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# THE DEPENDENCE OF OPEN FIELD BURNING EMISSIONS AND PLUME CONCENTRATIONS ON METEOROLOGY, FIELD CONDITIONS AND IGNITION TECHNIQUE

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**Abstract**—A program of field and laboratory measurements of emissions from the burning of agricultural residues (primarily cereal straw and stubble) and plume behavior is described. Relationships investigated include the dependence of total emissions and plume concentrations on fuel management, field ignition technique and ambient meteorological conditions.

Total particulate emissions (by mass) were found to increase strongly with increasing residue moisture content but are reduced to one half through the use of a backfire field ignition technique versus the head fire ignition method. Increased emissions from headfires is attributable to smoldering in the burned over areas. Backfire fuel consumption rates are typically about one-fifth that for headfires, resulting in a further reduction of particle concentrations in backfire plumes. Increased fuel loading reduces emissions, especially for headfires. The mass median diameter of particles from either fire ignition technique is less than 0.2  $\mu\text{m}$  and in the average about one half of these particles are chloroform soluble.

CO and gaseous hydrocarbon emissions were also found to be directly proportional to residue moisture content, but independent of field ignition technique.

Plume rise is maximized (ground level concentration minimized) by using headfires in light winds ( $<4 \text{ m s}^{-1}$ ). At higher wind speeds, limited plume rise and increasing fumigation increases ground level concentrations but this can be minimized through the use of backfires. As the effluent plume ages, the size spectrum shifts to smaller diameters suggesting significant evaporation with time.

The results of fuel drying studies and cost analyses for the various techniques are also presented.

## INTRODUCTION

It is estimated that 4-5 million metric tons (MT) of agricultural waste are burned in California each year, with approximately one half of this waste material being straw left after the harvest of rice, wheat and barley. In addition to waste volume reduction, open field burning can facilitate tillage operations, aid in disease control, improve stand establishment and increase productivity of the following crop.

The two serious alternatives to burning are soil incorporation and residue utilization. Incorporation of rice straw in fields which are not double cropped, under optimum field conditions (dry fields) would have cost \$5.00-\$7.50 per hectare in 1971 (Burkhardt *et al.*, 1975) but would cost about \$12.50-\$17.50 per hectare in 1976. Costs for residue utilization are considerably higher, in that baling and roadsiding of rice straw alone would cost between \$52.50 and \$70.00 per hectare (Dobie *et al.*, 1973), and economically viable uses for the residues are extremely limited. Therefore, until more economically acceptable tech-

niques for residue utilization or disposal are developed, agricultural burning is likely to continue.

The characteristic emissions from combustion of agricultural residues is documented for laboratory situations (e.g. Boubel *et al.*, 1969; Darley *et al.*, 1966) and fairly well documented for field situations (e.g. Meland and Boubel, 1966). For grass type fuels, burned in a laboratory situation, typical emissions in units of kilograms per metric ton ( $\text{kg MT}^{-1}$ ) of fuel burned are: particles (2-23),  $\text{CO}_2$  (900-1500), CO (30-120), and gaseous hydrocarbons (GHC) (i.e. olefins, acetylene, ethylene, etc.) (2-13).  $\text{NO}_x$  production is less than  $1 \text{ kg MT}^{-1}$  (Darley, 1966). The most obvious effects of burning on local air quality are visibility reduction and odors.

Efforts to minimize ground level concentrations of these emissions in California have centered on the declaration of permissive burns or no-burn days in accordance with forecast meteorological conditions, primarily the vertical dispersion potential and horizontal transport expected (e.g. Thuillier and Sandberg, 1971; Duckworth, 1965). An additional means of reducing downwind concentrations is the reduction of emissions at the source by the use of improved combustion techniques. This report is primarily concerned with the evaluation of the relationships of

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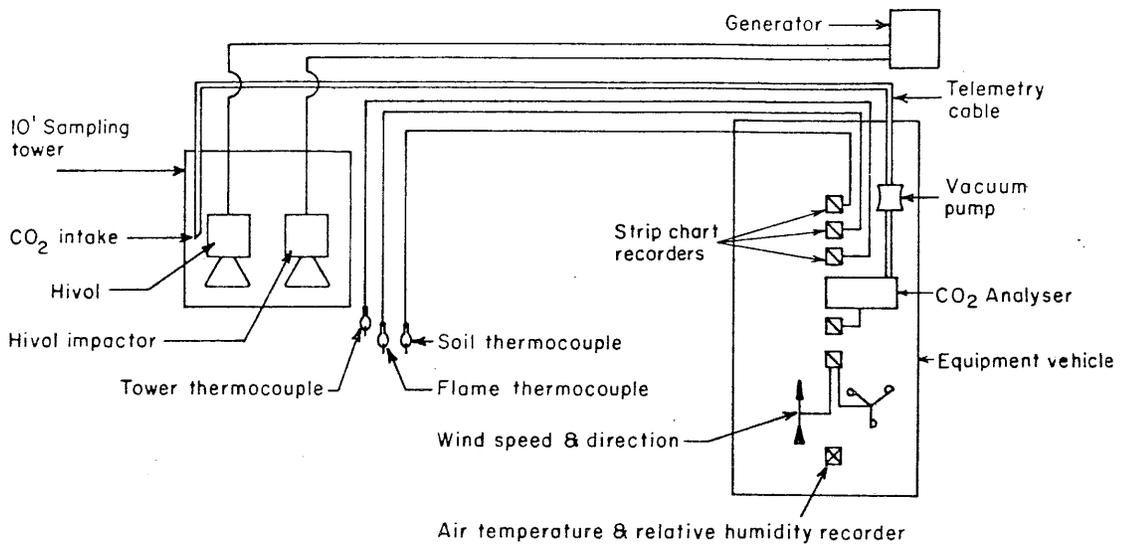


Fig. 1. Schematic diagram of ground level field sampling equipment and instrumentation.

various field practices, burning techniques and fuel properties to open field burning emissions and their effect on local visibility.

The work was divided among investigators performing field studies at the University of California at Davis and laboratory studies at the Statewide Air Pollution Research Center, Riverside. The field studies examined: particulate emission levels produced by burns conducted under various field and atmospheric conditions, methods of minimizing particulate emissions and their impact on visibility, and the costs involved. Laboratory studies were used to confirm field measurements, to study other relation-

ships under more controllable conditions, and to provide data on CO, CO<sub>2</sub> and GHC emissions.

METHODOLOGY

A detailed description of this work is contained in Carroll (1973) and Darley *et al.* (1974). The field burns were monitored 3 m above ground level by the equipment shown in Fig. 1, utilizing techniques similar to those developed by Boubel *et al.* (1969). Prior to each burn, straw and stubble quantity and moisture content samples were taken along with stubble height measurements. After the burn, unburned straw and stubble quantity and moisture samples were collected as well as ash samples to determine ash quantity and carbon content. Rate of flame advance

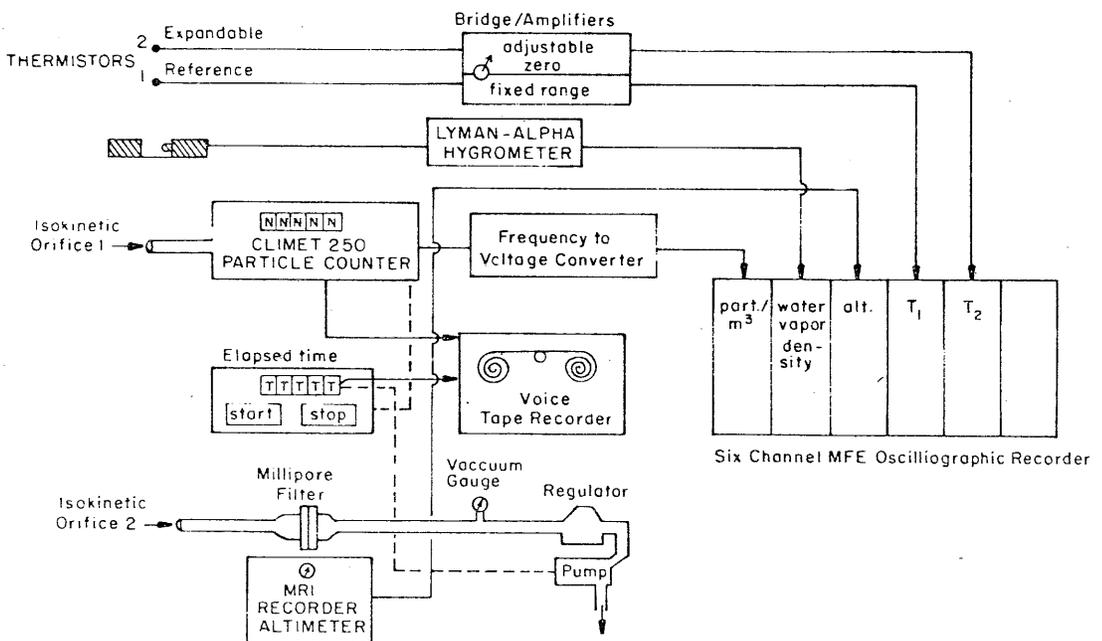


Fig. 2. Schematic drawing of aircraft instrumentation.

measurements were made on a number of trials. Laboratory analysis of field collections included: chloroform extraction of high volume particulate samples; carbon content analysis of straw and post burn ash; moisture content determinations of the straw and stubble samples; and gravimetric determination of particle concentrations and size distributions.

In addition, 25 selected burns were monitored by a Cessna 336 aircraft instrumented as shown in Fig. 2. The aircraft was used to measure the three-dimensional atmospheric thermal structure, water vapor distribution, particle number concentrations and size distributions. These same variables were measured at various altitudes within the fire plumes. The average particle concentrations were computed from the total count displayed by the Climet 250 counter, which detects all particles having equivalent optical diameters  $\geq 0.4 \mu\text{m}$ . The size distribution within this population was determined by manually sizing and counting the particles collected on filters having a mean pore size of  $0.45 \mu\text{m}$ . This size analysis utilized light field microscopy with Nomarski differential interference contrast optics. The central portions of each filter were examined with the conditions that 0.2% of the filter area must be sampled and not less than 300 particles per sample counted. Differentiation between amorphous and angular particles was made where possible. Since ambient particle concentrations were often high, this background was subtracted from the plume data to yield the net fire contributions. The net concentration was determined by subtraction of the time weighted background concentrations at the time and altitude of a pass from the total concentrations measured within the plume. The net fire size distribution was determined by subtracting the particles attributable to the background from the pass totals for each size range.

The plots burned for monitoring purposes ranged from about 0.2 to 2 ha, which is smaller than typical operational fires. The advantages of the smaller size are: (a) by burning only parts of a given field at a time, several techniques can be tested within the same field and the effects of each technique can be evaluated with reasonable assurance that the fuel state, field conditions and related variables are comparable, and (b) limited size means a shorter time between trials so that the ambient wind, stability conditions and the fuel state, primarily its moisture content, remain nearly constant among burns.

Three residue management techniques and six fire management techniques were studied in the field trials. The straw was: (a) left in windrows, (b) spread uniformly over the stubble, or (c) spread straw was raked together after several days of drying. The six fire techniques were: (a) lighting a single line fire perpendicular to the wind on the leeward edge of the plot (backfire), (b) lighting the windward edge of the plot (headfire), (c) lighting the entire perimeter (peripheral light) on a calm day, (d) spot lighting the center of the plot only (center fire), (e) lighting in strips into the wind at 100–200 m (300–600 ft) intervals (into-the-wind striplight) and (f) lighting approximately 400 kg piles of straw. Headfires and backfires were not monitored unless the wind speed was greater than  $2 \text{ m s}^{-1}$ , to minimize the difficulty of defining the fire type under light and variable winds.

The cost analyses for open field burning of cereal grain residues was based primarily on the rate of flame advance for the various fire management techniques. Several averaged sized fields, approximately 40 ha were burned to verify the total time required to burn a field calculated on the basis of the plot data. The larger field trials were also used to evaluate the practicality of the proposed fire and residue management techniques.

The emission of particles, CO, CO<sub>2</sub> and GHC as a function of ignition techniques at various fuel loading and moisture content were monitored in the burning tower de-

scribed by Darley *et al.* (1976). Particle concentration and size distributions were gravimetrically determined. Fuel loadings of 2.7 and 0.9 kg were used for all straw types. The former, the typical loading for spread rice straw and windrowed wheat and barley straw, the latter being typical of spread wheat and barley straw.

## DISCUSSION OF RESULTS

Regression and correlation analysis techniques were used to evaluate both the field and laboratory burn data. The dependent variable in the regression analysis was the particulate emission level. The independent variables were: direction of burning (headfiring or backfiring), residue moisture content, fuel loading, absolute ambient humidity, relative ambient humidity, air temperature and wind speed. Direction of burn was considered a discrete variable and the correlation and regression analyses were performed separately on headfire and backfire data. Under light wind conditions, peripheral ignition is equivalent to a headfire, and center lighting equivalent to a backfire. The effect of spread, windrowed and raked straw was represented by the moisture content and fuel loading variables.

Particulate emission rates were determined for 80 field tests with rice straw, 50 with wheat and barley straw and 84 laboratory simulations with all fuel and fire types. The strong dependence of particle emissions on fuel moisture content is clearly shown in Fig. 3 and 4. For example, a reduction in residue moisture content from 25 to 10% can reduce emissions from 18 to 5  $\text{kg MT}^{-1}$  in a headfire. Also shown is the fact that backfires emit only about one half the mass of particles as a headfire at the same fuel moisture content.

The field data for wheat and barley straw are shown in Fig. 5. Since these grains are harvested in summer when the plants are senescent, and drying conditions excellent, these fuels are often burned at very low moisture contents (4–5%) as compared to rice straw which rarely dries to 10% moisture. With these very dry fuels, no significant differences were found between ignition technique or moisture content. This is largely due to the cumulative experimental error in the field trials of  $\geq \pm 1 \text{ kg MT}^{-1}$ , which is comparable in magnitude to the emission rates observed.

The third most important parameter affecting particle production was found to be fuel loading in both the laboratory simulations and the wheat and barley field tests. For example, in the latter, emissions from 2-m high straw pile fires were  $0.8 \text{ kg MT}^{-1}$  (7% moisture) as compared to spread straw emissions of  $2.5 \text{ kg MT}^{-1}$  (6% moisture) for headfires. In the laboratory simulations, the effect of fuel loading on reducing emissions was significant for simulated headfires only.

Although the other independent variables were not found to be statistically significant in determining particle production, this does not imply that they

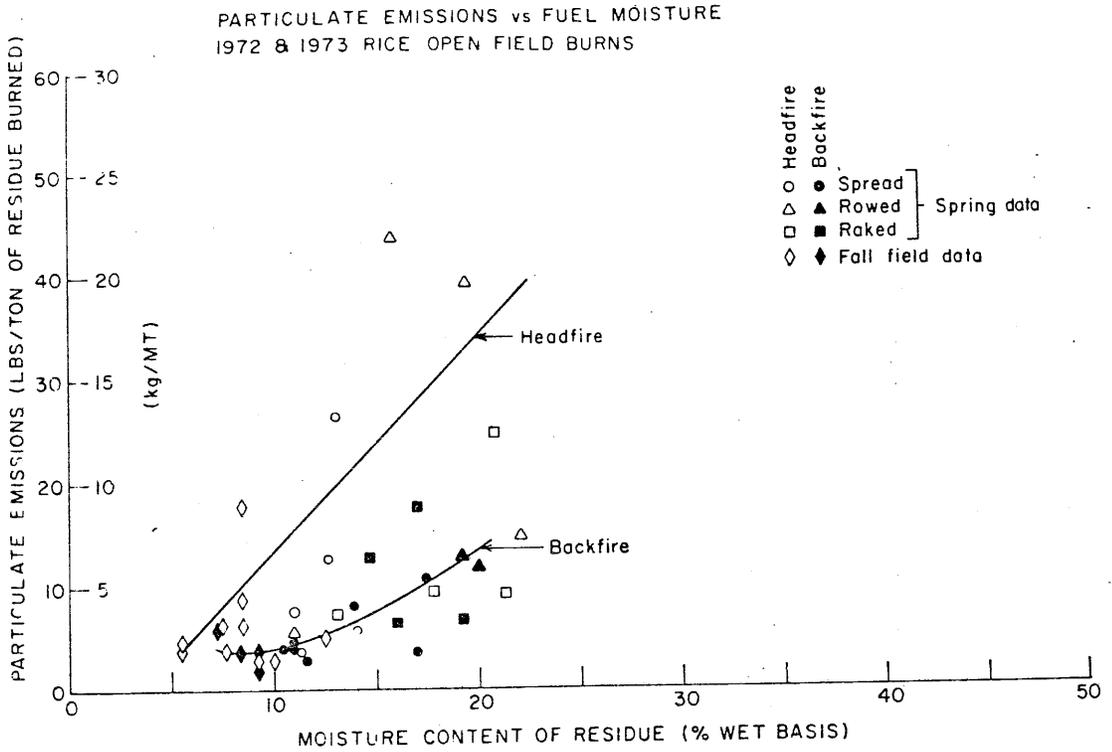


Fig. 3. Particulate emissions vs fuel moisture content for open field rice burns (spring and fall, 1972-1973).

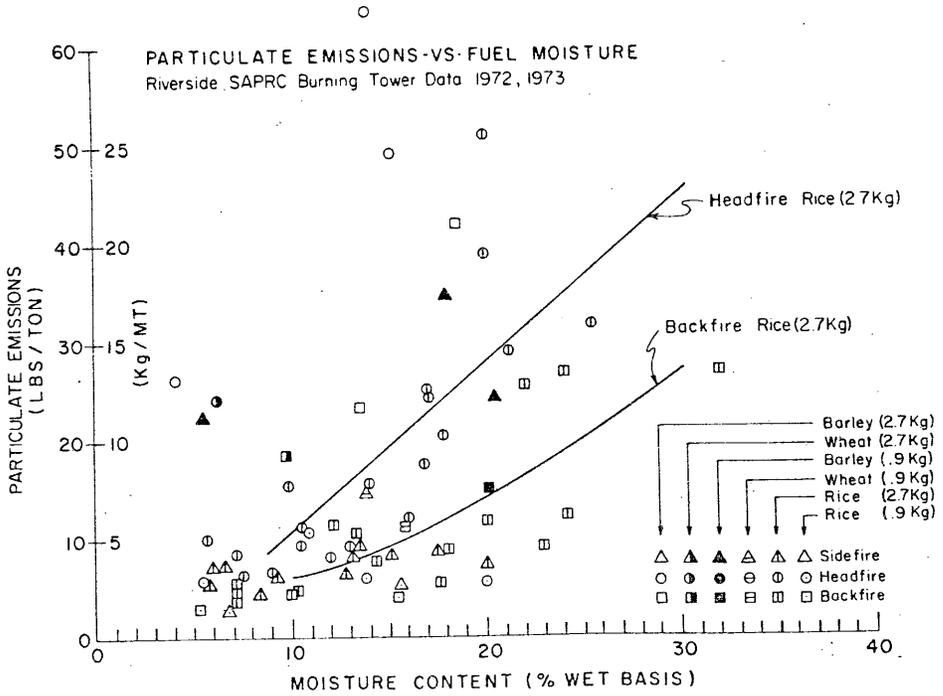


Fig. 4. Particulate emissions vs fuel moisture for various fuels (rice, barley and wheat straw) and simulated fire types in the SAPRC burning tower.

**PARTICULATE EMISSIONS -VS- STRAW MOISTURE  
(BARLEY AND WHEAT) 1971-72 FIELD DATA**

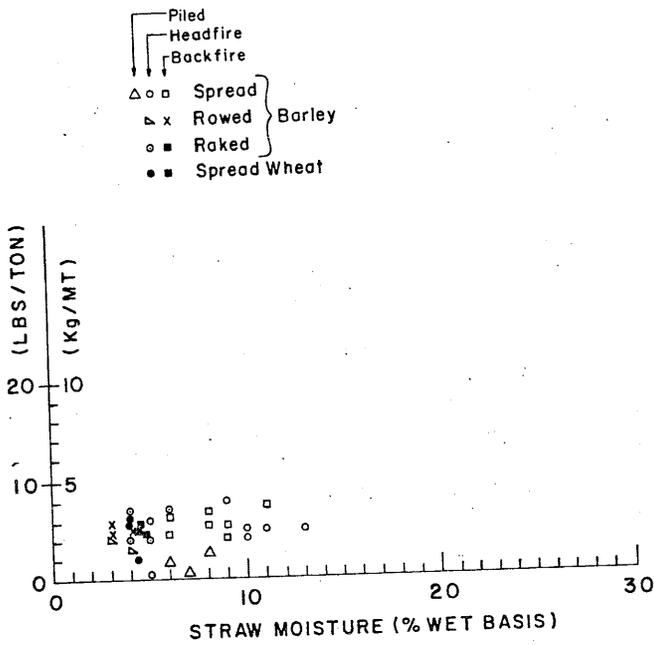


Fig. 5. Particulate emissions vs fuel moisture content for open field barley and wheat burns (summer 1971, 1972).

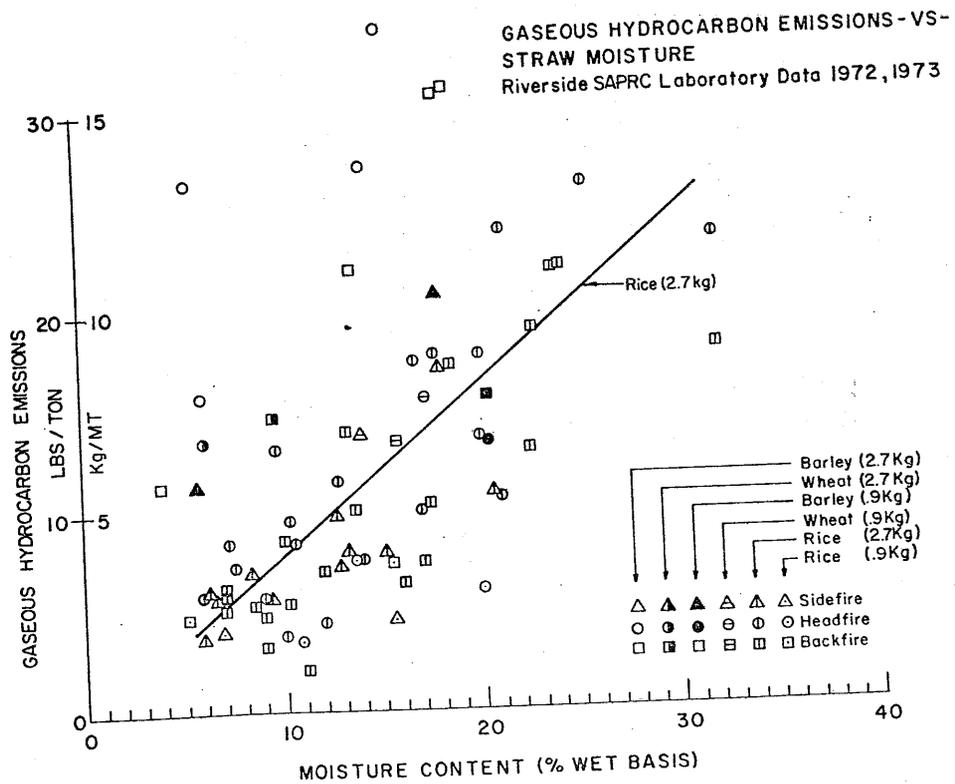


Fig. 6. Gaseous hydrocarbon emissions vs fuel moisture for same burns as in Fig. 4.

CO EMISSIONS - VS - STRAW MOISTURE  
Riverside SAPRC Laboratory Data 1972, 1973

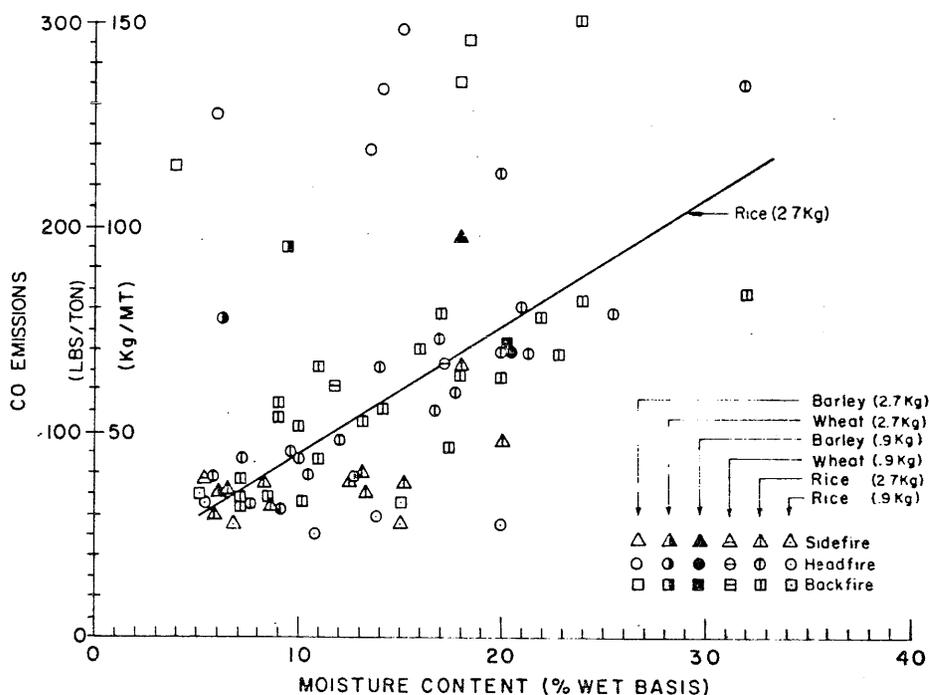


Fig. 7. Carbon monoxide emissions vs fuel moisture for same burns as in Fig. 4.

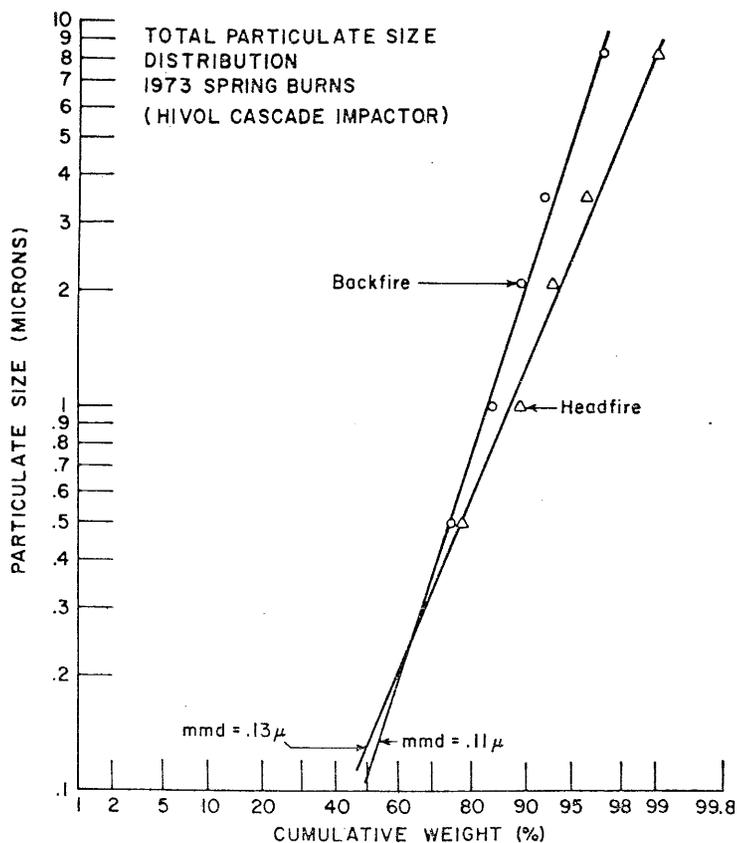


Fig. 8(a).

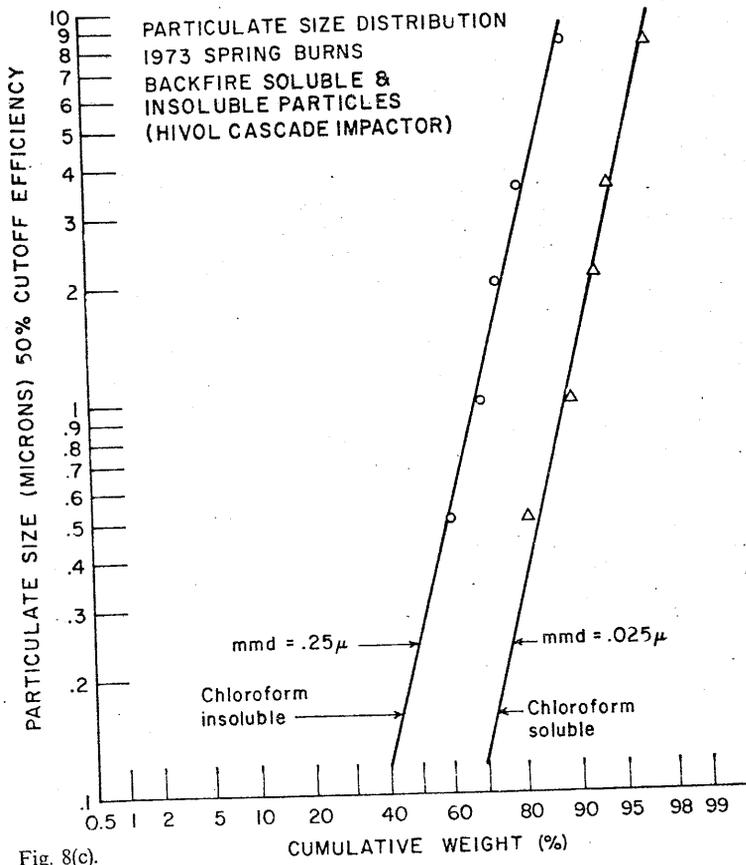
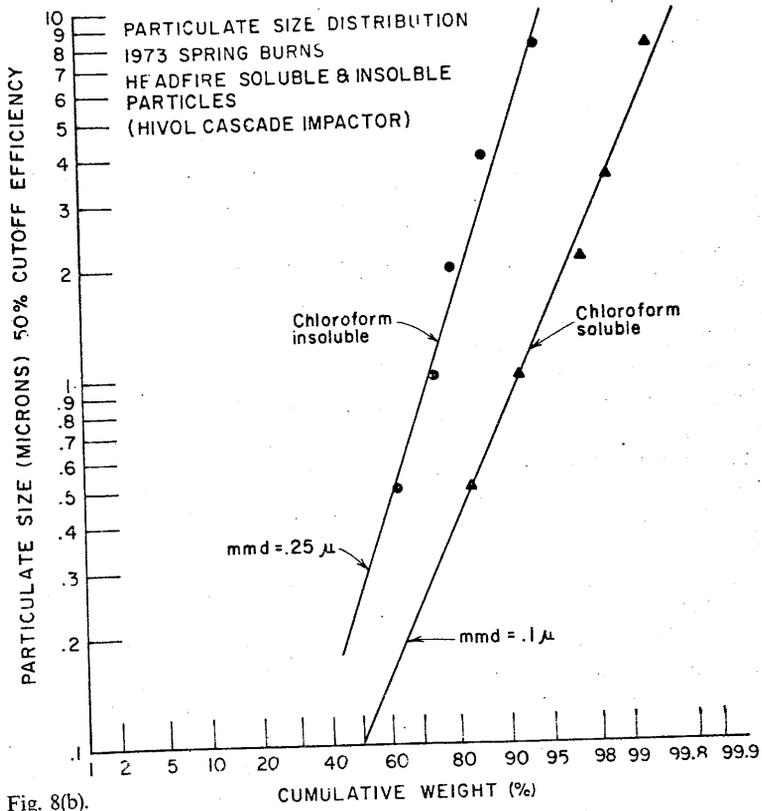


Fig. 8. Gravimetric size distributions determined from the ground level hi-vol impactor samples of spring rice burns. (a) Total particulate head vs backfires; (b) headfires: chloroform-soluble vs insoluble; (c) backfires: chloroform-soluble vs insoluble.

might not have an effect. Variations in the data caused by field inhomogeneities could easily obscure any effects these less significant variables might have had. However, any unsubstantiated significant variables will have small effects on particulate emission levels compared to moisture content and field lighting technique.

The gaseous hydrocarbon (GHC) data presented in Fig. 6 show that production is primarily determined by moisture content of the residue with no significant difference between headfires and backfires. Sixty eight per cent of the variability in the data was explained by moisture content alone. The trend of the dependence for each fuel and fire type is similar to the line drawn for the 2.7 kg rice data. A minimum GHC emission of  $2.5 \text{ kg MT}^{-1}$  is obtained when the moisture content is less than 7%. With moisture contents greater than 30%, GHC emissions of over  $13 \text{ kg MT}^{-1}$  are expected. Of the remaining variability, regression analysis indicated that low absolute humidity or increased residue loading will reduce hydrocarbon emissions.

Carbon monoxide emission data are summarized in Fig. 7 and show results similar to those for hydrocarbon. Moisture content is the most significant factor affecting emission levels with no dependence on ignition technique. The lowest emissions, about  $34 \text{ kg MT}^{-1}$ , are produced at 8% moisture and emissions of over  $100 \text{ kg MT}^{-1}$  are produced at moisture contents greater than 30%.

A series of 27 of the laboratory fires were also sampled for particulate size distribution with a high volume cascade impactor. Assuming a log normal particle size distribution, the average measured mass median diameter for the 27 fires was  $0.2 \mu\text{m}$ . This compares quite well with the mass median diameters obtained in the spring rice field trials (Fig. 8a, b, c). The laboratory data further revealed that there was a tendency for fires with higher particulate emissions to have larger mass median diameters than fires with lower particulate emissions. This may be due to the fact that while most of the particles from open field burning are probably formed by condensation, the higher the emission levels and particle concentrations, the faster these particles can grow through agglomeration.

The average mass median diameter for chloroform-soluble particles was  $0.23 \mu\text{m}$  and the mass median diameter for the chloroform-insoluble particles was  $0.16 \mu\text{m}$ . The small size of the insoluble particles suggests that these particles may also be formed by condensation and are perhaps condensed carbon (Green and Lane, 1964). Averaging over all fire types, about one-half of the total mass of particles from rice straw and a smaller fraction from wheat and barley straw is soluble in chloroform. Headfires produced a 30% larger fractional mass of soluble particles than backfires. The chemistry of the viscous, brown abstract is not known but is probably all organic material. Darley *et al.* (1966) found that for rice and barley

straw, gaseous hydrocarbon emissions contained 10% ethane, 15% olefins and 4% saturates and acetylenes. Many of these species are liquids at normal ambient temperatures. Extensive studies by Tebbins and his associates (e.g. Mukai *et al.*, 1965) indicate that chloroform-soluble particles formed by the combustion of cellulosic fuels are a complex mixture of perhaps hundreds of organic species which may be either solid or liquid at ambient temperatures.

The behavior of the fire plumes is governed by the vertical stability, the speed of the wind near the ground and the field lighting technique. In the limit, the maximum rise of the effluents is to or within the lowest significant stable layer. The predominant effect of wind, especially at ground level, is to reduce the efficiency of buoyant accelerations in terms of total plume rise. With very light winds ( $< 2 \text{ m s}^{-1}$ ) and with fires in fields larger than 0.5 ha, a well-defined nearly vertical columnar plume usually developed. With an elevated stable layer present, the effluent spreads horizontally at the base of and within the lowest part of the stable layer. Since the effluent is then embedded in a layer with a large static stability, vertical eddy diffusion is strongly suppressed and the effluent is transported downwind as a thin layer. A quantitative demonstration of this effect is illustrated by the two soundings shown in Fig. 9(a) and (b). These soundings were taken about 16 km downwind of a dozen large headfires in rice fields. The mean wind speed was about  $3 \text{ m s}^{-1}$ . The first sounding was in an air column containing few, if any, emissions from field burning. The second (40 min later) shows the effect of combined fire plumes near and within the inversion. Note that while the particulate concentrations ( $\geq 0.4 \mu\text{m}$ ) increased by 400% in and above the inversion, the ground level concentrations increased by only 6%.

As wind speeds increase, several effects prevent the formation of a well-defined vertical plume. These include: (a) decreased efficiency since each parcel is not emitted in to the wake of the previous parcel, (b) increased entrainment rates due to increased turbulence in the wind itself, especially near the ground and (c) larger buoyancy losses per unit rise since these parcels are surrounded by ambient air rather than by a plume-air mixture as in the case of a vertical plume. These factors all operate to produce a plume which is more horizontal than vertical, even for large hot fires, when ground level wind speeds exceed  $7 \text{ m s}^{-1}$ .

The effect of these processes is evidenced by the small magnitude of the temperature excess measured within the plume. For backfires, the difference in temperature between the plume and its horizontal environment at altitudes of 30–100 m above the fire, were  $0.1^\circ\text{C}$  or less. Headfire plumes had peak temperature excesses of  $0.5\text{--}3.0^\circ\text{C}$ . These temperature excesses generally decreased with increasing wind speed, and were comparable to those associated with normal thermal activity in the area.

Since the source temperatures for the fire plumes

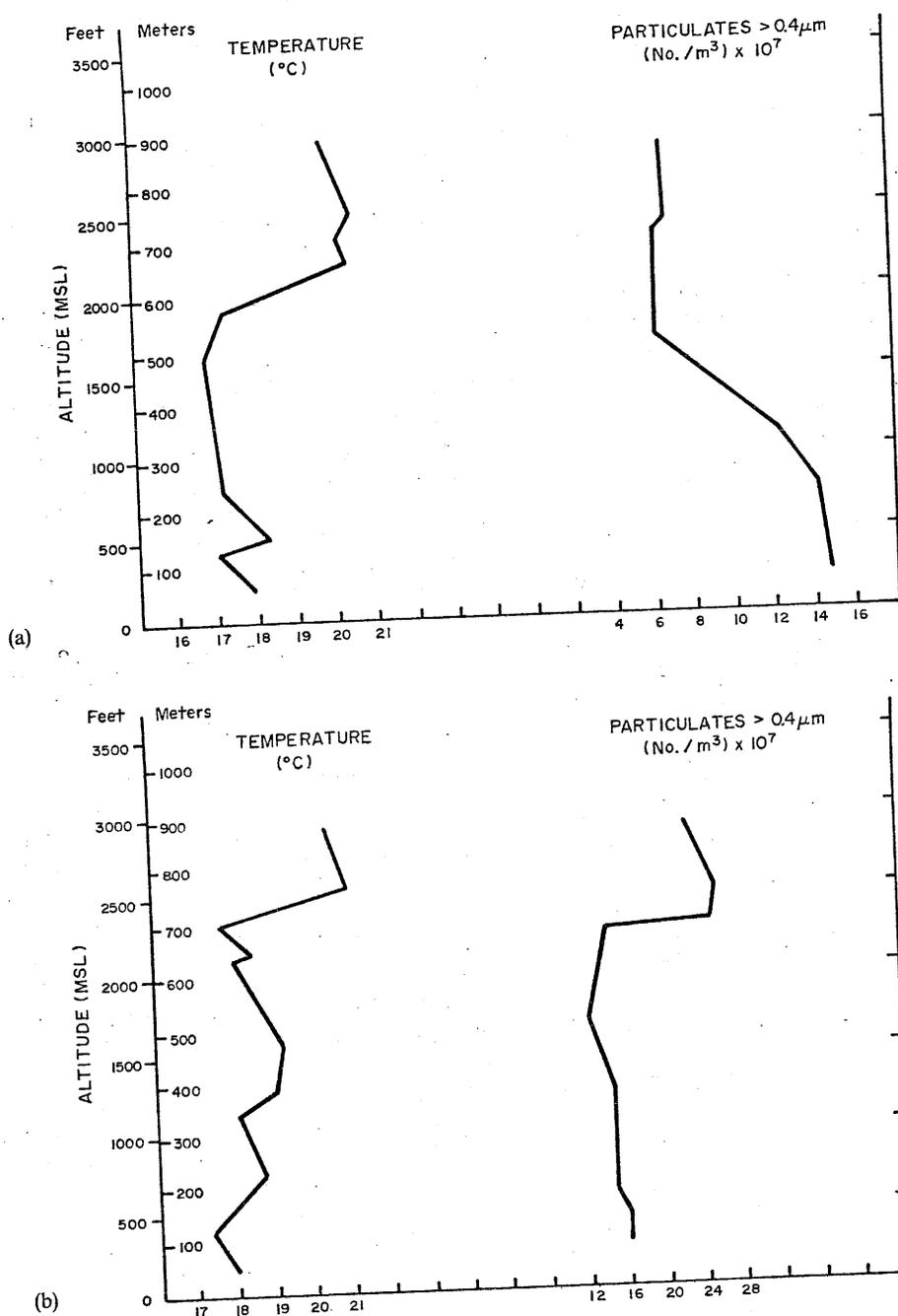


Fig. 9. Temperature and particulate concentration soundings taken 40 min apart 10 miles downwind of 12 large headfires. (a) Clear air which passed over burn area prior to ignition. (b) Air column which includes effect of combined plumes from the fully developed fires.

are much higher than for the naturally heated surfaces, the comparable plume temperatures at altitudes greater than 30 m implies a very rapid fall in temperature in the fire plumes during the first few meters rise. This is due to radiative loss and to very rapid entrainment of ambient air within the fire zone itself. Radiative heat transfer to the unburned fuel is an important mechanism for continued combustion and is also available to evaporate moisture and hydrocarbons from the unburned fuel. The radiant energy

is also absorbed by the soil and ash surrounding the fire zone making the areally averaged source temperature for a plume considerably less than the flame temperature. Therefore, the vertical acceleration in the plume as a whole is only a small fraction of that which would be calculated from the flame temperatures themselves.

A significant characteristic of headfires is that smoke from a headfire is generated from two distinct subsources, the active flame front, and the smoldering

area behind the flame front. The temporal and spatial separation of these two subsources increases with both the low level wind speed and the length of the burning field in the downwind direction. Visual evaluation of smoke density clearly indicates particle concentration is much less from the active fire areas than from the smoldering areas. At wind speeds greater than  $7 \text{ m s}^{-1}$ , fumigation of both plumes occurs and ground level concentrations remain high at distances the order of 8–16 km downwind of the fires. Since the smoldering plume is far less buoyant, fumigation of this dirtier plume is more pronounced.

The particle emissions from backfires appear to be comparable to those from the active flame zone of headfires; but backfires show no significant smoldering zones. However, the plume rise potential is less than for headfires so that fumigation of backfire plumes is more pronounced with increasing wind speed. However, the relatively low source strength of a backfire results in greatly reduced degradation of ground level air quality as compared to a headfire.

The particle data derived from the aircraft operations are summarized in terms of number concentrations not total emissions. The average concentration (by number) and RMS variations for the aircraft samples is shown in Table 1 for each sample type. The large deviations illustrate the fact that individual fires vary greatly in terms of fuel status and ambient conditions and therefore relative trends

Table 1. Average concentrations of particles greater than  $0.4 \mu\text{m}$  in dia. and their root mean square deviations for all available aircraft data. Fire data are net plume concentrations taken between 30 and 300 m above terrain

Type of sample	Concentrations	
	Sample size	Particles ( $\text{m}^{-3}$ )
Background av.:	25	$6.60 \times 10^7$
r.m.s. dev.:		$8.50 \times 10^7$
Backfire av.:	8	$1.90 \times 10^7$
r.m.s. dev.:		$2.60 \times 10^7$
Head and perimeter av.:	11	$4.810 \times 10^7$
r.m.s. dev.:		$5.50 \times 10^7$
Pile Fire* av.:	2	$8.10 \times 10^7$
r.m.s. dev.:		$102.0 \times 10^7$

\* Rice straw at high moisture content ( $\geq 25\%$ ).

found between sets of fires which are nearly alike are more significant than absolute values for any one fire or averages of absolute values for all fires.

Emission concentration comparisons were made between individual sets of one back and one headfire within the same field and both burned within about 1 h. Averages of the individual ratios of headfire to backfire particulate concentrations for six sets of fires show that headfire plumes contain between five and six times the particle concentration of backfires. Estimates of fuel consumption rates indicate that headfires burn four to five times faster than backfires. Therefore the aircraft data are consistent with the ground data in that both particle concentration and total emissions are reduced by backfiring.

The average size distribution, by number, of the samples is shown in Table 2. What the table clearly shows is that for other than pile fires, over 90% of all particles larger than approximately  $0.4 \mu\text{m}$  are less than  $1.3 \mu\text{m}$  in dia. The summarized data indicates that the number median diameter for the particles detectable is close to the detection threshold size. It is therefore safe to assume that the  $0.4 \mu\text{m}$  threshold precludes detection of the true number density. Although this may appear to be a serious flaw in the experiment, particles between  $0.4$  and  $4.0 \mu\text{m}$  diameter are the major contributors to visibility degradation; and the ground-based measurements indicate only a slight difference in particle size distribution between head and backfires (Fig. 8a) which is evident in Table 2. Therefore while the  $0.4 \mu\text{m}$  lower cutoff means the aircraft instrumentation samples only 20–40% of the total mass of particles, changes in this sub-set should reflect changes in the total population.

A comparison of non-backfire subsources is made in Table 3. The number of samples represented is small because matched sets of data from individual fires are necessary to evaluate trends independent of burn conditions. The "aged" data were taken 10–15 min after the burn in the elevated plume. The most obvious characteristics of the comparison are that the relative sizes of particles emitted from the active flame area are significantly smaller than for the smoldering areas and that the size distribution within the aged plume does not approach the background distribution (Table 2), but shows very high relative numbers

Table 2. Average and root mean square deviations for the net cumulative size distribution (by number) of particles  $>0.4 \mu\text{m}$  and less than stated size—by type of fire

Data	Per cent of particles greater than $0.4 \mu\text{m}$ but less than stated size ( $\mu\text{m}$ dia.)						No. in sample
	0.7	1.3	2.7	5.3	10.6	20	
Av. bkgnd	69.0	90.8	97.2	99.0	100	100	12
r.m.s. dev.	13.8	4.9	1.8	0.7	<0.5	0	
Headfire	76.8	96.0	97.8	99.0	99.9	100	8
r.m.s. dev.	21.4	5.6	3.0	2.2	0.2	0	
Backfire	65.4	90.3	97.6	99.6	100	100	6
r.m.s. dev.	27.0	14.0	2.8	0.3	0	0	
Pile	51.5	85.1	94.7	98.5	100	100	2 samples of each
r.m.s. dev.	28.4	10.3	3.5	1.7	0	0	of 2 fires

Table 3. Comparison of cumulative size distributions (by number) from the active, smoldering and aged plumes of head and pile fires

Source type	Per cent of particles by number $\geq 0.4 \mu\text{m}$ but less than stated diameter						Sample size
	0.7	1.3	2.6	5.3	10.6	20	
Active	87.1	99.0	99.7	99.8	100	100	5
Smolder	54.9	85.4	93.3	96.6	100	100	4
Aged	93.2	94.0	100	100	100	100	4

of 0.4–0.7  $\mu\text{m}$  particles. Since an aged plume must include smolder emissions, the implications are that the smoke ages in such a way that the size distribution shifts toward the smaller ranges and that the background particulate concentrations are only partially due to agricultural burning.

The average concentration ratios (by number) for sets of plumes from smoldering and active zones of individual fires is 4:1. This verifies the qualitative visual observations that most of the smoke from a headfire is emitted by the smoldering areas. This also accounts for at least part of the greater emissions from headfires as compared with backfires.

An analysis of size distributions in terms of the ratio of amorphous to angular particles in each size range is presented in Table 4 for various sample types. These data indicate that the majority of particles of less than 1.3  $\mu\text{m}$  dia. in both ambient air and fire plumes is not crystalline in form. The samples taken at ground level show a similar relationship in that up to one half of the mass of the material collected in the submicron size range has a tarry appearance and is chloroform soluble. We do not have first-hand knowledge of the types of compounds present in this group, but they are most likely condensed carbon and liquid hydrocarbons.

The observed rapid decrease in temperature within a plume supports the interpretation that condensation processes contribute significantly to the plume particle concentrations. The source of the latter is probably the utilization of heat radiated to the unburned fuel zone to evaporate sap and other material with significant vapor pressures at temperatures greater than 50°C. Not all of the distillates will pass through the flame zone as they rise and little or no oxidation of these would be expected. Of those that do enter

the flame, oxygen deficiencies and relatively low flame temperatures may prevent total oxidation of at least some of them. In addition, reactions among these compounds could produce a myriad of new species (Mukai *et al.*, 1965). It is therefore expected that considerable masses of hydrocarbon are emitted from the fire zone in a gaseous phase and only partially oxidized. With the rapid cooling immediately above the fire zone, most of the large molecular compounds will condense adding a large number of liquid and solid condensates to the particulate load in the plume. As the material continues to rise and diffuse, continued entrainment of ambient air will lower the average gas phase mixing ratio for each compound, in turn reducing the ambient vapor pressure over the liquid phase material. Since the saturation vapor pressure increases rapidly with decreasing radius, it is likely that re-evaporation of these droplets would occur.

The observed size shift with ageing would appear to support the ageing by evaporation hypothesis presented above. It is, however, also quite possible that the observed size shift may be the result of chemical or photochemical reactions. Photochemical reagents are generally present in the area studied. Differential sedimentation is discounted since in a turbulent environment, this would have little effect on particles in these size ranges.

It therefore seems reasonable to conclude that most of the particles in smoke plumes less than 1.3  $\mu\text{m}$  in dia., which in turn are most of the particles detected in the plume, are carbon particles and medium and large molecule hydrocarbons. The majority of particles greater than 1.3  $\mu\text{m}$  appear crystalline and are presumed to be solid hydrocarbons, silica, other soil minerals and ash (Green and Lane, 1964).

Table 4. Average per cent of particles within each size interval that are amorphous in form

Source type	Sample size	Size $\mu\text{m}$ dia.					
		0.4–0.7	0.7–1.3	1.3–2.6	2.6–5.3	5.3–10.6	>10.6
Back ground	19	76	74	41	2	0	0
Headfire (active)	8	92	60	21	0	0	0
Headfire (smolder)	4	93	72	20	2	7	0
Aged	2	95	5	0	0	0	0
Backfire	5	98	49	21	17	0	0

## SUMMARY AND IMPLEMENTATION OF RESULTS

In summary, the field and laboratory data show that particle, gaseous hydrocarbon, and carbon monoxide emissions per unit of fuel burned are most strongly dependent on residue moisture content, i.e. the dryer the residue, the cleaner the burn. Increased fuel loading also appears to reduce emissions of particles and GHC. In addition, total particle emissions are reduced by up to one-half (by mass) using a backfire ignition technique as opposed to the more traditional headfire technique. A significant fraction of the mass of particles emitted are chloroform soluble and both the soluble and insoluble particles are primarily submicron in diameter.

As a result of the strong dependence of emissions on residue moisture, several studies of drying characteristics of these residues were conducted. Figure 10 illustrates the strong diurnal variation in straw moisture content and the fact that just three days of clear skies after harvest or rain can reduce residue moisture levels to  $\leq 10\%$ . In this example, the rowed straw drying rate is unusually fast because the residue was placed on top of 40 cm tall standing stubble. Under the more typical conditions of short stubble, the rowed straw would have taken 10 days or longer to dry. The strong diurnal variation implies that even though the residue may have dried to an acceptably low moisture content on one day, it may not be dry enough to burn until 11 or 12 o'clock the following

day. This same pattern has been observed for barley and wheat residues in the summer (Fig. 11). Solar radiation is the primary source of energy for drying.

Ignition technique is the second most important parameter affecting visibility degradation. Backfiring is by far the cleanest, in that both smaller masses of particles are produced per unit of fuel burned and emission per unit time is greatly reduced. Backfiring, however, cannot be used under as broad a range of field conditions as headfiring. A backfire has poorer fire propagation potential than a headfire flame, requires a higher fuel density to maintain a fire front and will not continue to propagate under higher residue moisture conditions. However, if a backfire cannot be maintained because of high residue moisture, the residue is too wet to burn by any method.

The difference in operational costs between headfires and backfires can be calculated from the length of time each method requires to burn an entire field. Rate of flame propagation was used to estimate total burn time. Backfires consistently progressed across the field at a rate of about  $1 \text{ m min}^{-1}$ . Flame propagation for headfire burns is more dependent on wind speed, residue moisture, residue conditions and type of residue. Propagation ranged from 7 to  $21 \text{ m min}^{-1}$  with an average of  $15.3 \text{ m min}^{-1}$  for rice straw. Using these propagation speeds, backfire burning would cost  $\$1.61 \text{ ha}^{-1}$  and headfire burning would cost  $\$0.30\text{--}0.48 \text{ ha}^{-1}$ . Raking the straw to speed drying would add approximately  $\$5 \text{ ha}^{-1}$ .

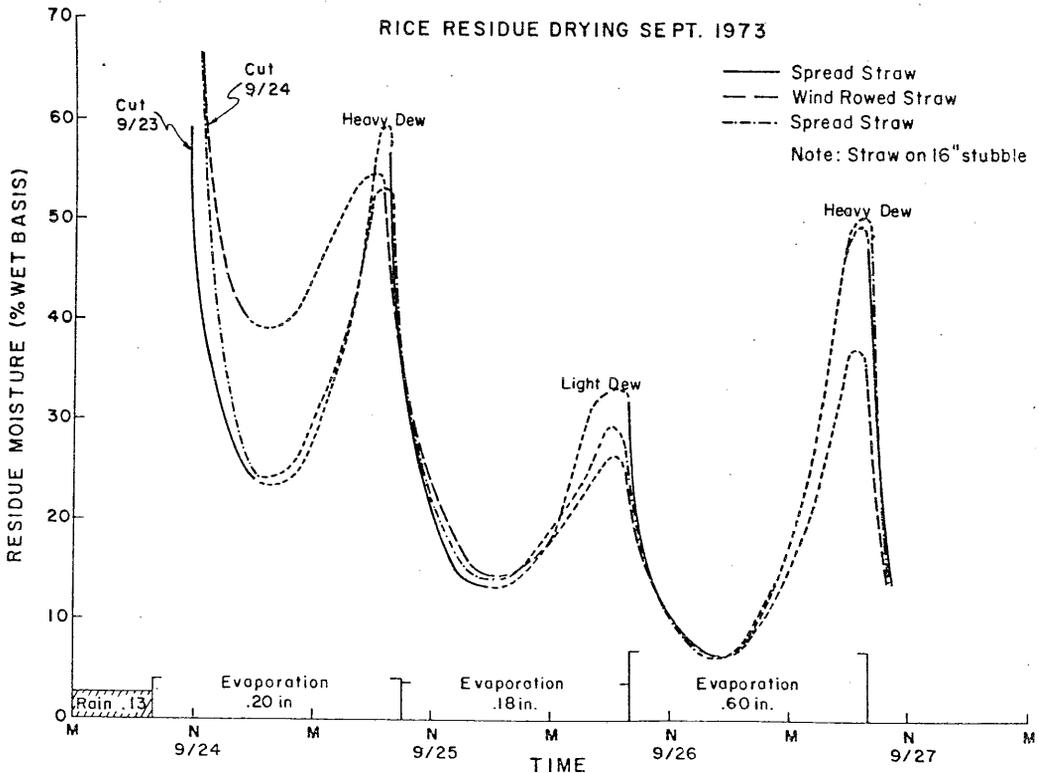


Fig. 10. Residue moisture content in rice fields as function of time for two field treatments (spread vs windrowed).

BARLEY RESIDUE DRYING ON TYPICAL SUMMER DAYS

Data taken : June 14, 19, 21, 22, 23, 27, 28 - 1972

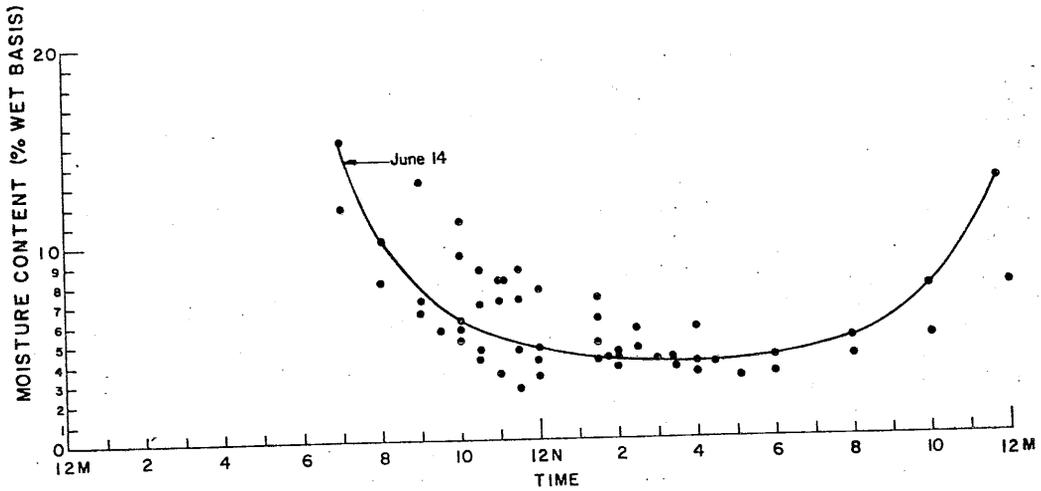


Fig. 11. Typical barley residue daily moisture content variations in summer.

Because of the disadvantages of the backfire ignition, a technique called "into-the-wind-striplighting" was developed which consists of backfiring the down-wind side of the field and then igniting lines spaced

100 m (300 ft)–200 m (600 ft) apart, directly into the wind. An observer in the air sees long adjacent wedges of flame front progressing across the field into the wind (see Fig. 12). This technique combines the

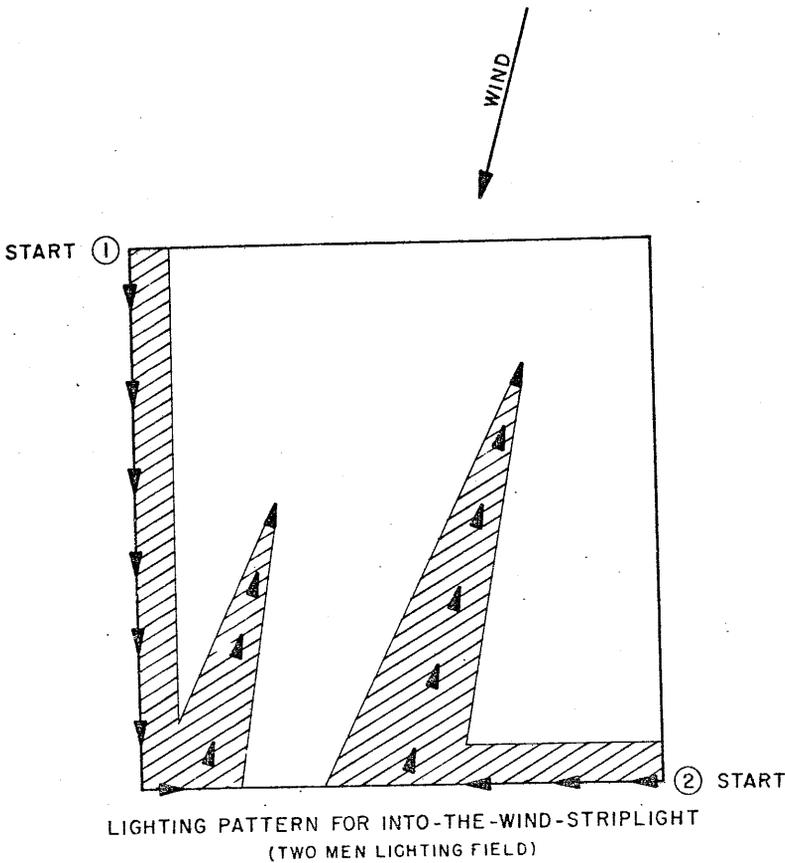


Fig. 12. Schematic representation of an aerial view of an into-the-wind stripfire.

benefit of slow movement of the fire front as in a backfire with a greatly increased length of flame front. Field tests are difficult to perform with this technique, but limited aircraft data and laboratory simulations indicate that emission levels for this technique are between those of backfires and headfires, but approaching backfire levels. It is estimated that this ignition technique would cost approximately  $50.60 \text{ ha}^{-1}$ .

Plume rise from an open field burn is very sensitive to both wind speed and to fire type. As a result, the choice of the optimal fire strategy depends on whether total emissions are to be minimized or if ground level concentrations downwind of the source are to be minimized. For a given fuel concentration, maximum plume rise is obtained with headfires in light winds. If an elevated stable layer is present, effluents are injected into the lower part of the stable layer and transported downwind as an elevated, thin layer of smoke.

With wind speeds increasing above about  $4 \text{ m s}^{-1}$ , the near-ground particulate concentrations downwind from a fire increase rapidly with considerable fumigation expected when the wind speeds exceed about  $7 \text{ m s}^{-1}$ . Since headfires have significantly higher emission rates, primarily from the less buoyant smoldering areas, the ground level concentrations downwind of headfires will be up to six times higher than for backfires at these wind speeds. Limited evaluation of into-the-wind-stripfiring, indicates that the plume rise characteristics appear to be comparable to headfires.

In conclusion, residue management, ignition technique and timing of a burn can be powerful tools for minimizing air quality degradation from this source. For example, by backfiring a given field when the residue moisture is about 10%, the mass of particles in the plume will be only 5% of what it would have been if headfiring at 25% moisture had been used. Comparable reductions in CO and gaseous hydrocarbon concentrations would also result. Burning by any technique upwind of a sensitive area when wind speeds exceed  $7 \text{ m s}^{-1}$  should be discouraged.

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