FIELD CHARACTERIZATION OF SMOKE EMISSIONS FROM BIOMASS FIRES USING COMPUTER-CONTROLLED MEASUREMENT TECHNIQUES[1]

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ABSTRACT: Because of the importance of emissions from fires in biomass fuels globally, we developed a highly portable Fire Atmosphere Sampling System (FASS) for sampling smoke emissions. Emissions were sampled with the FASS packages from a variety of fuel and combustion conditions in Canada, the United States, and Brazil. The ratios of emissions released for boreal, upland hardwood, savanna, and tropical fuel types are being studied in more detail in our controlled environment combustion laboratory. The FASS employs an onboard computer to control sampling protocols of sensors for measuring the fire, environment, and operating parameters. The system measures in real time the concentration of CO, CO_2, NO, and O_2; temperatures at several locations; and vector wind. Grab samples of particulate matter and trace gases are collected over specified sample periods of flaming and smoldering combustion. Emission factors, combustion efficiency, source strength, rate of fuel consumption, and rate of heat release are calculated from the measurements.
Keywords: smoke, emissions, sampling protocols, combustion.

INTRODUCTION

Smoke emissions from fires in biomass fuels are of concern to the public, managers responsible for using prescribed fires and suppressing wildfires, and air quality regulators. There is a need to know more about the composition of smoke since many of the products of incomplete combustion are harmful to human health (Ward 1989) and, along with CO_2, may impact global climate (Crutzen and Andreae 1990). Methods for predicting the emissions from both prescribed and wild fires are needed to more effectively manage smoke from wildland fires (Ward and Hardy 1991). While the burning of biomass fuels is recognized as a major source of emissions to the atmosphere on a global scale, the characteristics and quantities of these emissions are not fully known. On a global scale, approximately 6.4 Pg (1 petagram = 10^{15} g) of biomass is consumed per year (Hao 1991). For 1988, even considering the large extent of the fires in Yellowstone National Park, only about 2% of the total

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biomass consumption occurred from fires in the United States. Global biomass consumption is a major source of emissions to the atmosphere which affects atmospheric chemistry, the radiation balance of the atmosphere, and potentially has an impact on the rate of change of climate.

In this paper, we discuss the development and deployment of the Fire Atmosphere Sampling System (FASS) packages. The FASS packages were developed because of the lack of data on biomass fires and because of the need to measure the emissions released, the fuel consumed, and the heat released from fires burned under a range of conditions. Presently, there is insufficient data on the combustion efficiency, emission factors, ratios of emissions, and the temporal and spatial distribution of the release of emissions from biomass burning. By continuing to measure emissions from fires in a broad range of fuel types and ecosystems, algorithms can be developed for estimating the quantity and characteristics of smoke released into the atmosphere. Additional knowledge is needed concerning smoke emissions to understand key problems including:

1) The influence of biomass fires on emissions released on a global and temporal scale that affect atmospheric chemistry and radiation transfer through the atmosphere. **Large international research projects are underway to explain causes of the decrease in O_3, increase in CH_4, and atmospheric radiation effects from particulate matter released in the atmosphere.**

2) The effect of smoke emissions on local and regional air quality for the development of smoke management strategies. **Methods are needed for estimating the emissions of gases and particulate matter into the atmosphere from fire management practices.**

3) The strategies needed to reduce smoke emissions from prescribed burning. **Methods for evaluating the reduction of emissions into the atmosphere affected by fire management alternatives including meteorological scheduling, physical removal of fuel, alternative ignition techniques, and others.**

4) The characteristics of emissions from wildfires and prescribed fires of concern to the health of firefighters and local populations. **There is a need to know more about the characteristics of smoke emissions that are responsible for health problems.**

5) The winds generated by wildfires and the influence of size of fire on smoke emissions. **Fire induced winds coupled with local meteorological conditions can create hazardous situations.**

The FASS instruments provide ground-based measurements needed to sense the rate of release of gases and particulate matter during the life cycle of the fire--from the time of ignition to dieout. The packages are battery powered, compact for transport and deployment, computer controlled for making rapid changes in sampling protocols, deployable for extended periods prior to a fire, and provide accurate measurements of the fire parameters. The instrument developed senses CO, CO_2, NO, O_2, temperature, and tri-directional wind velocity in real time. In addition, grab samples of gases and particulate matter are collected for different periods of time during the flaming and smoldering combustion phases. The grab samples are typically analyzed for trace gas content and the filter samples of particulate matter for carbon and inorganic content.

DEVELOPMENT OF FASS

The system was designed to collect information needed to characterize the atmosphere immediately above the fire zone. Data collected includes real time combustion gas concentrations, particulate matter production, combustion gas samples, and several fire dynamics parameters. The instruments can be attached to standard television antenna towers at a height of 12 m above ground (Susott et al. 1990a). In 1990, the system was modified (Ward et al. 1991) so that the particulate matter collection system and other sensors including those for vertical wind vector and temperature were attached to a multisectioned mast with the primary control system placed underground (Fig. 1). This increased the portability and decreased the risk associated with the use of towers (and the potential loss of equipment) in the hostile fire environment.

The FASS instrument contains an ONSET Corporation Model 5 computer for controlling the acquisition of data as well as the sampling protocol. The test, calibration, and data acquisition programs are written using TTBASIC (a special version of BASIC that runs on this computer) and loaded into the instrument from a laptop computer. The laptop computer is used to display FASS data during calibration and testing, and is used to retrieve data from the FASS at the end of a field experiment. Over 8 000 samples of each sampled parameter can be saved in the FASS memory during a fire.

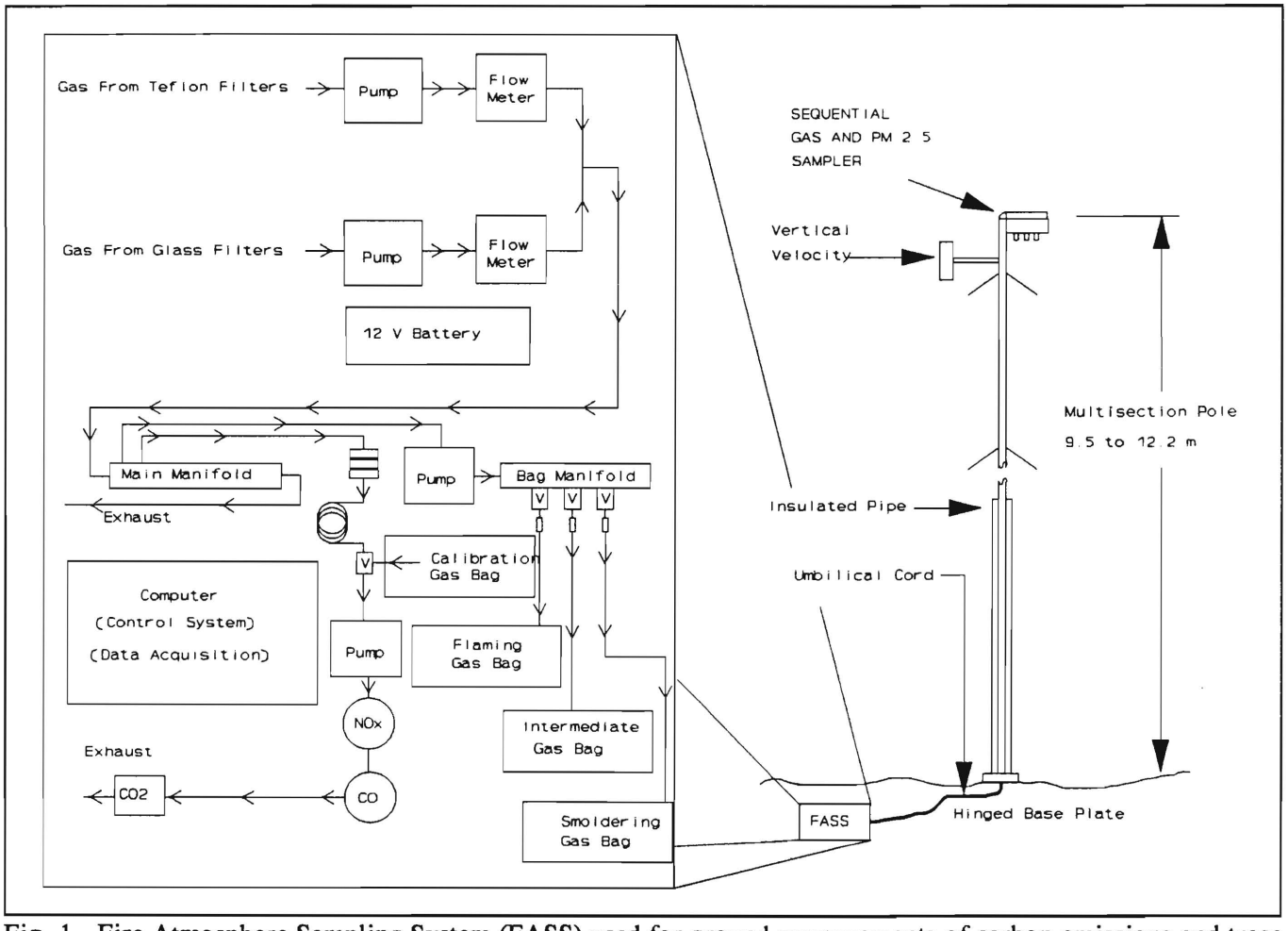

Fig. 1. Fire Atmosphere Sampling System (FASS) used for ground measurements of carbon emissions and trace gases. Two of the FASS units were used on 5 test fires in Brazil.

Probably the most unique feature of the FASS is its capability to measure important combustion gases in real time. Electrochemical type sensors are used to measure O_2 (0 to 21%), NO (0 to 50 ppmv), and CO (0 to 2 000 ppmv) concentrations. The output of the CO, NO, and O_2 sensors are linear over their specified ranges. A nondispersive infrared sensor is used to measure the concentration of CO_2 (0 to 20 000 ppmv). The output of this sensor is non-linear and corrections, based on multi-point calibrations, are applied to the raw CO_2 data. During normal FASS operation, sample gases are pumped through the sensors at a rate of 250 ml/min. The FASS has an onboard supply of calibration gas permitting calibration of the sensors prior to and during the fire experiment.

Both glass fiber and teflon filters are exposed simultaneously to collect samples of the particles less than 2.5 μm. A regulated flow of 2 L/min is provided to each of the filters exposed. A cyclone presampler provides the 2.5 μm cutpoint. For each phase (flaming, smoldering 1, and smoldering 2), two filters are exposed--1 glass fiber and 1 teflon. The glass-fiber filter is used for mass of PM2.5 concentration and content of graphitic and organic carbon of the PM2.5. The teflon filter provides a second measure of concentration of mass of PM2.5 and the content of inorganic materials (e.g., S, Cl, K, P, Fe, Pb, Hg). Samples of combustion gases are collected in bags over the same periods of exposure of the filters. This is necessary in the calculation of emission factors, combustion efficiency, etc. (discussed in greater detail in Appendix A).

DEPLOYMENT OF FASS

Boreal Forest, Ontario, 1989 and 1990

In 1989, the Defense Nuclear Agency requested the Forest Service to implement a study of large fires in Canada with emphasis on modeling the fire-induced winds generated by the large fires. The Hill Township Prescribed Burn (490 ha in size), located near Chapleau, Ontario, Canada, was studied by both United States and Canadian scientists. This site was selected because of the uniformity of fuels and the relatively flat terrain. The site consisted of tramped fuels of white birch and poplar with some jack pine and black spruce. The total fuel loading was 19.4 kg/m^2. It was hoped that our 6 FASS packages (configured on a 25-m grid spacing) would be located in the general area of a confluence of flame fronts and monitor both the wind field phenomena as well as the chemical changes of the smoke emissions from the large area fire (Susott et al. 1990b).

The FASS instruments were configured to measure the linkage between dynamic processes and chemical processes occurring in the mass-fire environment. In particular, the FASS instruments measured a decrease in O_2 concentration averaging 91.7% of normal for the 6 packages during the active flaming combustion. The calculated fuel consumption from the carbon mass balance flux measurements was 11.46 kg/m^2 in comparison to the inventory measurement of 10.63 kg/m^2. Emission factors for particulate matter averaged 7.2, 14.2, and 25.6 g/kg for the flaming, smoldering 1, and smoldering 2 phases, respectively. Combustion efficiency averaged 95, 89, and 82%, respectively, for the same combustion phases (Susott et al. 1990a).

Streamlines of air trajectories through the array of packages showed periods of convergence and divergence while the fire was spreading through the array. The divergence of the streamlines of airflow through the array was particularly pronounced for one 5 minute period of time during which the

distribution of wind direction across the array showed a 20 degree differential wind direction over the 50-m spacing of the packages from north to south. This period accompanied a large several ha area of convergence of fire fronts to the south of the array of FASS packages (Susott et al. 1990a).

Tropical savanna and Primary Green Forest, Brazil, 1990

Two of the FASS packages with towers were transported to Brazil and used to study emissions and fuel consumption for three distinct fuel types--cerrado or grassland type (3 tests), tropical green primary forest deforestation (1 test), and secondary forest clearing of fields (1 test). Ward and Hao (1991) developed algorithms using data from the 3 cerrado fires (Ward et al. 1991) combined with laboratory measurements (Hao et al. 1991a, Hao et al. 1991b, and Hao 1991) that demonstrate emissions of CH_4 for the savanna ecosystems to be 20% of previous estimates. Deforestation fires in the Amazon Region produced 100% greater CH_4 than previous estimates made by Crutzen and Andreae (1990). The combustion efficiency measurements for the cerrado type are higher than for other types measured in North America and for other measurements made from airborne samples in Brazil. Savanna biomass burning accounts for approximately 50% of the annual global biomass consumption (Hao 1991).

Although the analysis of the graphs presented in Fig. 2 is not complete, the duration of the smoldering combustion phase is dramatically different between the cerrado and tropical deforestation tests. The measurement of combustion efficiency over the duration of the fire coupled with the flux of emissions demonstrates the importance of weighting the emission factors based on the carbon released by the fire for each phase of combustion (Appendix A, Eq. 6). The carbon release for the deforestation fire of the primary forest lasted for over 5 days--we sampled for 8 hours (Fig. 2). For the cerrado tests, the carbon release was complete in approximately 4 minutes (Fig. 2).

Upland hardwoods, North Carolina, 1990

The use of the FASS equipment in North Carolina was part of a larger study funded, in part, by the U.S. National Committee for the Man and the Biosphere Program. The general objective for the work was to study the impact of high-intensity prescribed fires on forest ecosystems in the southern Appalachian Mountains of western North Carolina. Measurements were made on three sites and exhibited the highest rate of carbon release of any fire sampled to date (exceeding 300 $g/s/m^2$ for a period of 60 s). This is equivalent to a rate of heat release of 6 000 kW/m^2. Emission factors for the primary combustion products were measured along with the emissions of trace gases. Emissions of trace gases and the content of the measured particulate matter will be reported in a separate paper.

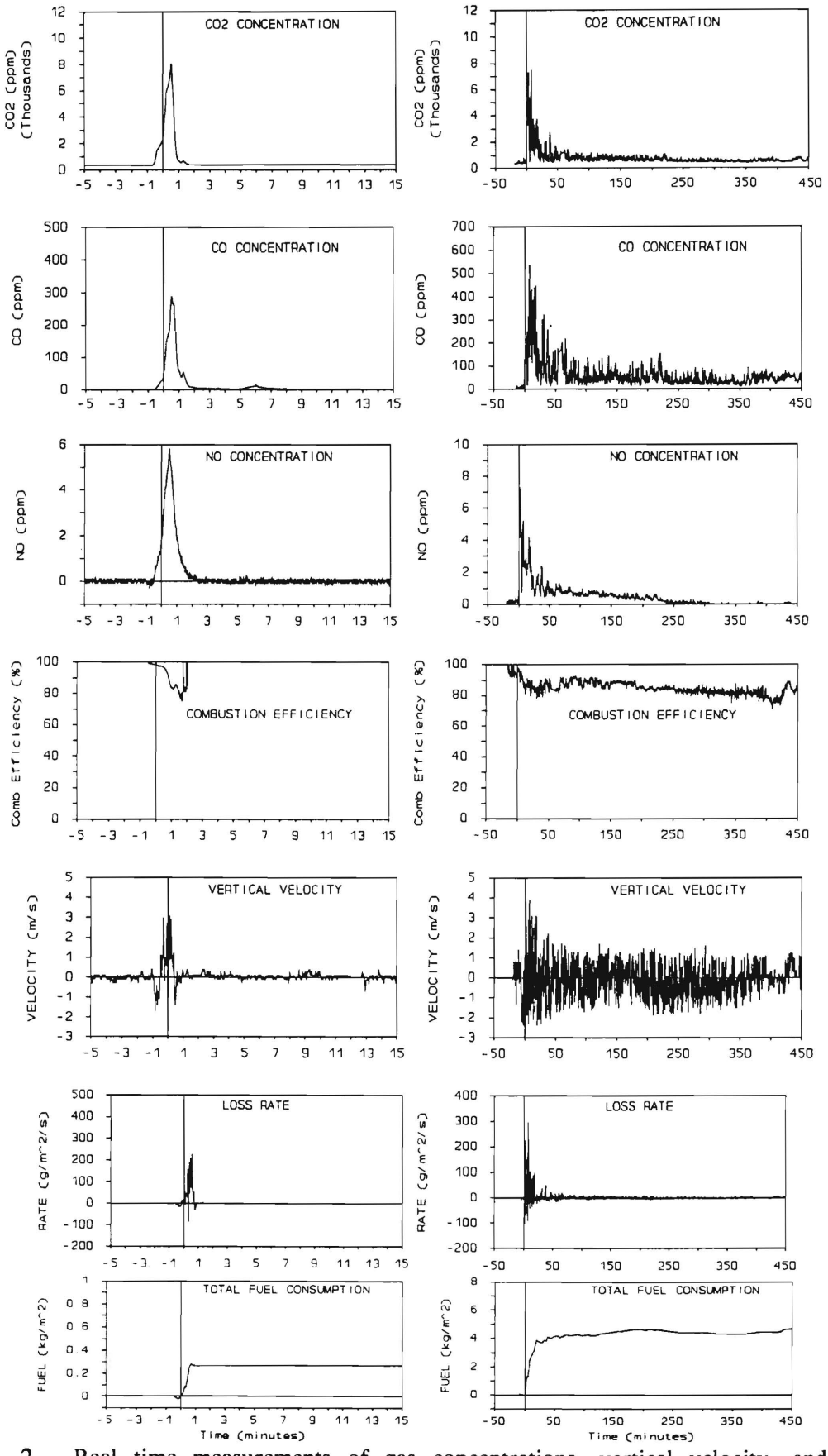

Fig. 2. Real time measurements of gas concentrations, vertical velocity, and temperature for a savanna-type fire and a primary deforestation fire in Brazil.

FUTURE USES FOR FASS

The FASS packages provide the protocol measurements needed to refine estimates of global emissions from fires in biomass fuels. Additionally, the system is being used to determine optimal fuel and weather conditions for ameliorating the smoke produced from prescribed fires in logging slash, underburning, and rangeland fires. In 1991, we anticipate deploying the FASS packages on fires in sagebrush fuels of Wyoming, further measurements of fires in the cerrado grassland fuels of Brazil, mixed-conifer logging slash in British Columbia, ponderosa pine underburning in Montana, and savanna fires in Africa. The FASS packages have been updated to provide for improved reliability of operation and easier deployment.

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APPENDIX A. CALCULATED PARAMETERS

The carbon mass balance (CMB) method is used to estimate the amount of fuel consumed that produced the emissions. The technique was first used for ground measurements by Ward et al. (1979) and forms the basic measurement. All other parameters are derived from the CMB. The method is based on the stoichiometric partial oxidation of a typical fuel ($C_6H_9O_4$) to CO_2 and products of incomplete combustion. The carbon contained in the fuel is assumed to be 50% of the mass. In this section, we review the methods used to calculate useful parameters from the data collected by the FASS.

The fuel consumption required to produce the emissions in a unit volume is computed by accounting for the carbon contained within a unit volume as follows:

$$W_v = \frac{\Sigma C_n}{R} \qquad (1)$$

where,

W_v	=	fuel consumed, g/m^3,
C_n	=	the mass of carbon in emission n, g/m^3,
n	=	CO_2, CO, PM, CH_4, and
R	=	the carbon fraction of the fuel.

It immediately follows that an emission factor (EF) for a specific emission can be computed by dividing the mass of the emission contained in a unit volume by the total fuel consumed in producing the emissions in that volume as follows:

$$EF_{n[p]} = \frac{E_{n[p]}}{W_v} \qquad (2)$$

where,

$EF_{n[p]}$	=	emission factor for emission n, g/kg
$E_{n[p]}$	=	concentration of emission n, mg/m^3, and
$_{[p]}$	=	phase of combustion--flaming (F), smoldering 1 (S1), smoldering 2 (S2).

The rate of fuel consumption over the duration of a fire is measured by the carbon flux technique. By measuring the concentration of carbon, converting the carbon to fuel according to Eq. 1., and multiplying the fuel per unit volume by the vertical velocity of the emissions, the resulting flux represents the rate of fuel consumption (with units of mass per unit area per unit time), as follows:

$$\dot{w} = W_v V_z \qquad (3)$$

where,

$\dot{w}$	=	rate of fuel consumption, $g/m^2/s$, and
V_z	=	vertical velocity of plume, m/s.

Generally, for all the fires measured to date, the sum of the carbon of CO and CO_2 accounts for 95% or more of the carbon released from the fire. By measuring the CO and CO_2 concentrations, the error associated with the fuel consumption calculation is small. A cumulative fuel consumption is calculated by integrating the rate of fuel consumption curve from time i to j as follows:

$$W = \int_{i=1}^{j} \dot{w} dt \approx \sum_{i=1}^{j} \dot{w} \Delta t \qquad (4)$$

where,

W = total fuel consumed, g/m^2, and
Δt = time interval between measurements of the rate of fuel consumption, s.

The rate of a specific emission (n) release by phase of combustion (p), or the source strength ($\dot{e}_{n[p]}$) in units of g/s, is computed similarly to the rate of fuel consumption by:

$$\dot{e}_{n[p]} = E_{n[p]} v_z. \qquad (5)$$

Average emission factors for a fire, EF_n, for a specific emission, n, can be calculated by weighting the emission factors for each phase of combustion by the percent of fuel consumed during the respective phase of combustion as follows:

$$EF_n = (EF_{nf} W_f + EF_{nS1} W_{S1} + EF_{nS2} W_{s2})/W. \qquad (6)$$