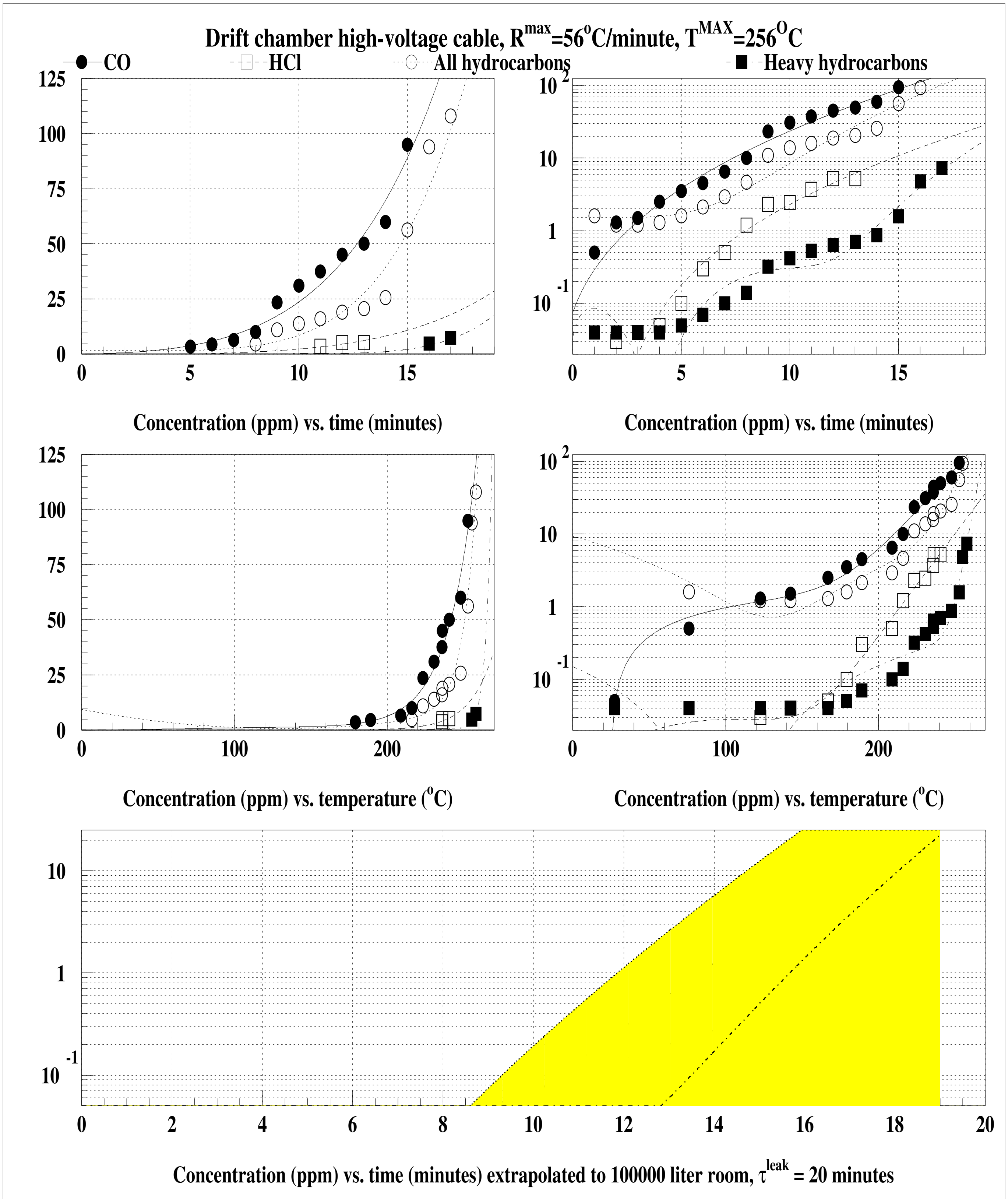
7.0 Drift Chamber High-Voltage Cable (and HCl Transport Test)

The drift chamber high voltage cable contains a number of individual wires with Teflon jackets, contained within a copper braid surrounded by a PVC jacket. It is approximately 1 cm in diameter. Although significant currents are not normally carried by these cables, they are routed near other cables which do, through inaccessible portions of the drift chamber.

Fig. 13 shows the results of the heating test of this cable. During this heating test the length of the tubing going to the HCl detector was varied (see extensive discussion in the previous section). In Fig. 13 a 66” Tygon tube is used through minute 9, then a 168” tube was use for minutes 10 and 11; then the 66” tube was used for minute 12, and the 168” tube was used for minute 13; then the 66” tube was used during minute 14, but no point is plotted because the gas concentration began to rise very rapidly and went off-scale (maximum is 10 ppm for this detector); all gases began to have a rapid rise at this point, as can be seen in the linear plot of concentration vs. time.

The transport time in the longest tube is less than 10 seconds; the detector rise time (to 90% of full value) is 30 seconds. Therefore if significant absorption occurs in the tubing one would expect a jump in the data between minute 11 and minute 12, and between minute 13 and 14. A small jump is seen between 11 and 12, and a jump is seen between minute 13 and the off-scale value at minute 14; the latter may be due to the intrinsic rapid rise in the gas concentration. In conclusion, dramatic absorption of HCl in very low-humidity data does not seem to be occurring when comparing the 66” tube and the 168” tube.

FIGURE 13. Drift chamber high-voltage cable heating tests, and HCl transport test.



8.0 RG-58 Coaxial Signal Cable (and Ethane Atmosphere Test)

Figures 14 and 15 contain the results from the heating tests of RG-58 coaxial cable. Unlike all other cables, the jacket on this cable did not melt and drip off but rather shrank more tightly to the rest of the cable. Once the polyethylene core melted, it was squeezed out either end of the cable by the shrinking jacket.

One of the reasons for choosing the Foxboro TVA 1000 hydrocarbon detector was that it contains two detectors, the FID and the PID mentioned in section 2. The PID is ethane-blind, while the FID measures all hydrocarbons including ethane. This is of interest since there may be an ambient level of ethane in the endstation due to small leaks in the drift chambers, which use an argon-ethane mixture.

The heating test shown in Fig. 15 was performed with an ambient level of ethane and argon present. The ethane-argon mixture was deposited in the chamber at the beginning of the heating process, and was pumped out at the rate shown in Fig. 2. (This is actually different from the conditions in the end station, where the ambient concentration will be nearly constant.)

The first observation is that the PID reading doubled as soon as the argon-ethane mixture was deposited, changing from an initial level of 0.12 ppm to 0.25 ppm. The ethane concentration at the same time was 1443 ppm. The most likely interpretation of this is that there was a small contamination of heavy hydrocarbons in the argon-ethane mixture, since the heating had not yet begun in the test enclosure. It is believable that such a contamination could exist; this corresponds to a ratio of about 1 part heavy hydrocarbons per 10^4 parts ethane.

The next observation is that the ethane admixture affected the measured gas concentration of carbon monoxide. It is possible that carbon monoxide was produced directly at the hot wire; however there was plenty of oxygen present and the normal combustion of alkanes simply produces carbon dioxide and water vapor. Another possible explanation is a cross-sensitivity of the CO electrochemical detector to ethane. A check of available literature on one model of CO and HCl detectors (manufactured by a different company) revealed that the CO detector had a 90% response to ethene (C_2H_4) while the HCl detector had only a 2% response to ethene. (No information was available on ethane.) This explanation is not satisfactory, however. Upon introducing the argon-ethane mixture to the test enclosure, the measured CO level rose from 0.1 ppm to 1.4 ppm, and stayed there for two minutes. Upon turning the heat on, the registered CO level rose to 10 ppm in one minute, and 45 ppm in the second minute. Therefore, the heating played an important part in raising the CO level or the level of a gas which has a cross-sensitivity with the CO detector such as ethene. In any case, in a fire safety system, the measured gas signal could conceivably be slightly larger in an ambient level of ethane.

The original idea of using the ethane-blind detector to “see” the combustion gases in the ethane environment does not seem to be very well supported by the data, since the concentration of heavy hydrocarbons is only a small part of the gases produced by the heated cables.

FIGURE 14. RG-58 co-axial cable heating tests.

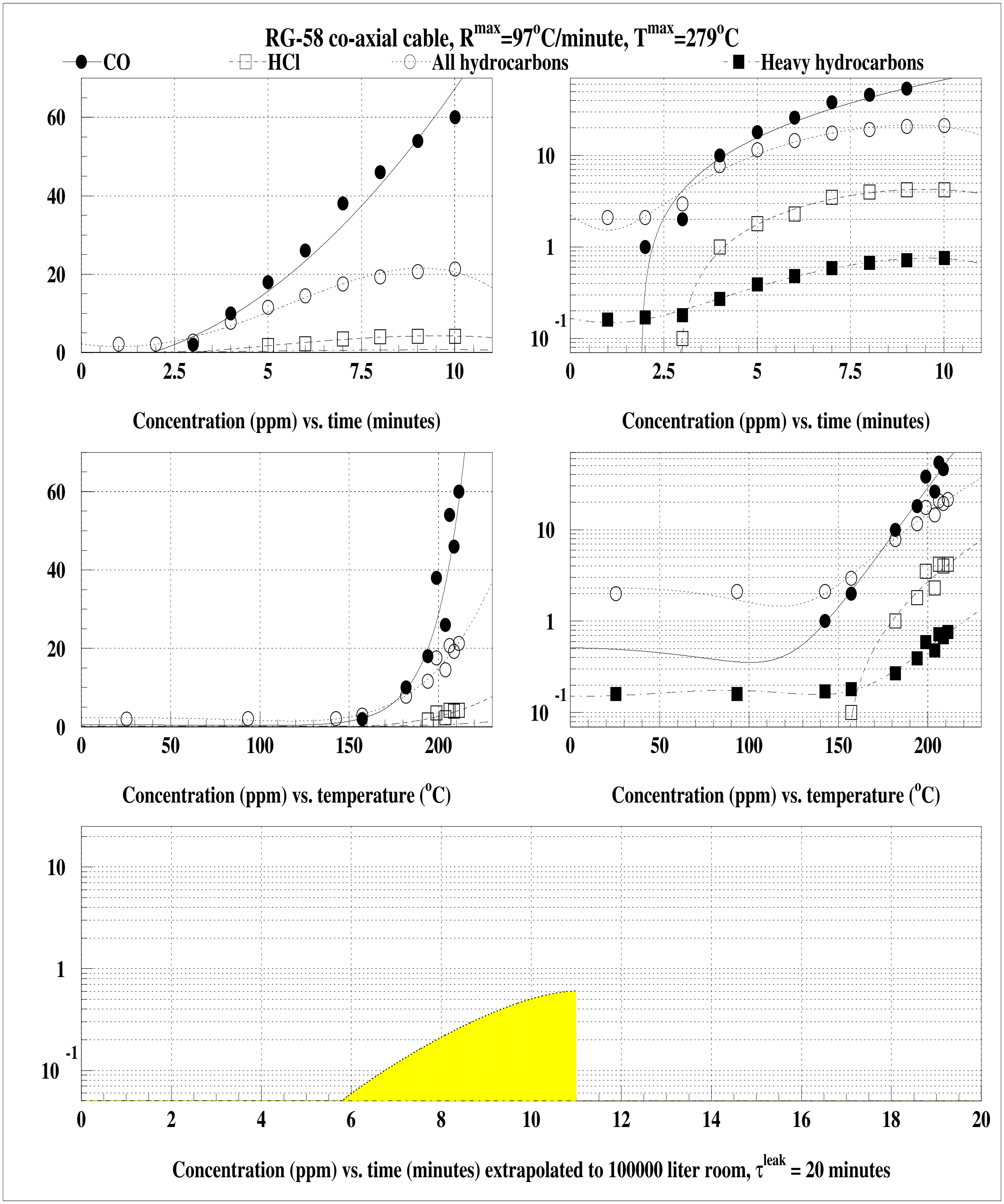
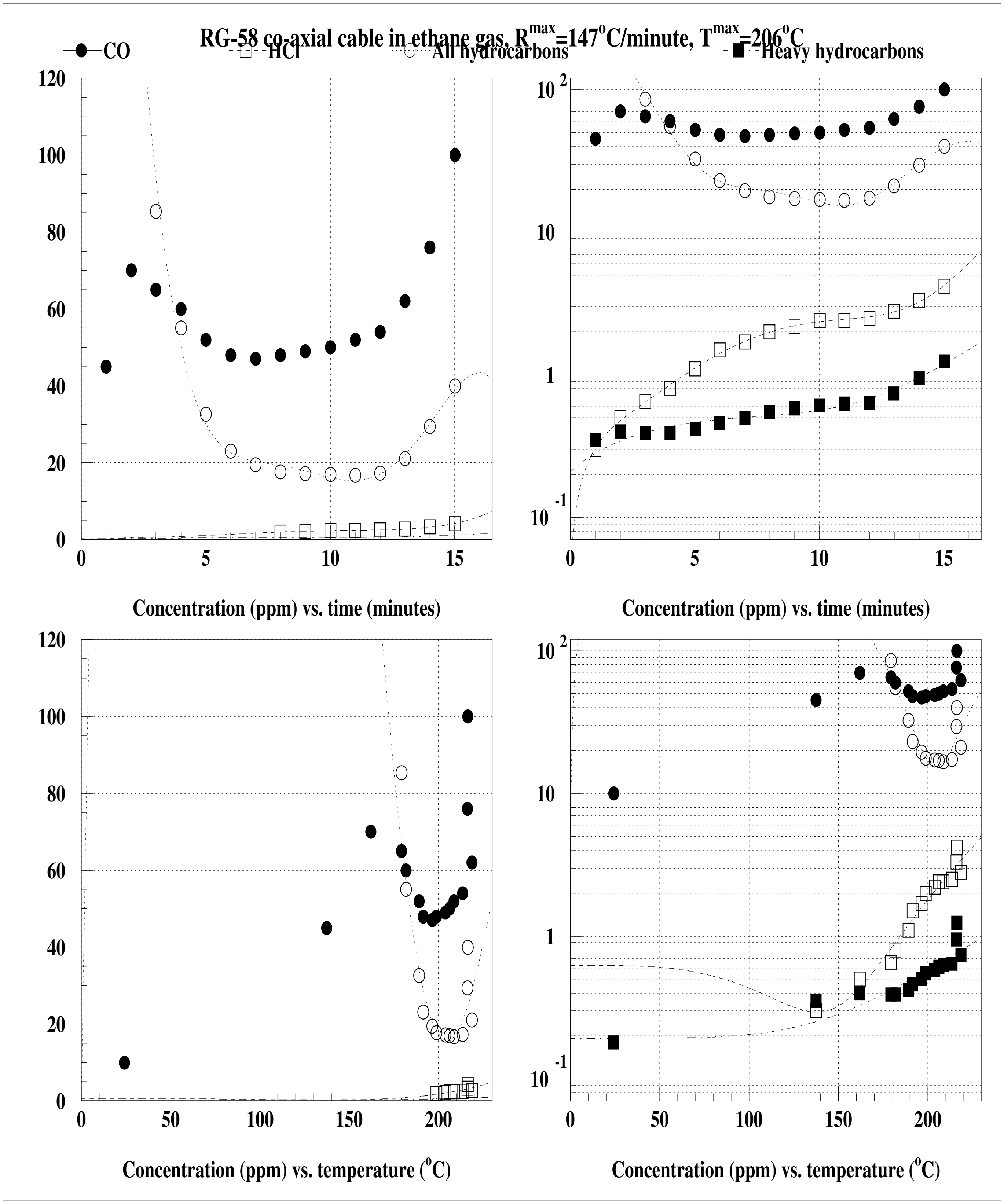


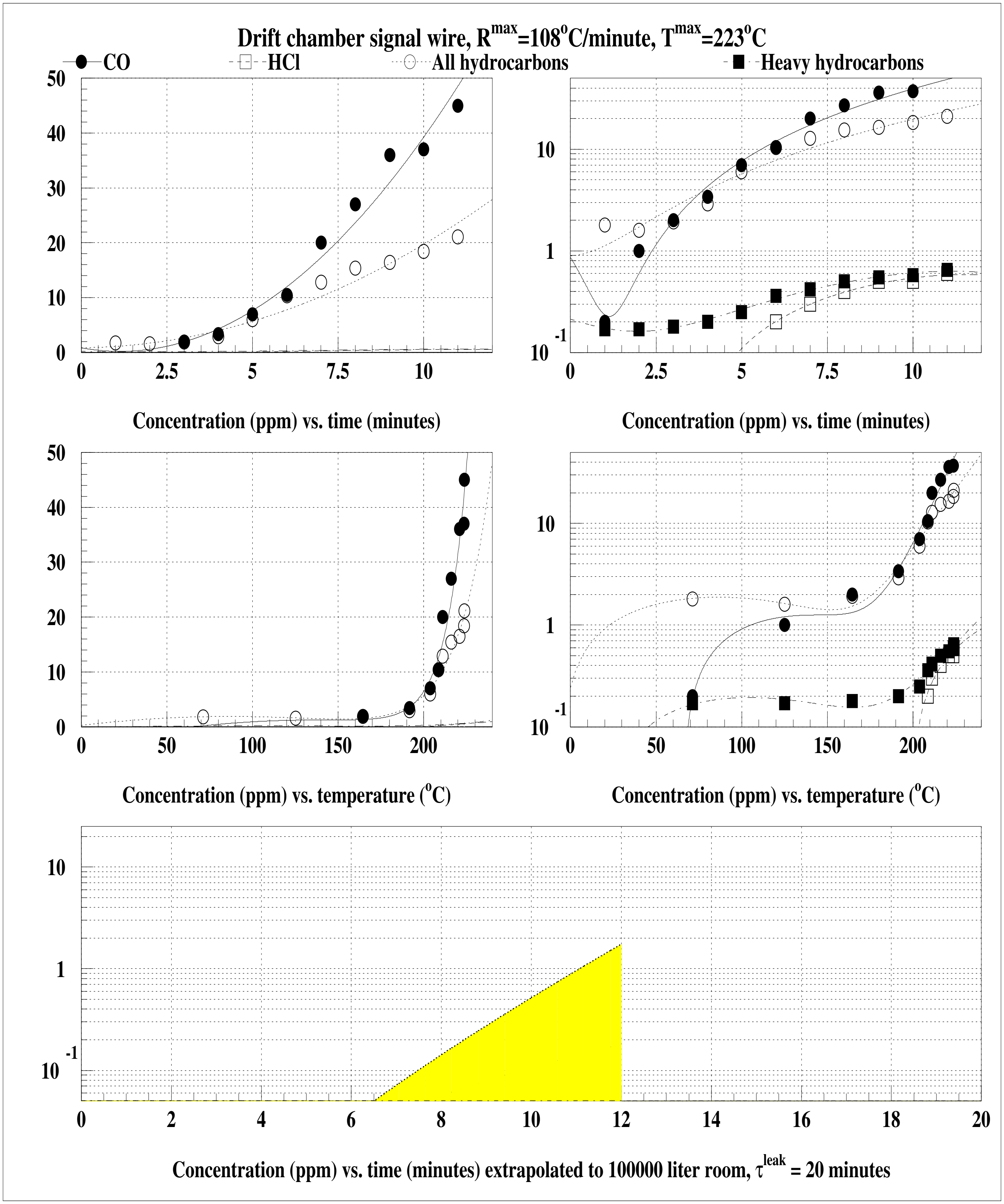
FIGURE 15. RG-58 co-axial cable heating tests in an argon-ethane atmosphere.



9.0 Drift Chamber Signal Wire

The drift chamber signal wire is a bundle of twisted pair cable packed cylindrically with a braid shield and a PVC jacket. The data from its heating trial is shown in Fig. 16. The threshold value here is about 200 ^{o}C.

FIGURE 16. Drift chamber signal wire heating tests.



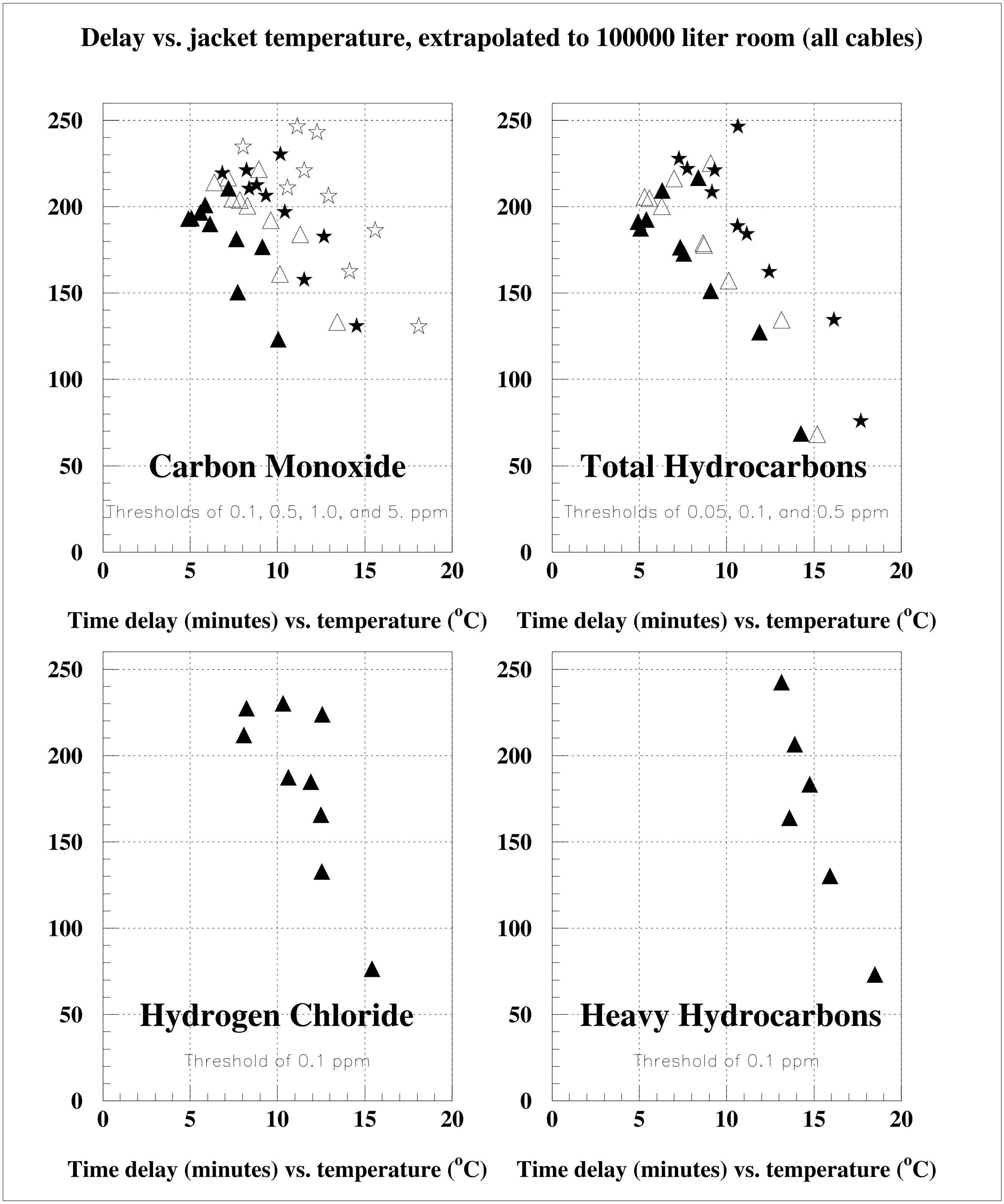
10.0 Global Features of the Data

Fig. 17 displays some global features of the data already presented which serves to establish the basic characteristics of the sampling problem as projected to the 100,000 liter room with a 20 minute leak time constant. Each of the four plots pertain to only one kind of gas. Within each of the four plots is data from all cable types tested. Each plot shows the raw time delay from the time the heat was turned on until the gas concentration crossed a given threshold. For the lower two plots, only one threshold is considered, at 0.1 ppm. In the upper two plots, multiple thresholds are shown; each symbol represents a different threshold value, and the different points represent different cable trials which spanned a range of jacket temperatures and time delays.

A very simple picture emerges here, despite small fluctuations from one cable sample to the next. For a given threshold, there is a family of data which has a negative slope; the higher the temperature of the jacket, the sooner the signal crosses that threshold. For higher thresholds, a similar family exists, but it is shifted to later times. Because the concentration as a function of time rises exponentially, the time shift for the higher threshold families increases only logarithmically with an increase in the threshold.

The data exhibit one general feature: the overall time delay ranges from 5 to 15 minutes for gas detection thresholds of 100 ppb and jacket temperatures of 150 - 250 ^{o}C. Higher thresholds could be used for carbon monoxide and total hydrocarbons, with a time penalty of 3 - 4 minutes for a 500 ppb threshold, or a 7 - 8 minute penalty if a 5 ppm threshold for carbon monoxide is used. The data measured in this study could not be extrapolated any further than what is shown in the plot, but the general features are likely to hold over a larger range. Most notably, if a high initial temperature occurs, the time delay for the carbon monoxide and the total hydrocarbons is likely to be of the order of 5 minutes for any reasonable threshold. It should be noted that this entire study has used 2” long cable samples. The extent of the cable being heated depends on the fault condition; the 2” length is reasonably representative of a single cable being heated by a hot connector to which it is attached.

Time delay as a function of temperature and threshold; all cable tests are shown.



11.0 Uncertainties

There are a few uncertainties in the measurement and extrapolation. First, electrochemical detectors are known to have a temperature dependent response. This is likely to be a 10 - 15% effect in the results presented (based on data for similar detectors), where a larger signal is measured for the CO detector, and a smaller signal is measured by the HCl detector at the elevated temperatures in this measurement, relative to the correct concentration value. A second uncertainty is the influence of the measured leak rate of the test enclosure on the extrapolation to the 100,000 liter room. Because the extrapolation involves an exponential time dependence, a small error in the measurement of a time constant can propagate into an arbitrarily large error in a concentration at large times. To be more specific, fitting two different regions of the data in Fig. 2 yields time constants for the test enclosure of 2.1 and 2.4 minutes, a 15% difference. Using equation (6), for a time delay of 5 minutes, this gives a change of 135% in the extrapolated concentration; for a time delay of 10 minutes this gives a change of 180% in the extrapolated concentration. This essentially translates into an uncertainty in the thresholds quoted for the extrapolation; the most reliable extrapolated data are at short time delays and smaller thresholds.

Practical measurements in a real 100,000 liter room will not have complete mixing of the gas as has been assumed here. Locating the sampling tube strategically can probably have the effect of increasing the effective concentrations; for instance, if the gases are produced as a result of the heating process, they are more likely to be concentrated near the ceiling than near the floor. An additional consideration is that all of these measurements and extrapolations are for a 2" length of cable. If the cable is attached to a hot connector, this may be a realistic effective length; if excessive current is passed through a long cable the signal will be correspondingly larger for the same jacket temperature. There are clearly many heating scenarios which are possible.

12.0 Implications for the Design of the CLAS Combustion Precursor Sensing System

In designing a practical system for the CLAS from this data it is necessary to consider several aspects of Fig. 17. First, based on the measurements in Table 1, there will be ambient levels of carbon monoxide and hydrocarbon gases at a level of about 1 ppm in Hall B during operation. Therefore for these gases the "thresholds" indicated in Fig. 17 are really the concentrations above background. Since the background levels can fluctuate over time, and the gas detectors can experience zero drifts (especially the electrochemical detectors), this imposes some sensitivity limit in a practical setting. This is somewhat offset by the capability of monitoring changes over time, so that small, persistent average increases in one particular room can be noted. In addition the system could be normalized to the background in the overall hall volume, which is too large to be changed by a small emission of gas in an enclosed electronics room. Notably, the expected background of HCl is zero ppm, somewhat offsetting the small signal it produces; similarly, the expected background of the heavy hydrocarbons is less than 5 ppb, according to Table 1.

A second consideration is that it is desirable to protect against a variety of cable ignition scenarios. It can be seen in Fig. 6 that a rapid rise in temperature will be accompanied by a sizable signal of carbon monoxide and hydrocarbon gases; in this measurement T^{max} = 250 ^{o}C. By contrast, however, it was observed in Fig. 10 that in the case of a lower temperature, T^{max} = 76 ^{o}C, no carbon monoxide was produced; yet at this lower temperature both hydrocarbon gases and hydrogen chloride gas were emitted, although at a lower rate. In a scheme where two out of three elevated gas concentrations are required to sound a fire warning, all three detector types would be needed to obtain sensitivity at both lower and higher jacket temperatures. Although it takes longer to accumulate enough gas to cross a given threshold, for the lower jacket temperatures it is much less critical to have a rapid warning. The real measure of the criticality of the time delay is how long it takes for the cable to approach the temperature at which a flame ignites. This might be a matter of hours for a small electrical fault, or a couple of minutes for a dramatic electrical failure.

Another practical issue is to determine the optimal cost to sensitivity ratio for the gas detectors. In this general range of sensitivity, one order of magnitude increase in sensitivity is generally accompanied by one order of magnitude increase in cost for conventional gas detectors. The practical lower detection limit depends somewhat on the gas type; 0.1 ppm can be attained for all three gas types, but this requires typically 2 minutes of signal integration and very low humidity for the HCl measurement, while CO detectors in the same price range can attain this sensitivity or better in less than half this time. The hydrocarbon detectors used in this measurement have an even faster time response with equal or better sensitivity compared to the CO detectors. Detectors based on electrochemical technology (for CO and HCl only) have similar time constants but the minimum detectable concentration is an order of magnitude larger if zero drifts are considered. The detector response time is an important parameter in a sequential sampling system, where the mean time between samples grows with increasing detector integration time.

From Fig. 17 it may be seen that a significantly early warning may be obtained with a 0.5 ppm threshold for the carbon monoxide and hydrocarbon (FID) detectors, and perhaps even lower if the threshold is considered a low level warning. Since the expected background is 1 ppm, this requires detectors with good resolution and good zero drift characteristics, as well as a controlled background measurement. Given the difficulties of sampling HCl, the minimum practical threshold for HCl is probably 0.5 ppm or more for a low level warning. The high stability of the heavy hydrocarbon (PID) detector which was employed for this measurement would allow a much lower threshold to be set than the 0.1 ppm shown in Fig. 17. This detector could probably be reliably set for a 10 ppb threshold. The information content from this detector may, however, not be very independent of that from the total hydrocarbon detector. If electrochemical detectors are used for the HCl measurement or the CO measurement, the minimum practical threshold is probably a few ppm for long-term measurements because of zero-drift problems, temperature stability problems, and false alarms from gases for which these detectors have cross-sensitivities.

13.0 Summary and Conclusions

A prototype of an early-warning fire safety system for the CLAS in Hall B has been tested. Cable samples were heated in a 38 liter glass enclosure by radiant heating; concentrations of carbon monoxide, hydrogen chloride, total hydrocarbons, and heavy hydrocarbons were measured using a calibrated gas sampling and analysis system. The total leak rate from the glass enclosure was measured and used to extrapolate the results to a 100,000 liter room with a 20 minute leak time constant. Gas concentration as a function of time and cable jacket temperature for all four gas types are presented for five different cable types. A qualitative evaluation of the feasibility of transporting hydrogen chloride gas through long sampling tubes was performed. A qualitative evaluation of the consequences of a small ambient level of ethane was performed, such as might be present in Hall B during operation. Ambient levels of all four gas types were measured in ten different environments on-site which are representative of areas dense in electronics and cables, or which are otherwise similar to the endstation environment. The final results of the extrapolation indicate that a system of this type would detect elevated cable jacket temperatures of 150 - 250 ^{o}C (significantly less than ignition temperatures) with a time delay of 5-15 minutes using a 0.1 ppm threshold for a 2" long cable sample. Increasing the threshold to 0.5 ppm is feasible for the carbon monoxide and total hydrocarbon gas measurement, and introduces a three to four minute additional delay. The results can be extrapolated to higher cable jacket temperatures and higher thresholds.