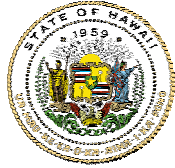


# **Analysis of Hawaii Biomass Energy Resources for Distributed Energy Applications**



**Prepared for**

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and Tourism**

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## Abstract

Distributed energy resources refer to small modular power systems that are employed near the point of electricity consumption. Biomass, a renewable fuel, can be used as the primary energy source for fuel cell, microturbine, and reciprocating engine applications. Of the renewable technologies, biomass is often a least cost alternative. As a fuel, biomass is highly flexible, as it can be used in direct combustion, combined heat and power (CHP) applications or it can be gasified (thermochemically or biologically) to produce a combustible gas that, after appropriate processing, can be used in gas-fuelled conversion technologies.

Samples of bagasse, sugarcane trash, fiber cane, banagrass, macadamia nut shells, hemp, and sewage sludge were collected from across the state and subjected to proximate, heating value, ultimate, and water soluble alkali analyses. In addition, samples of the ash derived from these biomass materials were analyzed for 12 chemical species (Si, Al, Ti, Fe, Ca, Mg, Na, K, P, S, Cl, and C (as CO<sub>2</sub>)). Ash deformation temperatures were also measured.

Ash content of plant-derived samples ranged from 0.8% for macadamia nut shells to nearly 16% for fiber cane that had been contaminated with soil. Ash content of sewage sludge samples was higher, ranging from 21.5 to 32% of fuel mass on a dry basis. Fuel heating values were inversely proportional to ash content and varied from 16.8 MJ per kg for fiber cane to 21.1 MJ per kg for macadamia nut shells. With few exceptions, the heating values of the remaining plant-derived samples ranged from 17.5 to 19 MJ per kg. Heating values of sewage sludge samples ranged from 16 to 18 MJ per kg despite high ash content.

Plant derived samples that were actively growing at the time of collection, sugarcane tops, banagrass, and fiber cane, generally possessed higher N concentrations (0.5 to 1%) than macadamia nut shells, processed fuels such as bagasse, and those that were essentially dead at the time of collection such as sugarcane leaves and ground trash. N content for the latter groups were in a range from 0.2 to 0.5% of dry fuel mass. Sewage sludge samples had order of magnitude higher N levels ranging from 5.4 to 6.7% of dry fuel mass. Fuel bound N can contribute to the formation of oxides of nitrogen, criteria pollutants in thermochemical conversion applications.

S levels in plant derived materials were all less than 0.3% on a dry mass basis. Sewage sludge samples were higher, ranging from 0.9 to 1.7%. S can form SO<sub>2</sub>, H<sub>2</sub>S, and acid gas emissions depending upon the conversion technology employed.

Cl levels in components of sugarcane trash varied from 0.1 to 0.7% of fuel mass with tops generally exhibiting higher concentrations than leaves and ground trash. Banagrass and fiber cane also had Cl concentrations near the top of this range. Bagasse and macadamia nut shells were substantially lower, <0.05%. Cl can react with alkali species and form deposits on heat exchange surfaces, causing corrosion and degrading system performance. HCl formation is also likely. Sewage sludge samples contained less than 0.3% Cl on a dry mass basis.

As indicated by tests for water soluble alkali, K may be expected to play a larger role than Na in contributing to alkali vapor generation under high temperature for the plant derived fuels. Na and K contributions for sewage sludge samples may be expected to be roughly equal.

As evidenced by the elemental ash analyses, plant derived samples that were actively growing at the time of collection, sugarcane tops, banagrass, fiber cane, and hemp possessed higher K concentrations than macadamia nut shells, processed fuels such as bagasse, and those that were essentially dead at the time of collection such as sugarcane leaves and ground trash. Other major constituents of ash included Si and Ca. Fuels that had been exposed to soil contamination also had high levels of Al and Fe. In thermochemical conversion applications, K reacts with S and Cl and serves as a leading contributor to slag formation and ash deposits on heat exchange surfaces. In fluidized bed conversion systems, potassium sulfates and chlorides may induce bed agglomeration and subsequent defluidization.

The ash composition of sewage sludge is marked by high levels of Si, P, and the soil contaminant indicator elements, Al and Fe. The high P levels in sewage sludge ash are unique among the samples analyzed, ranging from 14 to 29% (as  $P_2O_5$ ).

Ash deformation temperature is an indicator of a fuel's propensity to form slag in thermochemical conversion applications. Sugarcane tops and banagrass generally had the lowest initial ash deformation temperatures (oxidizing environment),  $\sim 1000^\circ\text{C}$ , of the samples analyzed and this is a result of their high K levels. The exception to this was hemp which also contained a substantial amount of K but with an accompanying concentration of Ca that served to elevate the ash melting point to  $1284^\circ\text{C}$ . Initial ash deformation temperatures (oxidizing environment) for the remaining plant-derived fuels and sewage sludge samples that had lower K concentrations ranged from 1100 to  $1284^\circ\text{C}$ . These same trends were also evident for deformation temperature measured in a reducing environment.

Total alkali content on a unit energy basis was calculated for each of the materials. Three samples, macadamia nut shells, clean bagasse, and sewage sludge from the Lihue WWTP were found to have less than 0.17 kg ( $K_2O+Na_2O$ ) per GJ, an upper limit associated with low risk for fouling and slagging. Bagasse that had been contaminated with soil, sugar cane leaves from varieties 7750 and B52298, and sewage sludge from the Ele'ele WWTP had values in a range from 0.17 to 0.34 kg ( $K_2O+Na_2O$ ) per GJ and present an increased risk of producing fouling and slagging problems. Values for the remainder of the fuels exceeded the 0.34 kg ( $K_2O+Na_2O$ ) per GJ limit and can be expected to present nearly certain slagging and fouling risks. Although these limits are derived from operating experience, actual performance can vary depending on the design and operation of the energy conversion device. Testing at the pilot and/or demonstration scale is recommended with new fuels in order to assess their operating characteristics prior to committing to long term fuel supply agreements. Fuel characteristics may be improved prior to use by processing to remove problem elements such K and Cl. Blending high and low alkali fuels to facilitate the use of the high alkali material is also an option.

Using the results of the fuel analyses for several biomass materials and assumed air fuel ratios, chemical equilibrium calculations were performed for representative combustion and gasification conditions over a range of reaction temperatures. The results for concentrations of minor species

in combustion and gasification applications were presented in graphic form. These minor species include those formed by the inorganic fuel constituents that are often important to pollutant emissions, slagging, and ash deposition.

Macadamia nut shells and sugarcane bagasse are currently used in distributed generation applications using conventional combustion-based, steam boiler technology. Potential for using the other biomass materials in DER application depends not only on fuel characteristics as discussed in this paper, but the local, national, and/or international market economics and the policy and regulatory environment.



## 1. Introduction

Distributed energy resources (DER) refer to a variety of relatively small, modular generating technologies located and operated near the point of power utilization [1]. These technologies include, but are not limited to, fuel cells, microturbines, gas powered reciprocating engines, wind, solar photovoltaic, and geothermal. Although these power sources may be connected to the utility grid, DER installations are more typically connected at the distribution level rather than the transmission level [2]. Biomass, a renewable fuel, can be used as the primary energy source for fuel cell, microturbine, and reciprocating engine applications. Of the renewable technologies, biomass is often a least cost alternative. As a fuel, biomass is highly flexible, as it can be used in direct combustion, combined heat and power (CHP) applications or it can be gasified (thermochemically or biologically) to produce a combustible gas that, after appropriate processing, can be used in gas-fuelled conversion technologies.

There are a wide variety of potential biomass fuels with varying degrees of DER applicability. Fuel availability and price are often factors of primary importance. In addition, the physicochemical characteristics of the fuel must be suitable for the particular energy conversion technology. A baseline of relevant physicochemical data for thermochemical applications may be obtained from a standard battery of fuel analyses. Further analysis may be warranted based upon the results obtained from this initial battery.

A recent study conducted by Turn et al. [3] inventoried biomass resources in the State of Hawaii. Among the materials included in the inventory were swine, dairy, and poultry manure, sugarcane bagasse and trash, pineapple processing waste, macadamia nut shells, municipal solid wastes, food waste from commercial food preparation facilities, sewage sludge, and fat, oil and grease wastes from food preparation activities. Samples of selected materials – bagasse, sugarcane trash, macadamia nut shells, and sewage sludge– were collected and analyzed. Samples of two crops under consideration for use as dedicated fiber sources, sun hemp and banagrass, were also analyzed. These analyses are the focus of this study.

Bagasse is the fibrous plant material remaining after sugar extraction has been completed in commercial milling operations. Sugarcane trash is a collective term that includes (1) dead leaves attached to the plant at harvest, (2) the top or growing point portion of the plant, and (3) detritus accumulated in the field over the period of the plant's growing cycle. This last quantity is commonly called ground trash. Steam based power plants are typically located adjacent to sugar factories and use bagasse as fuel to satisfy process heat demand, provide motive power, and generate electricity required in sugarcane production and processing. During the cane grinding season, sugar factories are commonly energy self sufficient and frequently export excess power to the utility grid. At present, sugarcane trash is not used for power production but is instead open burned in the field prior to harvest in order to reduce the volume of material transported to, and processed by, the factory. In Hawaii and in many parts of the world, this practice faces an uncertain future due to its impacts on the environment and population centers that have developed in cane growing areas. Recovery and utilization of the cane trash resource has become an area of increasing interest by sugar producers in the state.

Macadamia nut shells are generated from macadamia nut processing operations. Shells are commonly burned to generate steam for use as process heat in nut drying operations and for power generation if the processing facility is sufficiently large to warrant the investment.

Sewage sludge or biosolids are generated from waste water treatment plants. Sludge is often stabilized using anaerobic digestion and then dewatered prior to final disposal at landfills or as an ingredient in compost production. Both the methane rich gas from the anaerobic digester and the sewage sludge stream present opportunities for energy generation.

Results of the analyses of the biomass resources identified above are the focus of this report. The analytical results provide a common quantitative basis for comparison of different fuels, information necessary for determining the suitability of utilizing a given fuel in a particular application, and data required for energy conversion facility design. Equilibrium calculations using the results of the fuel analyses were performed for conditions representative of combustion and gasification technologies.

## **2. Materials and Methods**

Samples of bagasse, sugarcane trash, macadamia nut shells, sewage sludge, hemp, and banagrass were collected and analyzed as described below.

### **2.1 Sample Description**

#### *2.1.1 Bagasse and sugarcane trash*

Sugarcane and bagasse samples were obtained from the Hawaiian Commercial & Sugar Co. (HC&S) plantation on Maui. Bagasse samples were collected from milling operations at the Puunene sugar factory on Maui and sugarcane trash was collected from commercial plantings and experimental plots.

Bagasse samples were collected on two occasions and the material that the samples were drawn from had different histories. Bagasse and coal cofiring tests were conducted in January of 2002. The bagasse used in these tests was stored in open piles on bare soil for roughly one month prior to the tests. For testing, bagasse was recovered from the storage yard using a payloader and returned to the power plant. Storage deterioration and incorporation of extraneous material during handling were likely to have occurred. Samples were obtained as the bagasse was conveyed back to the boiler for use in the cofiring tests. This material is identified in subsequent discussion as Bagasse (01/02 Cofiring Tests).

Fiber cane was also used in the cofiring tests. Sugarcane variety B52298 exhibits higher fiber content than varieties currently used by HC&S for commercial sugar production. B52298 was selected as a fiber cane cultivar for use in the cofiring tests. Roughly 20 acres of fiber cane were planted by HC&S and subsequently harvested in December, 2001. The fiber cane was spread on an abandoned air strip to dry prior to the cofiring tests. Unseasonable weather resulted in the material being rained on several times during the weeks prior to the tests. It was recovered with a payloader and trucked to the bagasse storage house. Samples were obtained from the trucks

prior to unloading. Deterioration due to extended periods at high moisture and incorporation of extraneous material during handling were likely to have occurred. This material is identified in subsequent discussion as Fiber Cane (01/02 Cofiring Tests).

A second bagasse lot was obtained from HC&S for experimental gasification tests conducted at the University of Hawaii (UH). This material was loaded into super sacks in the bagasse house adjacent to the Puunene sugar factory. Bagasse is transported to the bagasse house from the sugar factor by conveyor with little, if any, opportunity for the material to be contaminated. The super sacks were shipped to Oahu via Young Brothers and the bagasse was dried in a forced-draft, ambient-air, bin dryer at UH. The dried fuel lot was sampled. This material is identified in subsequent discussion as Clean Bagasse (02/03 PSI Tests). This label refers to the gasifier tests that were conducted using the bagasse as fuel.

Samples of trash from five varieties of sugarcane were collected from plantings at HC&S. Trash was separated into three components; (1) *leaves*: dead leaves attached to the plant at harvest, (2) *tops*: the top or growing point portion of the plant, and (3) *ground trash*: detritus accumulated in the field over the period of the crop's growing cycle. In some cases ground trash samples were not collected and only leaves and tops were analyzed. Samples were chopped using a forage chopper and air dried. Several of the samples were further reduced in particle size using a Wiley mill equipped with 0.125 inch screen prior to analysis. In the following discussion, trash samples are identified by their HC&S variety number; i.e. 7750, B52298, 3567, 7052, or 4153, and the plant component, tops, leaves, or ground trash. Varieties have generally been selected based on their demonstrated potential for sugar production as well as favorable agronomic characteristics.

#### *2.1.2 Macadamia nut shells*

Samples of macadamia nut shell were collected from the Mauna Loa Macadamia Nut Corporation processing facility in Kea'au. Mauna Loa burns the shells to raise steam for drying and electricity generation. Samples were obtained from the fuel conveyor leading to the boiler.

#### *2.1.3 Sewage sludge/biosolids*

Sewage sludge samples were collected from the Kahului waste water treatment plant (WWTP) on Maui and four WWTP's on Kauai, Ele'ele, Waimea, Lihue, and Wailua. All of these facilities are operated by their respective counties. Samples were taken to UH and dried at 103°C for 24 hours prior to shipment for analysis.

#### *2.1.4 Potential fiber crops*

Hemp and banagrass have been considered as potential fiber crops for use in dedicated feedstock supply systems. Both have been cultivated in experimental plots to establish cultural practices and obtain yield data. Samples of hemp were obtained from experimental plots at HC&S.

Production of banagrass progressed beyond the experimental stage in mid 1990's. A 20 acre demonstration plot was planted on Molokai and the Dole Food Company planted more than a

thousand acres on Oahu for use as boiler fuel. Both efforts have since been terminated. Early experimental plantings were conducted by the former Hawaiian Sugar Planters' Association. This organization has since become the Hawaii Agriculture Research Center (HARC) and HARC currently uses banagrass as windbreaks throughout the fields at their Kunia farm. Banagrass was obtained from HARC's windbreaks and chipped by a local tree pruning company. The chipped material was dried in a forced-draft, ambient-air, bin dryer at UH. Samples for analysis were obtained from the dried fuel lot. This material is identified in subsequent discussion as Banagrass (02/03 PSI Tests). This label refers to gasifier tests that were conducted using this banagrass lot as fuel.

## 2.2 Analytical Methods

Samples of the biomass materials described above were subjected to proximate, ultimate, Cl, heating value, and water soluble alkali analyses. Major ash species (Si, Al, Ti, Fe, Ca, Mg, Na, K, P, S, Cl, and C as CO<sub>2</sub>) and ash deformation characteristics in oxidizing and reducing atmospheres were also determined. These analyses were performed by Hazen Research, Inc., Golden, CO.

## 3. Results

### 3.1 Fuel analyses

Results of the analyses described above are presented in Table 1-A through 1-C. Characteristics of the different materials are discussed below.

#### 3.1.1 *Sugarcane Trash*

Results of the proximate analyses indicate that the components of sugarcane trash generally have ash contents in the range of 6 to 10%. No particular component exhibits consistently high or low ash values across the different varieties analyzed. Conversely, no particular variety exhibits consistently high or low ash values across its various components. Similar trends are observed for the volatile matter content, with values ranging from 74 to 80%. Fixed carbon values ranged from 12 to 17% and tops consistently had 1.5 to 5% (absolute) higher fixed carbon content than the leaves. Reasons for this difference are not apparent.

Heating values for the sugarcane trash components ranged from 17.7 to 18.9 MJ per kg with the lower values generally associated with samples containing higher ash content.

Results of the ultimate analyses reveal that N, S, and Cl are generally present in the components of sugarcane trash at levels generally less than 1%. N levels are in the upper part of this range (0.7 to 1%) in tops and in a range of 0.2 to 0.5% for leaves and ground trash. The higher N content in the tops is consistent with active growth and the reduced levels of the other components can be attributed to N recovery by the plant at the time of leaf senescence.

S and Cl concentrations in the tops, leaves, and ground trash were consistently in the range from 0.1 to 0.3% and 0.1 to 0.7%, respectively, with no distinct concentration patterns evident between varieties or trash component.

Results of the analysis of the ash components of sugarcane trash show higher concentrations of K, P, and Cl in the tops compared to the other two components. The only exception to this is the P concentration in the ground trash of variety 3567 which is higher than that found in both the tops and the leaves. Unlike 3567, the P concentrations in ground trash and leaves from variety 4153 are comparable. A possible explanation of this inconsistency may be sample contamination. Higher K concentrations in the tops are consistent with what would be expected in actively growing plants. Lower concentrations in the leaves and ground trash may be due to nutrient translocation by the plant during leaf senescence and leaching that can occur from contact with rainfall or other water sources.

Greater concentrations of K, P, and Cl in samples of tops are offset by lower concentrations of Si and Al. Al is often present in plant material analyses due to surface contamination with soil although this is normally accompanied by elevated levels of soil Fe as well. Leaf and ground trash components did not contain higher Fe concentrations compared to the tops.

Water soluble alkali measurements provide an indicator of the amount of K and Na present in a fuel sample that may be expected to volatilize during combustion. As shown in the ash analysis, K is present in greater abundance than Na in all components of the sugarcane trash, consistently by an order of magnitude. K present in the tops is consistently more water soluble than that present in the leaves and ground trash and thus would be expected to contribute vapor phase alkali in combustion products more readily. Vapor phase alkali sulfates and chlorides can contribute to fouling of heat exchange surfaces when they condense, forming deposits.

Ash deformation temperatures indicate the range over which ash may be expected to melt and form slag. Data for oxidizing and reducing environments relate to combustion and gasification applications, respectively. Ash deformation temperatures measured for the components of sugarcane trash generally show a minimum difference in initial deformation temperatures in an oxidizing environment of 100°C between values for tops and those for leaves and ground trash. Initial deformation temperatures for tops in an oxidizing environment are in a range from 1030 to 1100°C and similar data for leaves and tops fall in a range from 1130 to 1240°C. Greater differences between deformation temperatures for tops vs. leaves and ground trash were found for reducing environment data, with the later two components having temperatures 150 to 250°C higher than those determined for tops.

Table 1-A. Analyses of biomass materials found in the State of Hawaii.

Material	Sugar Cane											
Variety	7750		B52298		3567			7052		4153		
Plant Component	tops	leaves	tops	leaves	tops	leaves	ground trash	tops	leaves	tops	leaves	ground trash
Proximate Analysis												
Moisture	0	0	0	0	0	0	0	0	0	0	0	0
Ash	6.67	7.61	9.10	8.72	6.40	5.83	6.13	7.31	9.66	6.82	9.52	10.21
Volatile	75.95	77.75	73.61	79.12	77.41	79.59	78.36	76.47	75.75	76.82	76.55	75.59
Fixed C	17.38	14.64	17.29	12.16	16.19	14.58	15.51	16.22	14.59	16.36	13.93	14.2
Heating Value												
BTU/lb	8101	7721	7971	7816	8140	7920	7900	7988	7622	7911	7660	7590
MJ/kg	18.8	18.0	18.5	18.2	18.9	18.43	18.38	18.6	17.7	18.4	17.82	17.66
Ultimate Analysis												
Moisture	0	0	0	0	0	0	0	0	0	0	0	0
C	47.10	46.26	46.36	46.31	48.53	48.32	48.58	48.31	46.84	47.39	46.94	45.37
H	4.64	5.53	4.38	4.94	5.20	5.38	5.46	5.35	5.23	5.26	5.23	5.09
N	0.67	0.26	0.90	0.22	0.91	0.46	0.49	1.02	0.40	0.84	0.46	0.4
S	0.12	0.12	0.17	0.13	0.14	0.12	0.13	0.21	0.28	0.18	0.23	0.2
Ash	6.67	7.61	9.10	8.55	6.40	5.83	6.13	7.31	9.66	6.82	9.52	10.21
O (by diff)	41.79	40.26	39.74	40.04	38.84	39.75	39.07	37.83	37.44	39.55	37.58	38.69
Cl	0.74	0.37	0.30	0.11	0.56	0.48	0.33	0.57	0.47	0.57	0.65	0.24
Water Soluble Alkali (%)												
Na <sub>2</sub> O	0.027	0.026	0.021	0.030	0.018	0.016	0.017	0.047	0.028	0.050	0.037	0.031
K <sub>2</sub> O	1.971	0.707	1.852	0.350	1.828	0.802	0.675	2.106	1.204	1.864	1.226	0.491

Table 1-A (continued). Analyses of biomass materials found in the State of Hawaii.

Material	Sugar Cane											
	7750		B52298		3567			7052		4153		
Plant Component	tops	leaves	tops	leaves	tops	leaves	ground trash	tops	leaves	tops	leaves	ground trash
Elemental Analysis of Ash												
SiO <sub>2</sub>	38.32	75.07	53.37	74.54	36.63	50.11	57.5	47.31	69.87	44.25	64.70	69.04
Al <sub>2</sub> O <sub>3</sub>	4.26	5.31	2.76	4.92	3.76	7.65	4.45	2.66	3.49	1.46	2.43	4.54
TiO <sub>2</sub>	0.41	0.37	0.14	0.40	0.54	1.00	1.04	0.46	0.41	0.35	0.18	0.78
Fe <sub>2</sub> O <sub>3</sub>	3.92	1.78	2.39	1.61	2.12	4.24	1.33	2.17	2.10	1.44	1.39	3.02
CaO	5.80	5.81	8.09	8.51	8.29	9.12	11.00	2.56	2.82	4.76	4.60	6.49
MgO	2.68	2.79	2.94	3.22	3.99	5.33	5.11	3.49	3.66	3.18	3.63	3.56
Na <sub>2</sub> O	0.56	0.50	0.55	0.49	1.14	0.62	0.71	1.42	0.80	1.12	0.56	0.51
K <sub>2</sub> O	29.20	7.73	20.30	4.18	28.80	13.1	9.94	27.00	11.30	26.60	13.6	5.60
P <sub>2</sub> O <sub>5</sub>	3.45	0.88	3.80	0.48	4.63	1.17	6.21	1.76	0.94	8.22	0.99	1.11
SO <sub>3</sub>	1.19	2.04	1.91	1.11	2.93	2.04	2.16	2.63	3.24	2.47	2.76	2.34
Cl	11.00	0.47	2.93	0.37	7.58	4.87	2.10	7.10	1.91	7.80	5.19	0.70
CO <sub>2</sub>	0.46	0.08	0.30	0.43	0.89	0.77	0.68	0.42	0.20	0.77	0.37	1.34
Ash Fusion Temperature (°C), Oxidizing Atmosphere												
Initial	1108	1237	1031	1235	1066	1169	1187	1074	1132	1031	1177	1202
Softening	1160	1322	1085	1320	1109	1242	1259	1127	1333	1108	1300	1256
Hemispherical	1228	1381	1162	1349	1150	1248	1281	1181	1373	1229	1332	1307
Fluid	1289	1413	1266	1409	1207	1263	1307	1241	1428	1266	1387	1392
Ash Fusion Temperature (°C), Reducing Atmosphere												
Initial	1046	1197	994	1238	1027	1230	1271	1039	1303	976	1217	1249
Softening	1085	1298	1061	1389	1074	1243	1278	1076	1359	1029	1407	1299
Hemispherical	1128	1318	1113	1408	1121	1274	1297	1109	1399	1097	1423	1318
Fluid	1158	1383	1230	1441	1196	1329	1367	1217	1410	1274	1441	1363

Table 1-B. Analyses of biomass materials found in the State of Hawaii.

			01/02 Cofiring Tests		02/03 PSI Tests	
Material	Hemp	Macadamia Nut Shells	Fiber Cane <sup>1</sup>	Bagasse <sup>2</sup>	Banagrass <sup>3</sup>	Clean Bagasse <sup>3</sup>
Proximate Analysis						
Moisture	0	0	0.00	0.00	0	0
Ash	4.06	0.82	15.68	12.38	6.86	2.49
Volatile	79.22	81.73	71.61	77.36	76.26	84.42
Fixed C	16.72	17.45	12.72	10.26	16.88	13.10
Heating Value						
BTU/lb	7889	9084	7220	7269	7977	8146
MJ/kg	18.4	21.1	16.8	16.9	18.6	18.9
Ultimate Analysis						
Moisture	0	0	0	0	0	
C	47.88	54.99	44.50	45.45	47.85	50.00
H	5.53	5.98	5.18	5.26	5.02	5.55
N	0.43	0.38	0.51	0.23	0.64	0.17
S	0.07	0.05	0.16	0.05	0.10	0.065
Ash	4.06	0.82	15.68	12.38	6.86	2.49
O (by diff)	42.38	37.83	33.84	36.65	39.52	41.71
Cl	0.22	0.02	0.43	0.04	0.70	0.04
Water Soluble Alkali (%)						
Na <sub>2</sub> O	0.420	0.004	0.021	0.017	0.097	0.022
K <sub>2</sub> O	1.262	0.107	0.998	0.131	1.861	0.165
<sup>1</sup> Average of 3 samples						
<sup>2</sup> Average of 4 samples						
<sup>3</sup> Average of 2 samples						



Table 1-B (continued). Analyses of biomass materials found in the State of Hawaii.

Sample ID	01/02 Cofiring Tests			02/03 PSI Tests		
	Hemp	Macadamia Nut Shell	Fiber Cane <sup>1</sup>	Bagasse <sup>2</sup>	Banagrass <sup>3</sup>	Clean Bagasse <sup>3</sup>
Elemental Analysis of Ash						
SiO <sub>2</sub>	22.69	25.38	47.26	45.90	46.83	46.39
Al <sub>2</sub> O <sub>3</sub>	11.80	7.41	12.83	20.56	1.06	17.48
TiO <sub>2</sub>	1.13	0.39	2.67	3.77	0.08	3.02
Fe <sub>2</sub> O <sub>3</sub>	5.76	3.73	10.64	15.45	0.92	12.61
CaO	11.10	13.00	6.80	4.32	4.10	3.84
MgO	3.86	6.80	4.23	3.22	6.21	3.56
Na <sub>2</sub> O	1.93	2.16	1.76	0.96	1.85	1.53
K <sub>2</sub> O	30.70	24.60	7.29	1.68	27.25	7.61
P <sub>2</sub> O <sub>5</sub>	1.23	3.33	1.25	0.89	4.11	2.11
SO <sub>3</sub>	0.76	4.63	1.48	0.41	0.67	1.14
Cl	4.23	0.04	1.49	0.00	9.70	0.03
CO <sub>2</sub>	5.15	6.98	0.21	0.13	0.08	0.13
Ash Fusion Temperature (°C), Oxidizing Atmosphere						
Initial	1284	1161	1163	1237	997	1178
Softening	1292	1180	1176	1262	1099	1201
Hemispherical	1304	1189	1200	1279	1155	1231
Fluid	1358	1204	1226	1304	1196	1274
Ash Fusion Temperature (°C), Reducing Atmosphere						
Initial	1231	1309	1113	1104	977	1111
Softening	1242	1312	1130	1147	1043	1129
Hemispherical	1248	1314	1142	1179	1146	1134
Fluid	1321	1317	1162	1209	1220	1141
<sup>1</sup> Average of 3 samples						
<sup>2</sup> Average of 4 samples						
<sup>3</sup> Average of 2 samples						

Table 1-C. Analysis of sludge from Maui and Kauai waste water treatment plants.

Island	Kauai	Kauai	Kauai	Kauai	Maui
Waste Water Treatment Plant					
	Ele'ele	Lihue	Wailua	Waimea	Kahului
Sample ID	Sludge	Sludge	Sludge	Sludge	Sludge
<b>Proximate Analysis</b>					
Moisture	0	0	0	0	0
Ash	21.58	25.33	25.13	32.00	24.48
Volatile	66.77	67.03	68.42	60.75	68.38
Fixed C	11.65	7.64	6.45	7.25	7.14
Heating Value					
BTU/lb	7532	7816	7251	6880	7595
MJ/kg	17.52	18.18	16.87	16.01	17.67
<b>Ultimate Analysis</b>					
Moisture	0	0	0	0	0
C	43.13	43.8	41.85	39.19	43.79
H	5.62	5.93	5.29	5.22	5.91
N	6.30	6.10	6.32	5.39	6.71
S	1.08	1.76	0.94	1.21	0.88
Ash	21.58	25.33	25.13	32.00	24.48
O (by diff)	22.10	19.43	21.75	17.57	18.82
Cl	0.31	0.08	0.12	0.23	0.15
<b>Water Soluble Alkali (%)</b>					
Na <sub>2</sub> O	0.197	0.077	0.317	0.172	0.228
K <sub>2</sub> O	0.085	0.069	0.237	0.193	0.268
<b>Elemental Analysis of Ash</b>					
SiO <sub>2</sub>	29.92	26.17	27.24	34.77	33.65
Al <sub>2</sub> O <sub>3</sub>	23.14	19.53	13.46	14.70	18.23
TiO <sub>2</sub>	2.29	2.42	1.31	2.31	2.17
Fe <sub>2</sub> O <sub>3</sub>	8.21	9.45	6.07	8.96	8.36
CaO	2.40	12.10	20.60	11.70	11.30
MgO	2.09	1.71	5.94	3.72	3.67
Na <sub>2</sub> O	1.33	0.53	1.54	0.82	1.37
K <sub>2</sub> O	0.96	0.64	1.31	1.19	1.71
P <sub>2</sub> O <sub>5</sub>	29.24	18.43	14.30	20.64	19.62
SO <sub>3</sub>	0.31	5.51	3.06	1.44	1.73
Cl	0.01	0.00	0.17	0.02	0.11
CO <sub>2</sub>	0.04	0.28	1.61	0.15	0.15
<b>Ash Fusion Temperature (°C), Oxidizing Atmosphere</b>					
Initial	1252	1098	1196	1118	1117
Softening	1366	1123	1213	1160	1145
Hemispherical	1391	1134	1239	1169	1179
Fluid	1420	1142	1248	1197	1182
<b>Ash Fusion Temperature (°C), Reducing Atmosphere</b>					
Initial	1259	1098	1181	1114	1097
Softening	1306	1111	1193	1168	1150
Hemispherical	1321	1112	1199	1182	1169
Fluid	1349	1113	1210	1221	1177

### 3.1.2 Banagrass

Comparison of banagrass data with those from the tops component of the sugar cane trash discussion above indicate that the two materials are quite similar in all respects.

### 3.1.3 Bagasse

Results of bagasse analyses indicate differences between the two fuel lots that are largely due to incorporation of soil into the Bagasse (01/02 Cofiring Tests) material. The cofiring test samples contained more than 12% ash compared to the 2.5% ash content of the clean bagasse samples. On an ash free basis heating values are comparable at ~19.4 MJ per kg. The sugar milling process serves to remove many of the inorganic constituents from bagasse. Note the low N, S, and Cl contents, low levels of water soluble alkali, low K content of the ash, and relatively high initial ash deformation temperatures compare to banagrass or sugarcane tops. Notable differences are the elevated levels of Al and Fe in the ash due to the incorporation of soil from push rake harvest operations and open yard payloader reclaiming in the case of the cofiring test samples.

### 3.1.4 Fiber cane

The fiber cane analyses included in Table 1 are similar to the banagrass and sugarcane tops data discussed above with differences largely due to post harvest handling. As mentioned earlier, the fiber cane material used in cofiring tests in January, 2002, was spread on an unused air strip to dry it but was subjected to periodic rains. The material was recovered from the air strip using a payloader, resulting in incorporation of soil. Effects of the rain and payloader recovery are evident in the fuel analyses. Ash content of the fiber cane is roughly twice as high as that measured in banagrass and sugarcane tops samples indicating the presence of soil. Further evidence of this is seen in the high Al and Fe content of the ash.

A second effect of post harvest events is the reduced alkali and Cl content of the fiber cane. With no processing beyond particle size reduction with a forage harvester, the K and Cl levels in the fuel would be expected to be comparable to those in banagrass or sugar cane tops. Cl levels are reduced by nearly half in the fiber cane compared to the banagrass and sugarcane tops and the K content of the ash is lowered by roughly a factor of four. Water soluble alkali tests indicate that the levels in the fiber cane are about half those in banagrass and sugarcane tops. These factors indicate water soluble alkali and Cl were leached by rain water passing through the fuel mat as it lay exposed on the air strip.

### 3.1.5 Hemp

The hemp sample had an ash content of ~4% and a higher heating value of 18.4 MJ per kg. N (0.43%) and Cl (0.22%) levels are lower than the fresh fuels such as sugar cane tops and banagrass but higher than a processed/leached fuel such as bagasse. The water soluble K<sub>2</sub>O value for hemp (1.26%) also lies in the range between these two fuel types. The water soluble Na<sub>2</sub>O value, however, is the highest of any sample included in the study, 0.42%, with no apparent reason for its outlier status. Hemp ash does not contain noticeably higher levels of Na<sub>2</sub>O than other fuels.

Although no evidence exists to indicate that the sample was contaminated, this possibility should not be ruled out. The banagrass sample had a water soluble  $\text{Na}_2\text{O}$  value of 0.097%, roughly one quarter of the hemp value, and was the second highest measured among the study materials. Hemp ash analysis revealed high levels of Si, Al, Ca, and K. The high Ca levels are unique to hemp and may explain the high initial ash deformation temperatures, in excess of  $1230^\circ\text{C}$ , in both oxidizing and reducing environments. The addition of Ca-rich dolomite to fluidized beds is a management technique used to raise ash melting temperatures and avoid deformation that may lead to bed agglomeration.

### 3.1.6 *Macadamia nut shell*

Macadamia nut shell is characterized by the lowest ash content, 0.82%, and highest higher heating value, 21.1 MJ per kg, of any of the samples included in the study. Macadamia nut shell contains a moderate amount of N, 0.38%, and low levels of S (0.05%), Cl (0.02%), and water soluble alkali. Macadamia nut shell ash is characterized by high levels of Si and K and contains elevated levels of Al and Fe, most likely from soil contamination during nut sweeping harvest operations. The initial ash deformation temperature measured in an oxidizing environment was  $1161^\circ\text{C}$  making it comparable to the clean bagasse sample discussed earlier. The deformation temperature in a reducing environment,  $1309^\circ\text{C}$ , was the highest measured among the samples included in the study.

### 3.1.7 *Sewage sludge/biosolids*

Ash content of sewage sludge samples was the highest among the samples included in the study ranging from 21 to 32% on a mass basis. The high ash content resulted in lower volatile and fixed carbon content compared to the plant derived materials discussed above. Higher heating values were generally lower, ranging from 16 to 18 MJ per kg. Biosolid samples contained high levels of N (5.4 to 6.7%) and S (0.9 to 1.7%) and moderate amounts of Cl (0.08 to 0.31%). Ash composition is characterized by high levels of Si, Al, Fe, Ca, and P. The highest  $\text{P}_2\text{O}_5$  concentration measured in the ash from plant derived materials was 8.2%. In comparison,  $\text{P}_2\text{O}_5$  levels in the ash from sewage sludge samples ranged from 14 to 29%. Initial ash deformation temperatures in both oxidizing and reducing environments were in excess of  $\sim 1100^\circ\text{C}$  making them comparable to the values determined for clean bagasse (02/03 PSI Tests).

## 3.2 Alkali content comparison

Alkali content is another useful indicator of a fuel's suitability for a use in thermochemical conversion facilities. Alkali species are the primary source of fouling in biomass-fueled combustion and gasification power generation systems particularly when S or Cl is present. The ratio of alkali content to energy content is a useful index that can be used to compare biomass fuels. Data from the fuel analyses were used to derive the alkali concentration on a unit energy basis shown in the in Figures 1 and 2.

High alkali levels present one of the biggest challenges in utilizing biomass fuels for power generation. Miles et al. [4] reported that fuels containing  $>0.34$  kg ( $\text{K}_2\text{O}+\text{Na}_2\text{O}$ ) per GJ were almost certain to cause fouling or slagging in boilers. Furthermore, alkali concentrations between 0.17 and 0.34 kg ( $\text{K}_2\text{O}+\text{Na}_2\text{O}$ ) per GJ were at an increased risk of causing fouling. Fuels with concentrations

below 0.17 kg (K<sub>2</sub>O+Na<sub>2</sub>O) per GJ can be considered to be low risk fuels for fouling and slagging. Figures 1 shows that of the plant derived materials, only five samples – macadamia nut shells, Clean Bagasse (02/03 PSI Tests), Bagasse (01/02 Cofiring Tests), and sugarcane leaves from varieties 7750 and B52298 – fall below the 0.34 kg (K<sub>2</sub>O+Na<sub>2</sub>O) per GJ limit. Only macadamia nut shells and Clean Bagasse (02/03 PSI Tests) are below the 0.17 kg (K<sub>2</sub>O+Na<sub>2</sub>O) per GJ limit.

Figure 2 shows that alkali levels for sewage sludge vary by WWTP. Lihue WWTP has alkali per unit energy content of 0.163 kg (K<sub>2</sub>O+Na<sub>2</sub>O) per GJ, falling below the 0.17 kg (K<sub>2</sub>O+Na<sub>2</sub>O) per GJ fouling limit. The Ele'ele WWTP at 0.282 kg (K<sub>2</sub>O+Na<sub>2</sub>O) per GJ, falls within the potential fouling range. The three remaining samples have values of ~0.4 kg (K<sub>2</sub>O+Na<sub>2</sub>O) per GJ and do not greatly exceed the 0.34 kg (K<sub>2</sub>O+Na<sub>2</sub>O) per GJ limit.

It is possible to reduce alkali material in biomass fuels with post harvest processing measures. Turn et al. [5] demonstrated the effectiveness of leaching and milling processes in reducing the levels of alkali and ash content of fiber cane. Naturally, fuels that do not require treatment are more valuable and easier to handle, however in applications where the fuel is a waste stream from a commercial process the value added by energy production could make up costs incurred to undertake fuel treatment. The development of efficient and cost effective treatment methods may facilitate the use of biomass fuels with higher alkali content for energy production.

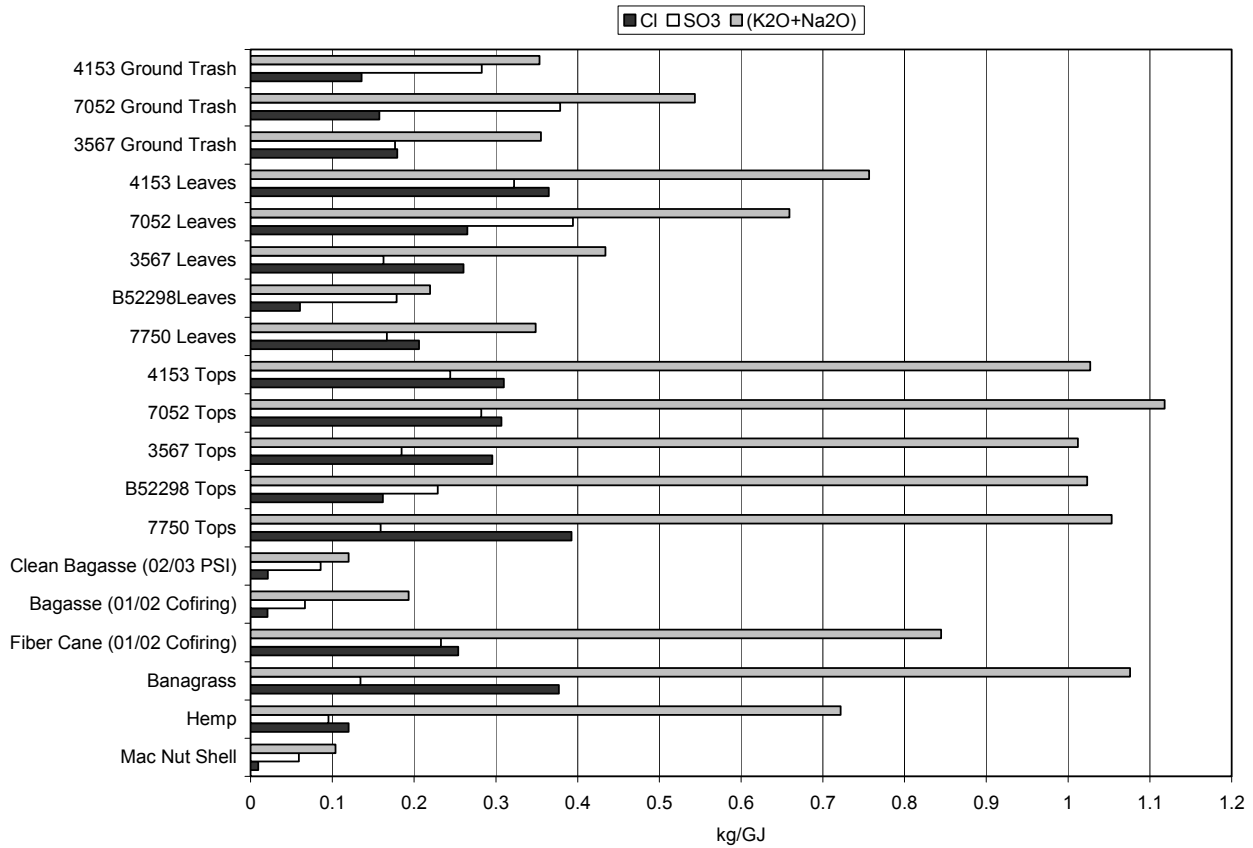


Figure 1. Total alkali (as oxide), Cl, and S (as oxide) concentrations on a unit energy basis for sugar cane varieties and biomass samples.

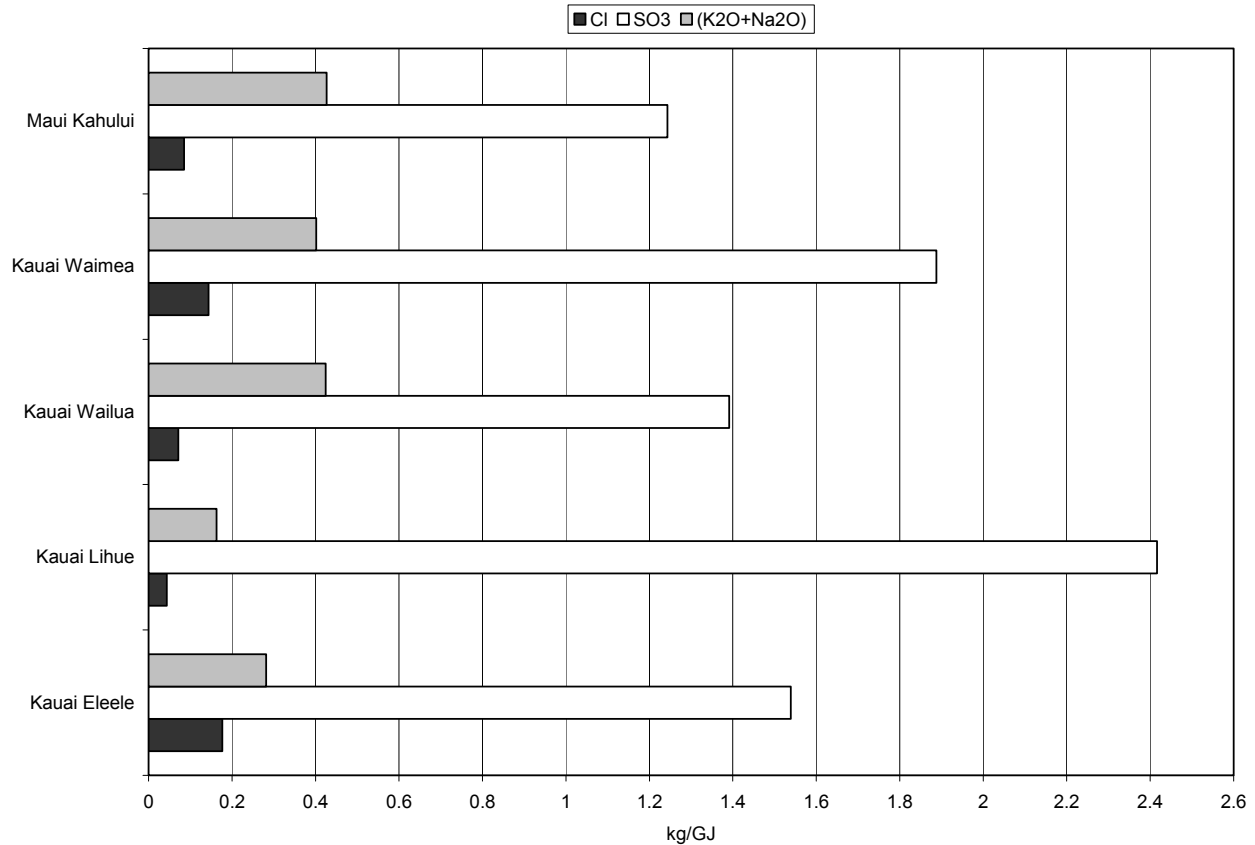


Figure 2. Total alkali (as oxide), Cl, and S (as oxide) concentrations on a unit energy basis for sewage sludge samples collected at WWTP's on Kauai and Maui.

### 3.3 DER Fuel Potential

Biomass fueled power generation is a valuable application in rural areas where it can fulfill the power supply needs of local farmers and other rural residents [1]. Due to the lower energy content of biomass materials compared to fossil fuels, it is important to have power generation facility located in close proximity to the fuel source in order to minimize transportation costs. The economic value of agricultural waste residues as fuel sources makes biomass conversion in rural areas a boon for farmers, enhances energy security, and reduces strain on the electricity grid in accordance with DER initiatives.

Both macadamia nut shells and bagasse are currently being used in DER-qualifying power generation in Hawaii. One advantage that these two fuels share is high energy contents and low alkali content. An important factor in the use of these fuels is that they are waste products of commercial sugar and macadamia nut operations and are collected in a central location as part of established crop processing activities. The energy derived from combustion of these fuels provides the processing plants' heat and power requirements.

One currently underutilized and potential DER fuel source is sewage sludge from municipal WWTP. Although utilization for compost production is the current disposal method on Maui and to

a lesser extent in Honolulu, a more common practice is to have the sludge trucked to landfills and deposited [3]. While effective, this method is expensive and represents a burden to ever diminishing landfill capacities. The fuel analyses show that, although sewage sludge has high ash content, it possesses an acceptable heating value. The high S content of sludge can present operating challenges in combustion and gasification systems. The formation of SO<sub>2</sub>, H<sub>2</sub>S, and acid gases can lead to corrosion of boiler operating surfaces and high sulfur emissions. Strategies exist for controlling sulfur emissions but may require specialized equipment and added expense.

Sugarcane trash represents a yet untapped fuel supply. The alkali, S, and Cl present in tops, leaves, and ground trash may require that suitable methods for managing these inorganic constituents be developed as part of any utilization program. Preliminary testing at a pilot scale and limited duration demonstration tests at full scale should be considered to assess fuel behavior under carefully prescribed conditions.

Many of the biomass materials identified in this report have never been tested in commercial or experimental facilities. While the preliminary data from fuel analyses suggests that some hold potential for DER applications in Hawaii, it is clear that more information is needed before commercial application can be considered. Calculation of chemical equilibrium composition for combustion and gasification conditions is a relatively low cost way of identifying fuels that may present operating difficulties for thermochemical conversion facilities. Chemical equilibrium predicts the final composition of products given a set of reactants and a reaction temperature and pressure. The limitation to these calculations is that they do not take into account the rate at which the reaction occurs, instead assuming that sufficient time exists to allow all reactions to proceed to completion. To perform an equilibrium calculation for biomass, the reactants are formed from the chemical data from Table 1 and an appropriate amount of air based on reaction stoichiometry. Temperatures and pressures typical of those found in energy conversion devices (e.g. boilers, gasifiers, etc.) are specified as input. The result of the calculation is the product composition (i.e. combustion products or gasifier product gas) and may include solid, gas, or liquid phase compounds.

For combustion cases, equilibrium calculations were performed covering a temperature range from 1000 to 1700°C at 100°C intervals. Zero percent moisture was assumed for all cases. This baseline moisture content creates a standard for comparison across all fuels. The moisture contents for many of the fuels tested can vary greatly depending on field conditions, harvesting and processing procedures, and storage conditions. The quantity of reactant air used in the calculation was varied to achieve a 5% O<sub>2</sub> concentration in the products, a level typical of stack gas in combustion applications.

For gasification cases, calculations were performed covering a temperature range from 700 to 1000°C at 50°C intervals with an equivalence ration of 0.3, i.e. thirty percent of stoichiometric air requirements. Ten percent moisture content was assumed for all fuels. While it is possible that a gasification system might operate with more than ten percent moisture it is unlikely that it would operate with less. Ten percent is also the ambient equilibrium moisture content that can be expected for most of the fuels considered in these calculations. In gasification systems steam is often added to the reactor input stream to increase carbon conversion, however no attempt was made to simulate steam addition in these calculations.

Chemical equilibrium calculations were performed for seven different fuels using FactSage™ software [6] to predict the composition of the product streams generated by both gasification and combustion conditions. The data from these calculations may help investigators and developers match fuels with power generation methods and equipment. These data can also reveal difficulties that might be associated with a specific fuel or power generation strategy. The results for concentrations of minor species in combustion and gasification applications have been summarized in graphic form in Appendix 1. These minor species include those formed by the inorganic fuel constituents that are often important to pollutant emissions, slagging, and ash deposition as described above.

#### **4. Summary and Conclusions**

Samples of bagasse, sugarcane trash, fiber cane, banagrass, macadamia nut shells, hemp, and sewage sludge were collected from across the state and subjected to proximate, heating value, ultimate, and water soluble alkali analyses. In addition, samples of the ash derived from these biomass materials were analyzed for 12 chemical species (Si, Al, Ti, Fe, Ca, Mg, Na, K, P, S, Cl, and C (as CO<sub>2</sub>)). Ash deformation temperatures were also measured.

Ash content of plant-derived samples ranged from 0.8% for macadamia nut shells to nearly 16% for fiber cane that had been contaminated with soil. Ash content of sewage sludge samples was higher, ranging from 21.5 to 32% of fuel mass on a dry basis. Fuel heating values were inversely proportional to ash content and varied from 16.8 MJ per kg for fiber cane to 21.1 MJ per kg for macadamia nut shells. With few exceptions, the heating values of the remaining plant-derived samples ranged from 17.5 to 19 MJ per kg. Heating values of sewage sludge samples ranged from 16 to 18 MJ per kg despite high ash content.

Plant derived samples that were actively growing at the time of collection, sugarcane tops, banagrass, and fiber cane, generally possessed higher N concentrations (0.5 to 1%) than macadamia nut shells, processed fuels such as bagasse, and those that were essentially dead at the time of collection such as sugarcane leaves and ground trash. N content for the latter groups were in a range from 0.2 to 0.5% of dry fuel mass. Sewage sludge samples had order of magnitude higher N levels ranging from 5.4 to 6.7% of dry fuel mass. Fuel bound N can contribute to the formation of oxides of nitrogen, criteria pollutants in thermochemical conversion applications.

S levels in plant derived materials were all less than 0.3% on a dry mass basis. Sewage sludge samples were higher, ranging from 0.9 to 1.7%. S can form SO<sub>2</sub>, H<sub>2</sub>S, and acid gas emissions depending upon the conversion technology employed.

Cl levels in components of sugarcane trash varied from 0.1 to 0.7% of fuel mass with tops generally exhibiting higher concentrations than leaves and ground trash. Banagrass and fiber cane also had Cl concentrations near the top of this range. Bagasse and macadamia nut shells were substantially lower, <0.05%. Cl can react with alkali species and form deposits on heat exchange surfaces, causing corrosion and degrading system performance. HCl formation is also likely. Sewage sludge samples contained less than 0.3% Cl on a dry mass basis.



As indicated by tests for water soluble alkali, K may be expected to play a larger role than Na in contributing to alkali vapor generation under high temperature for the plant derived fuels. Na and K contributions for sewage sludge samples may be expected to be roughly equal.

As evidenced by the elemental ash analyses, plant derived samples that were actively growing at the time of collection, sugarcane tops, banagrass, fiber cane, and hemp possessed higher K concentrations than macadamia nut shells, processed fuels such as bagasse, and those that were essentially dead at the time of collection such as sugarcane leaves and ground trash. Other major constituents of ash included Si and Ca. Fuels that had been exposed to soil contamination also had high levels of Al and Fe. In thermochemical conversion applications, K reacts with S and Cl and serves as a leading contributor to slag formation and ash deposits on heat exchange surfaces. In fluidized bed conversion systems, potassium sulfates and chlorides may induce bed agglomeration and subsequent defluidization.

The ash composition of sewage sludge is marked by high levels of Si, P, and the soil contaminant indicator elements, Al and Fe. The high phosphorous levels in sewage sludge ash are unique among the samples analyzed, ranging from 14 to 29% (as  $P_2O_5$ ).

Ash deformation temperature is an indicator of a fuel's propensity to form slag in thermochemical conversion applications. Sugarcane tops and banagrass generally had the lowest initial ash deformation temperatures (oxidizing environment),  $\sim 1000^\circ\text{C}$ , of the samples analyzed and this is a result of their high K levels. The exception to this was hemp which also contained a substantial amount of K but with an accompanying concentration of Ca that served to elevate the ash melting point to  $1284^\circ\text{C}$ . Initial ash deformation temperatures (oxidizing environment) for the remaining plant-derived fuels and sewage sludge samples that had lower K concentrations ranged from  $1100$  to  $1284^\circ\text{C}$ . These same trends were also evident for deformation temperature measured in a reducing environment.

Total alkali content on a unit energy basis was calculated for each of the materials. Three samples, macadamia nut shells, clean bagasse, and sewage sludge from the Lihue WWTP were found to have less than  $0.17$  kg ( $K_2O+Na_2O$ ) per GJ, an upper limit associated with low risk for fouling and slagging. Bagasse that had been contaminated with soil, sugar cane leaves from varieties 7750 and B52298, and sewage sludge from the Ele'ele WWTP had values in a range from  $0.17$  to  $0.34$  kg ( $K_2O+Na_2O$ ) per GJ and present an increased risk of producing fouling and slagging problems. Values for the remainder of the fuels exceeded the  $0.34$  kg ( $K_2O+Na_2O$ ) per GJ limit and can be expected to present nearly certain slagging and fouling risks. Although these limits are derived from operating experience, actual performance can vary depending on the design and operation of the energy conversion device. Testing at the pilot and/or demonstration scale is recommended with new fuels in order to assess their operating characteristics prior to committing to long term fuel supply agreements. Fuel characteristics may be improved prior to use by processing to remove problem elements such K and Cl. Blending high and low alkali fuels to facilitate the use of the high alkali material is also an option.

Using the results of the fuel analyses for several biomass materials and assumed air fuel ratios, chemical equilibrium calculations were performed for representative combustion and gasification conditions over a range of reaction temperatures. The results for concentrations of minor species in

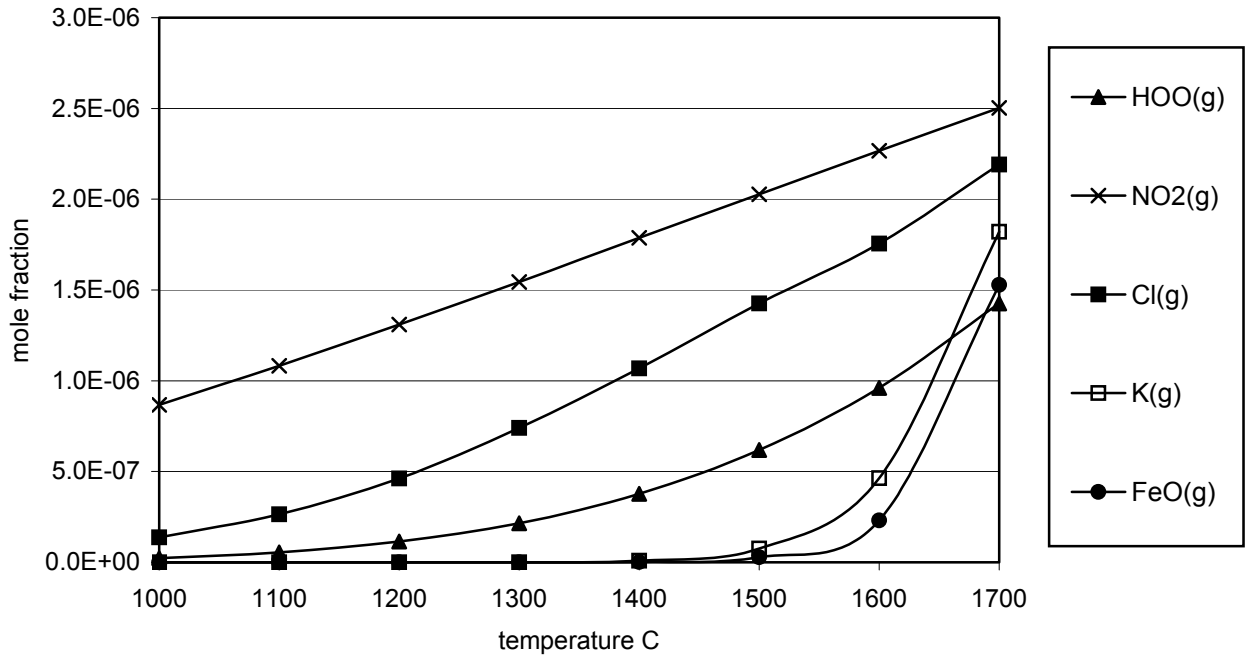
combustion and gasification applications were presented in graphic form. These minor species include those formed by the inorganic fuel constituents that are often important to pollutant emissions, slagging, and ash deposition.

Macadamia nut shells and sugarcane bagasse are currently used in distributed generation applications using conventional combustion-based, steam boiler technology. Potential for using the other biomass materials in DER application depends not only on fuel characteristics as discussed in this paper, but the local, national, and/or international market economics and the policy and regulatory environment.

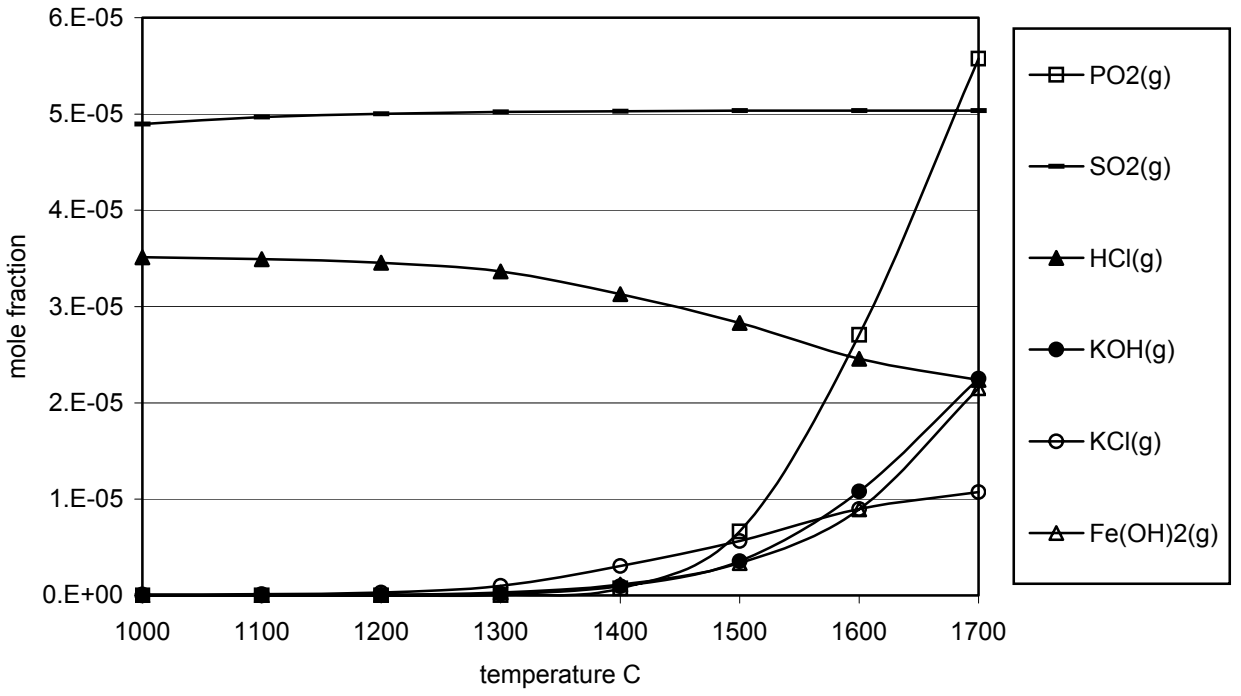
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## **Appendix A**

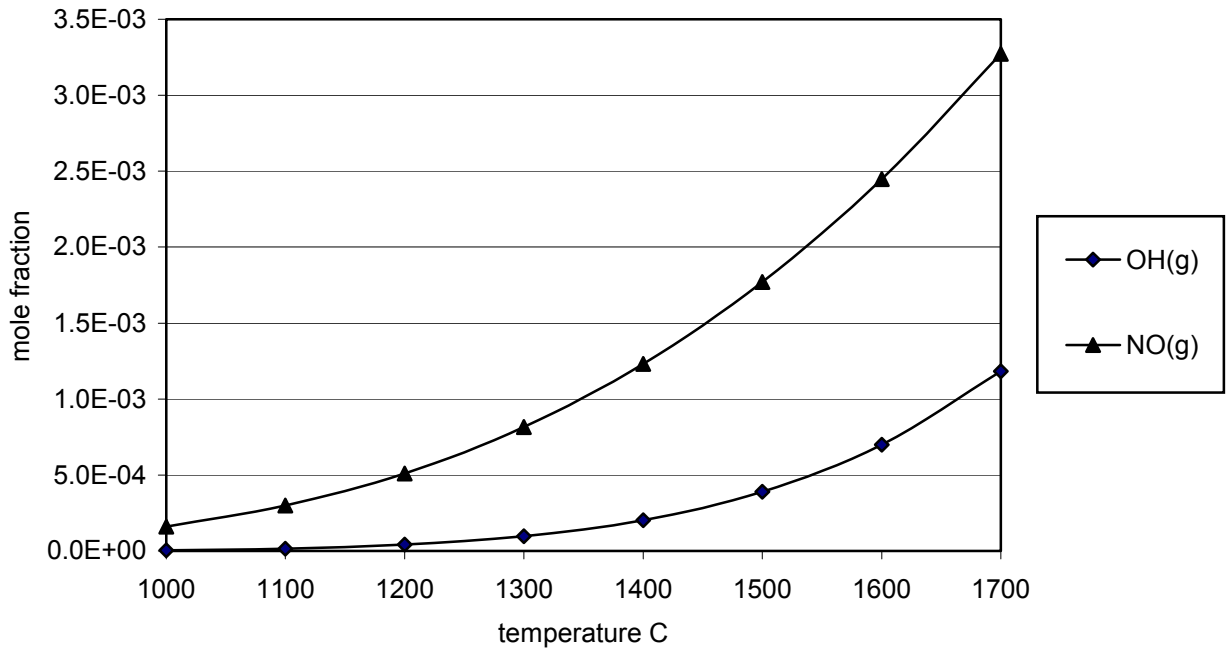


(a)



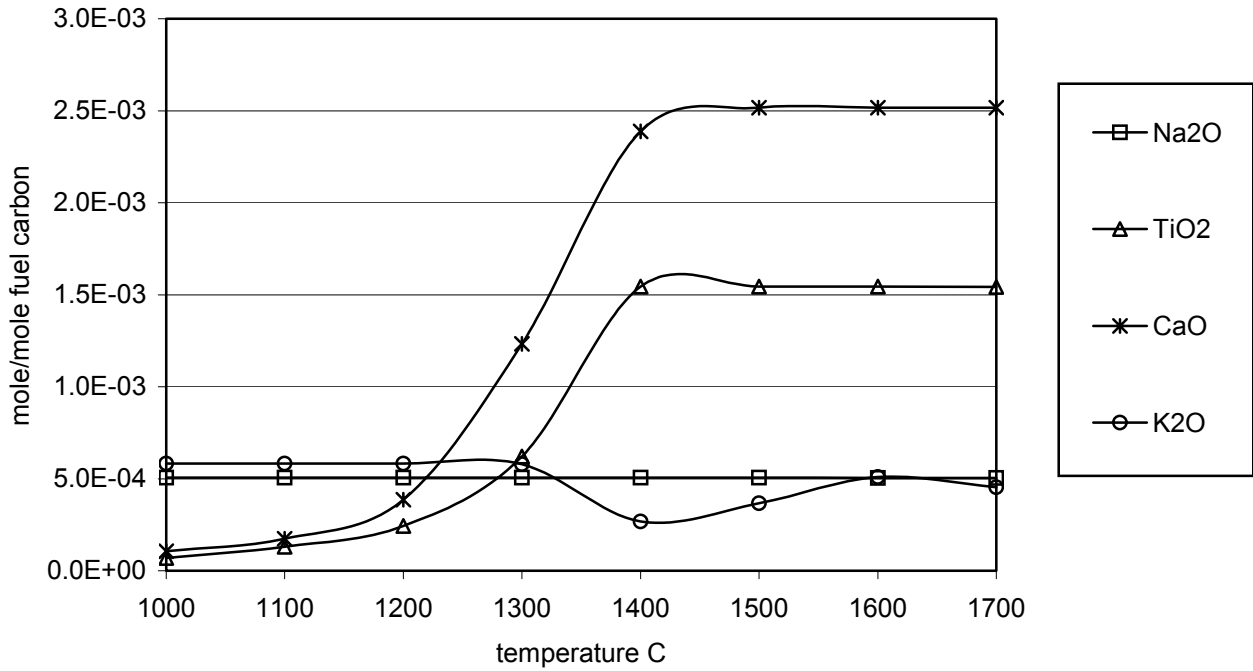
(b)

Figure A1.1. Equilibrium concentrations of gas species formed from combustion of bagasse (01/02 Cofiring Tests) (moisture content 0%) with 26% excess air. Note: Mole fraction includes water vapor.

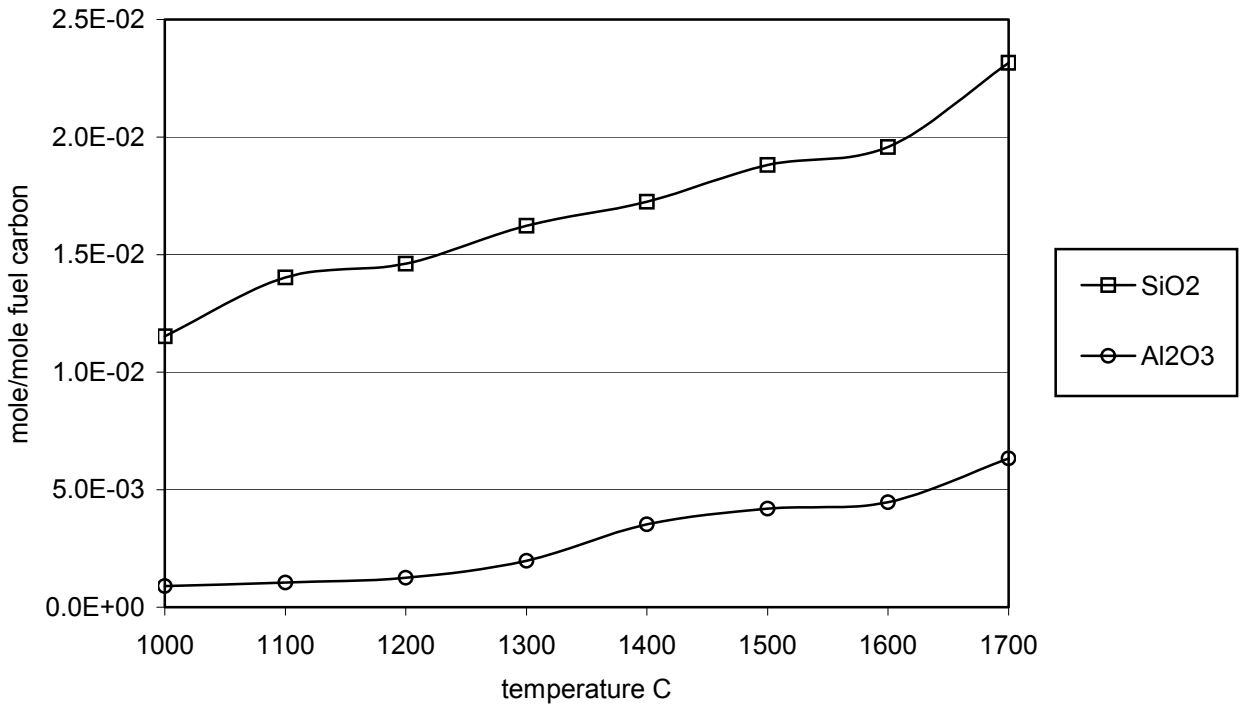


(c)

Figure A1.1. (continued) Equilibrium concentrations of gas species formed from combustion of bagasse (01/02 Cofiring Tests) (moisture content 0%) with 26% excess air. Note: Mole fraction includes water vapor.

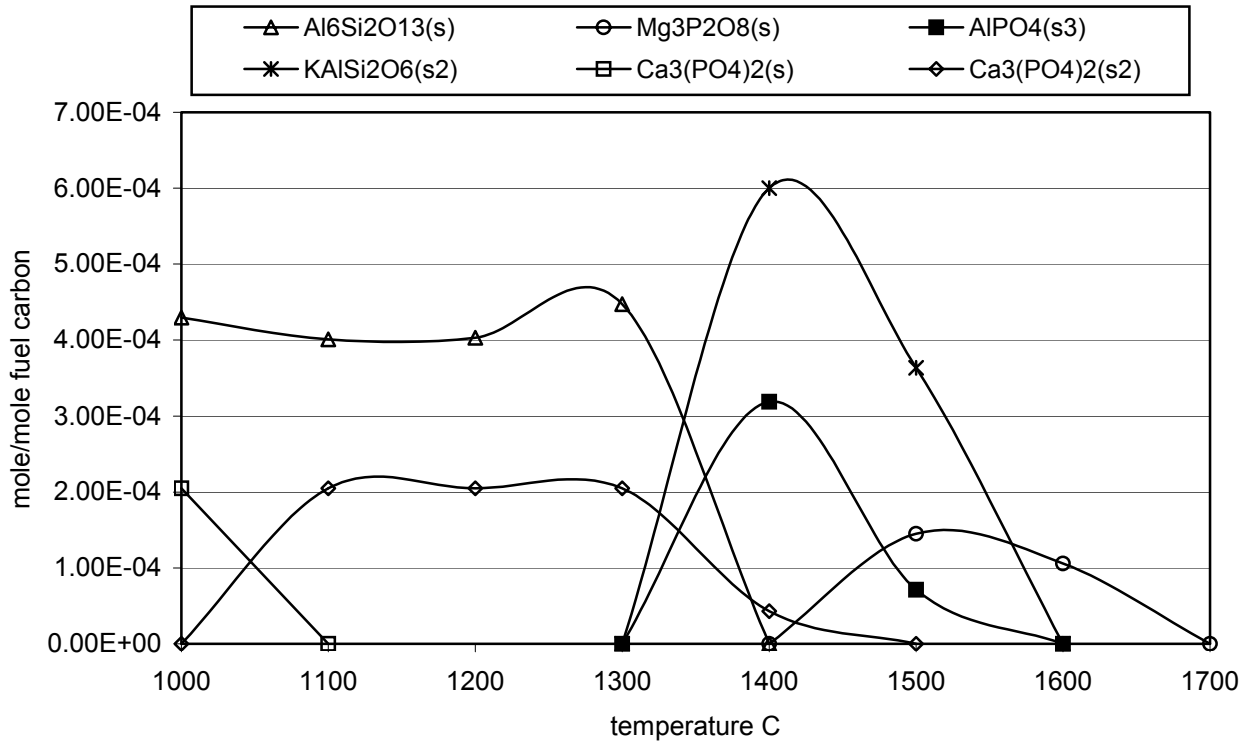


(a)

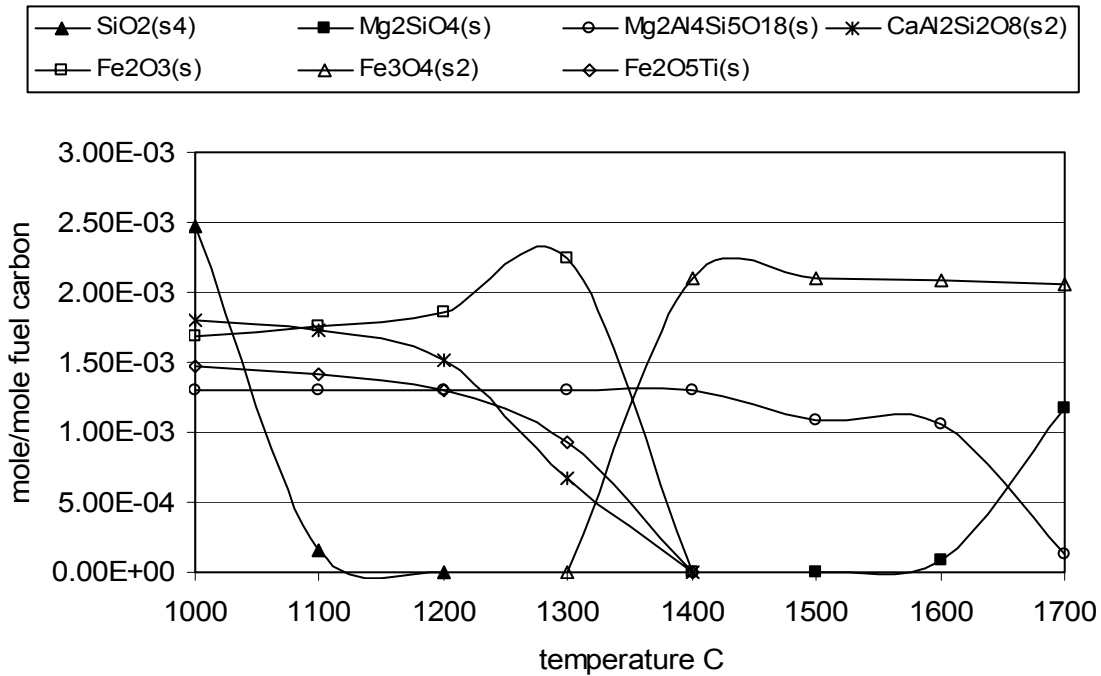


(b)

Figure A1.2. Equilibrium calculation of slag solution phase formed from combustion of bagasse (01/02 Cofiring Tests) (moisture content 0%) with 26% excess air.



(a)



(b)

Figure A1.3. Equilibrium calculation of solid phase species formed from combustion of bagasse (01/02 Cofiring Tests) (moisture content 0%) with 26% excess air.

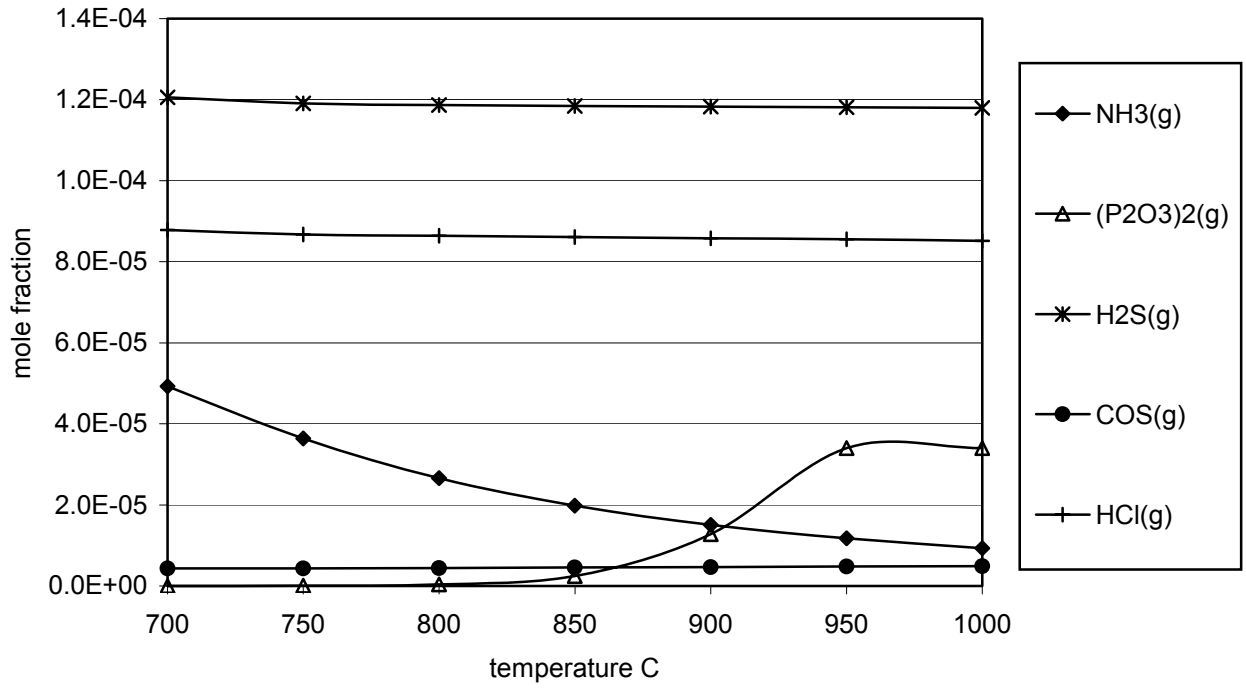
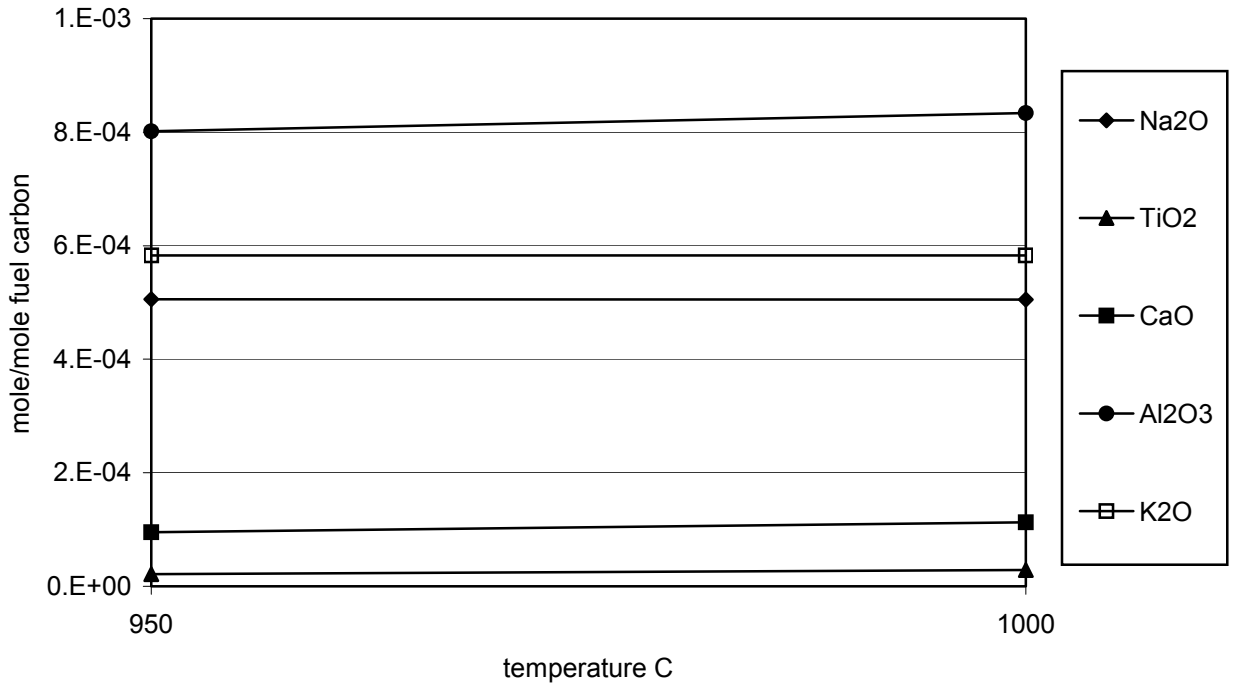
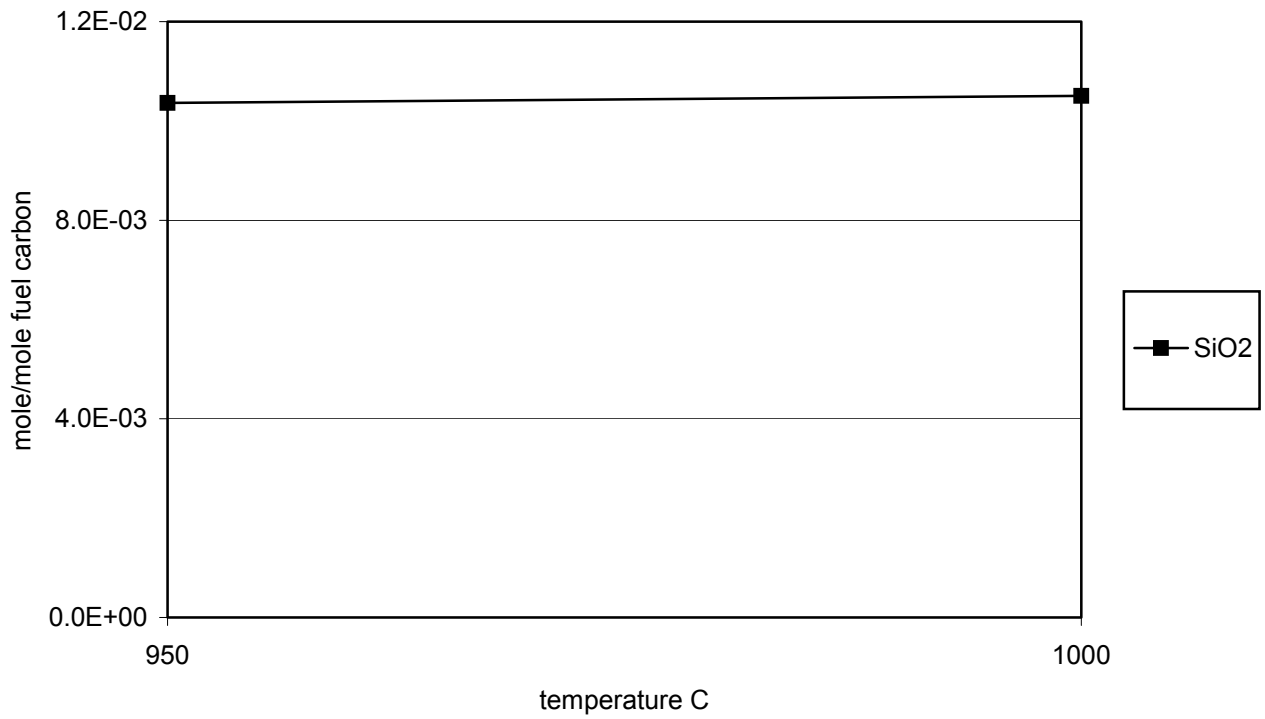


Figure A1.4. Equilibrium concentrations of gas species formed from gasifying bagasse (01/02 Cofiring Tests) (moisture content 10%) with an equivalence ratio of 0.3. Note: Mole fraction includes water vapor.



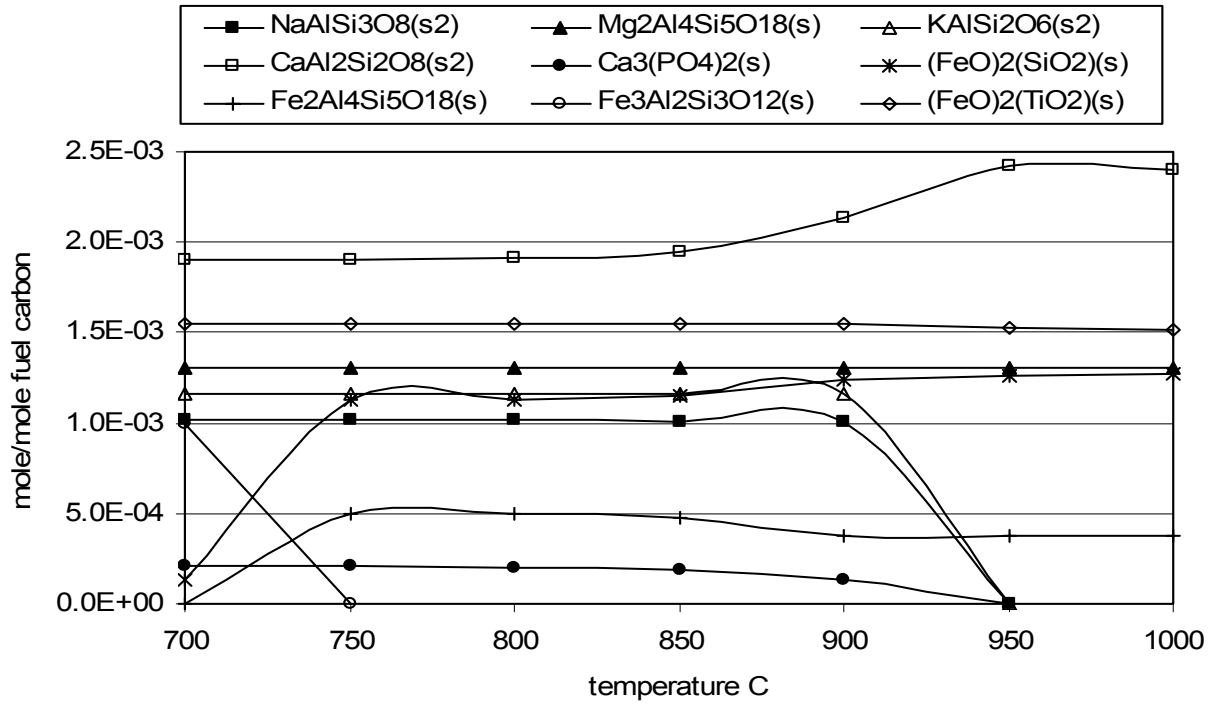


(a)

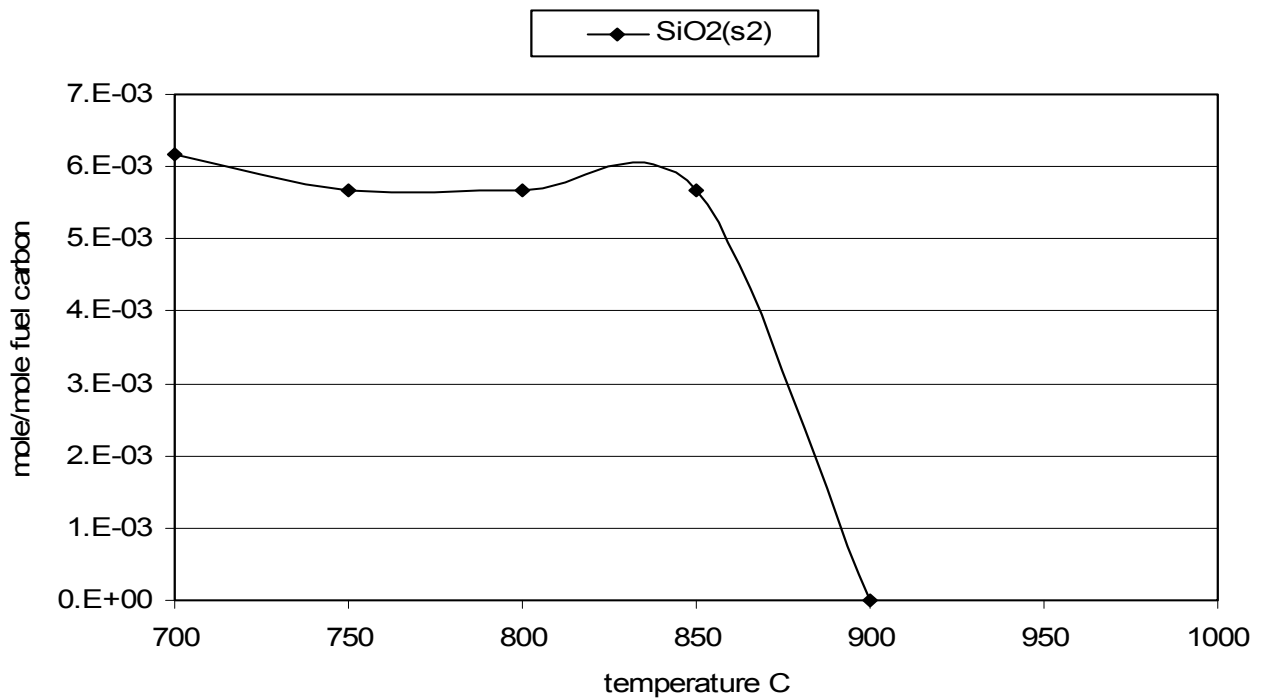


(b)

Figure A1.5. Equilibrium calculation of slag solution phase formed from gasification of bagasse (01/02 Cofiring Tests) (moisture content 10%) with an equivalence ratio of 0.3.

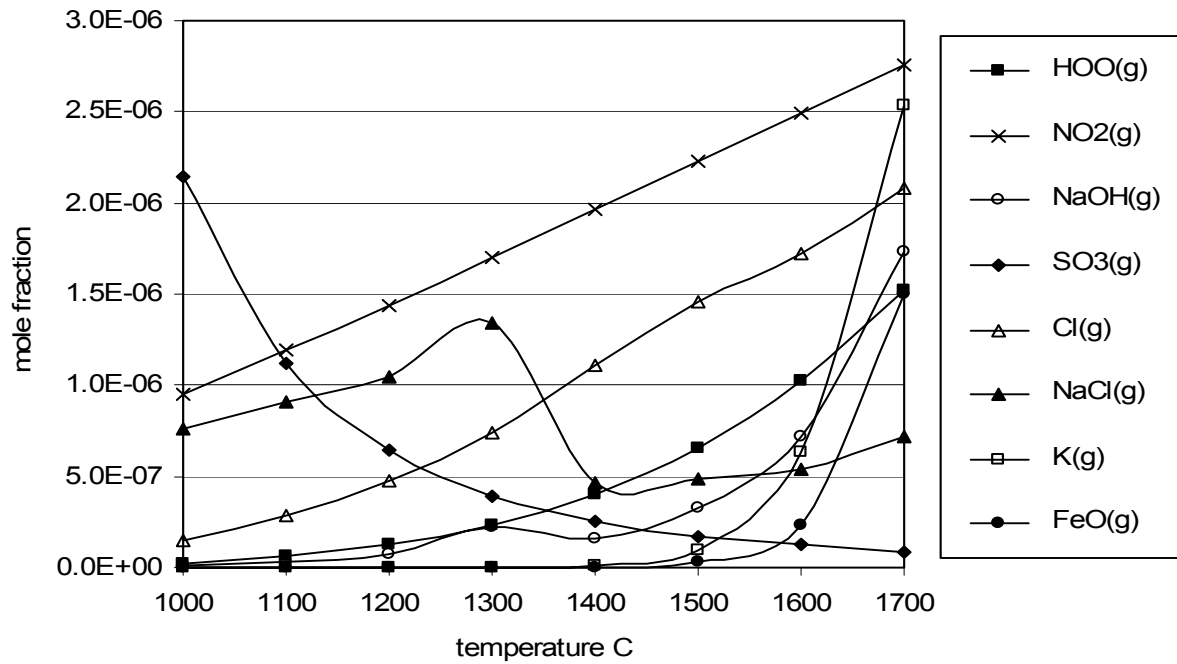


(a)

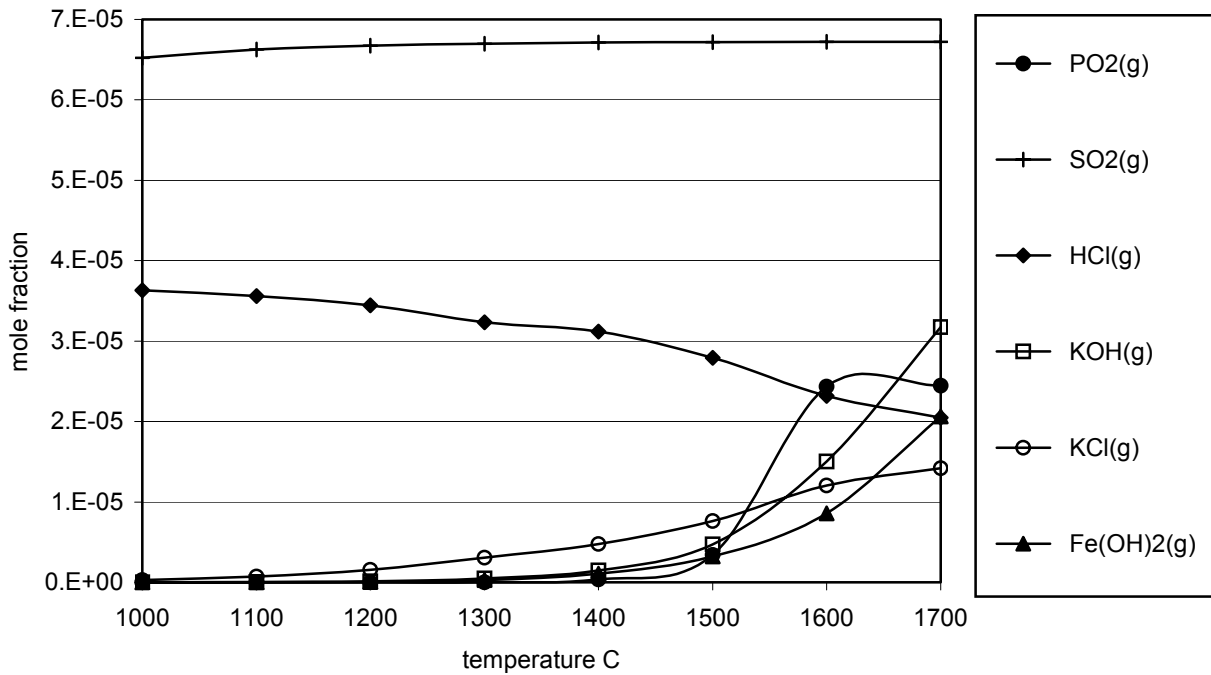


(b)

Figure A1.6. Equilibrium calculation of solid phase species formed from gasification of bagasse (01/02 Cofiring Tests) (moisture content 10%) with an equivalence ratio of 0.3.

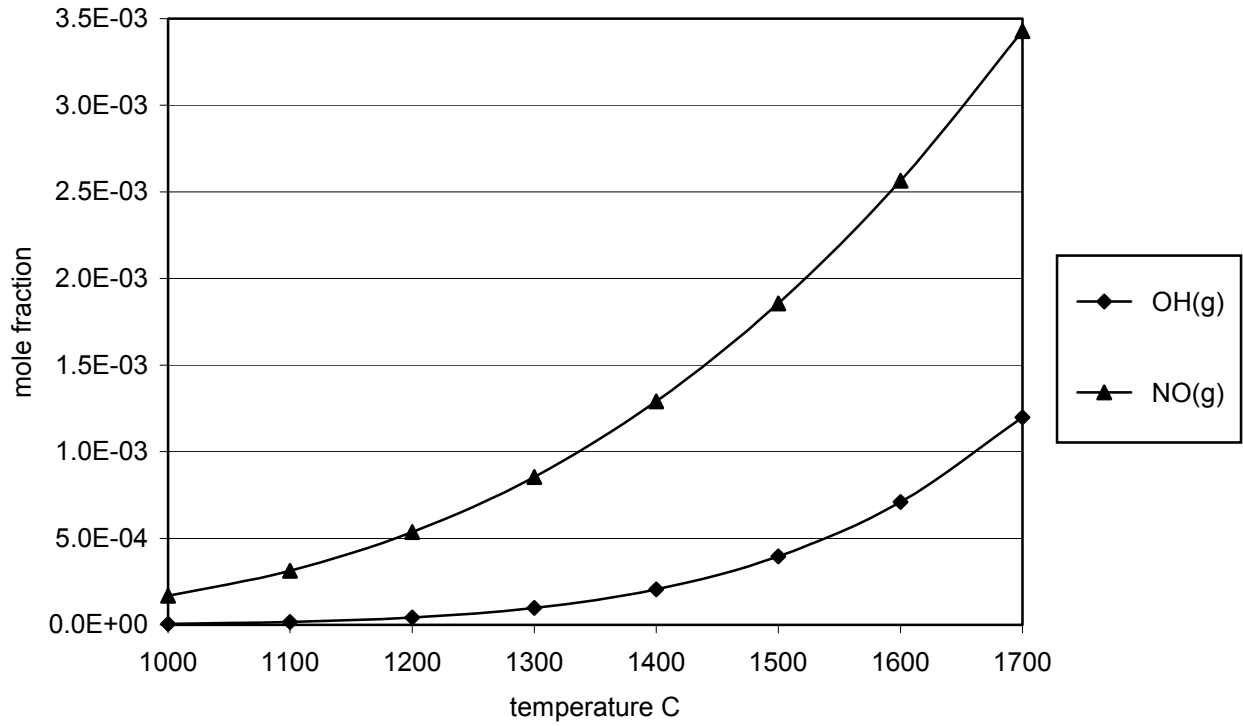


(a)



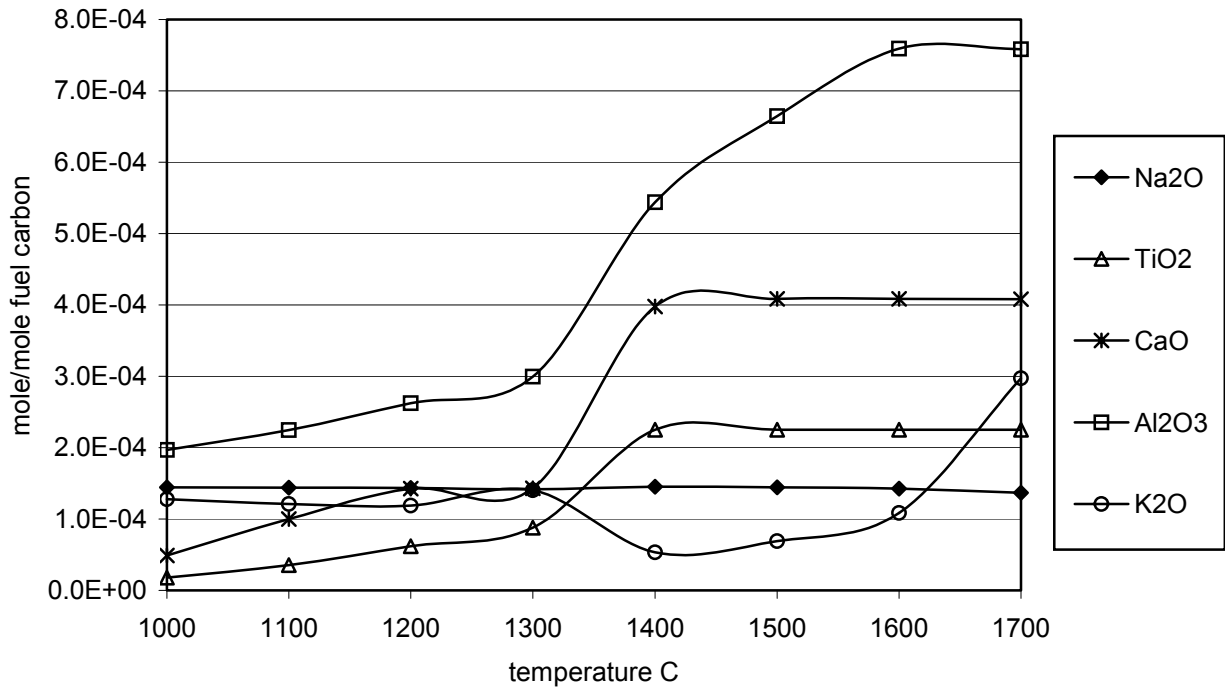
(b)

Figure A2.1. Equilibrium concentrations of gas species formed from combustion of clean bagasse (02/03 PSI Tests) (moisture content 0%) with 26% excess air. Note: Mole fraction includes water vapor.

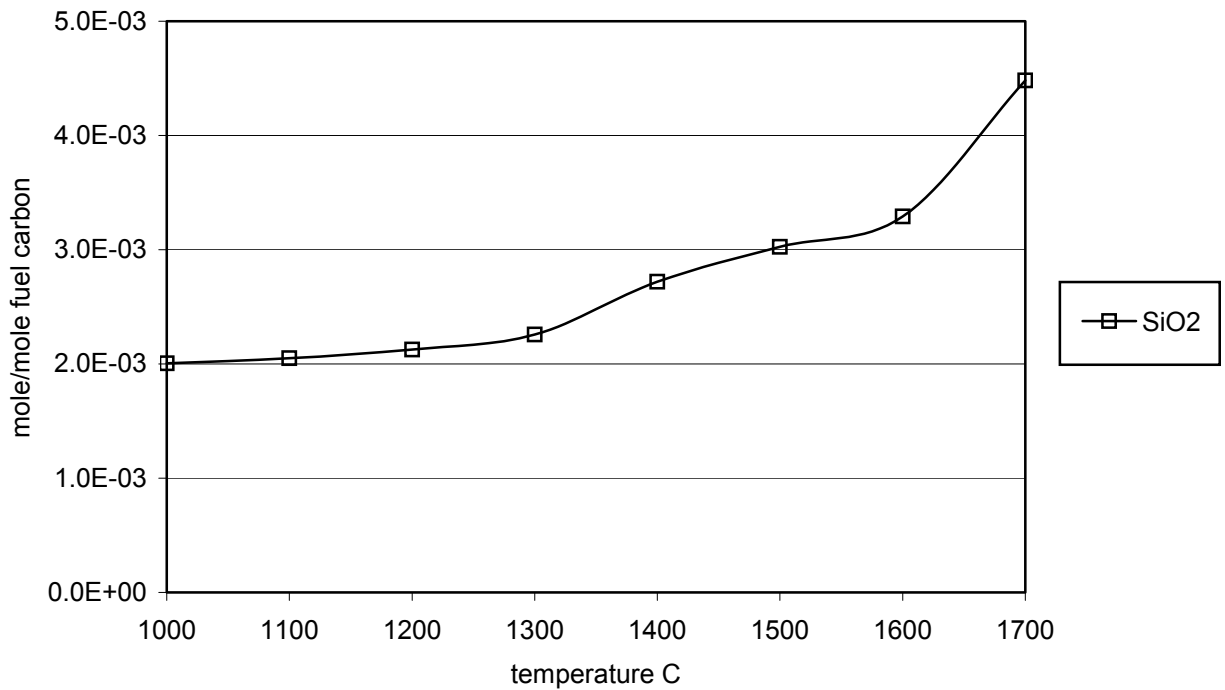


(c)

Figure A2.1. (continued) Equilibrium concentrations of gas species formed from combustion of clean bagasse (02/03 PSI Tests) (moisture content 0%) with 26% excess air Note: Mole fraction includes water vapor.



(a)



(b)

Figure A2.2. Equilibrium calculation of slag solution phase formed from combustion of clean bagasse (02/03 PSI Tests) (moisture content 0%) with 26% excess air.

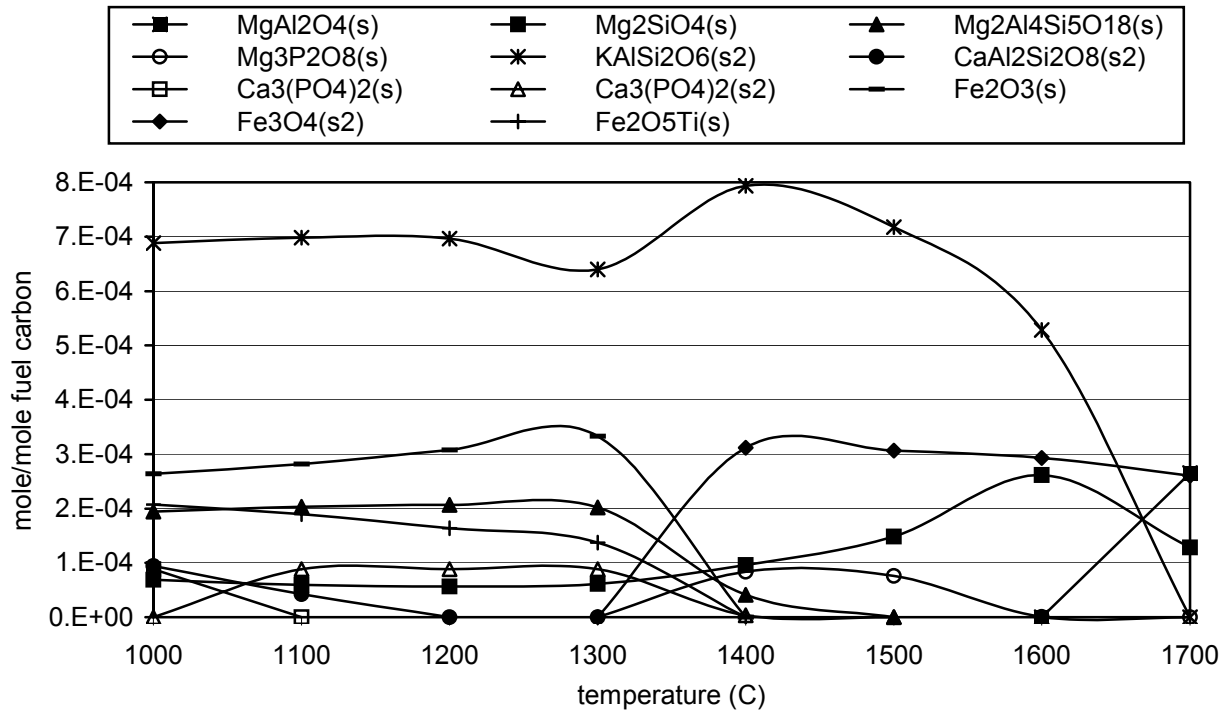


Figure A2.3. Equilibrium calculation of solid phase species formed from combustion of clean bagasse (02/03 PSI Tests) (moisture content 0%) with 26% excess air.

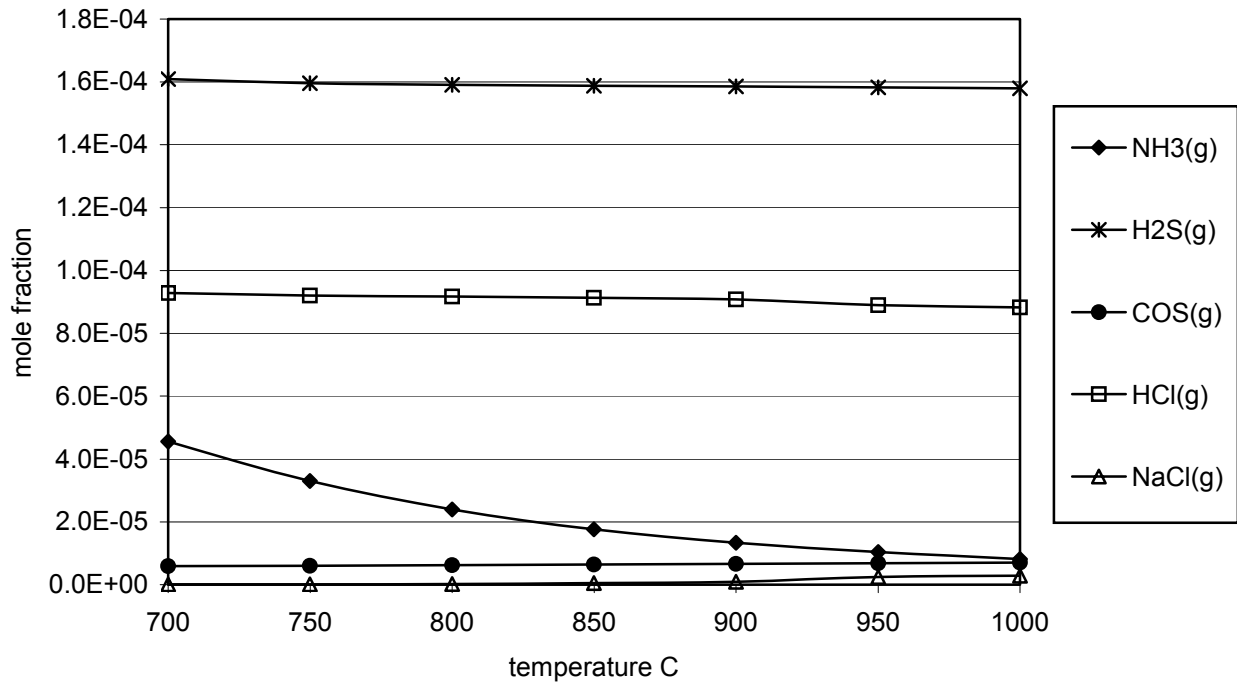
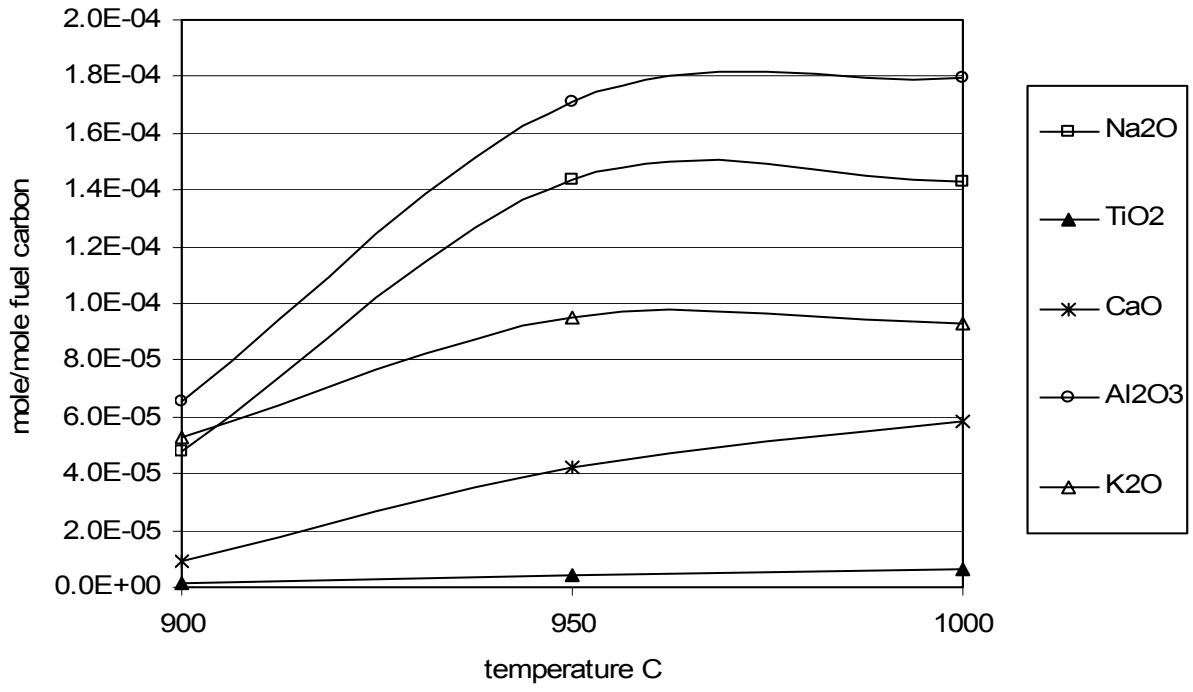
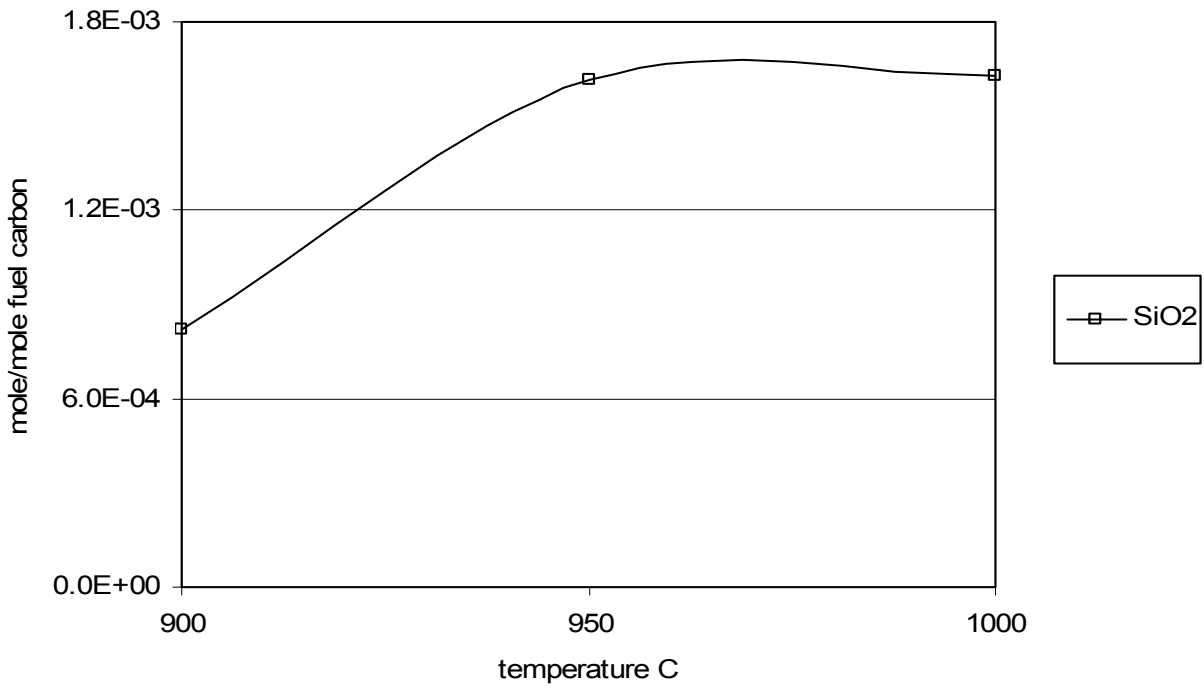


Figure A2.4. Equilibrium concentrations of gas species formed from gasifying clean bagasse (02/03 PSI Tests) (moisture content 10%) with an equivalence ratio of 0.3. Note: Mole fraction includes water vapor.



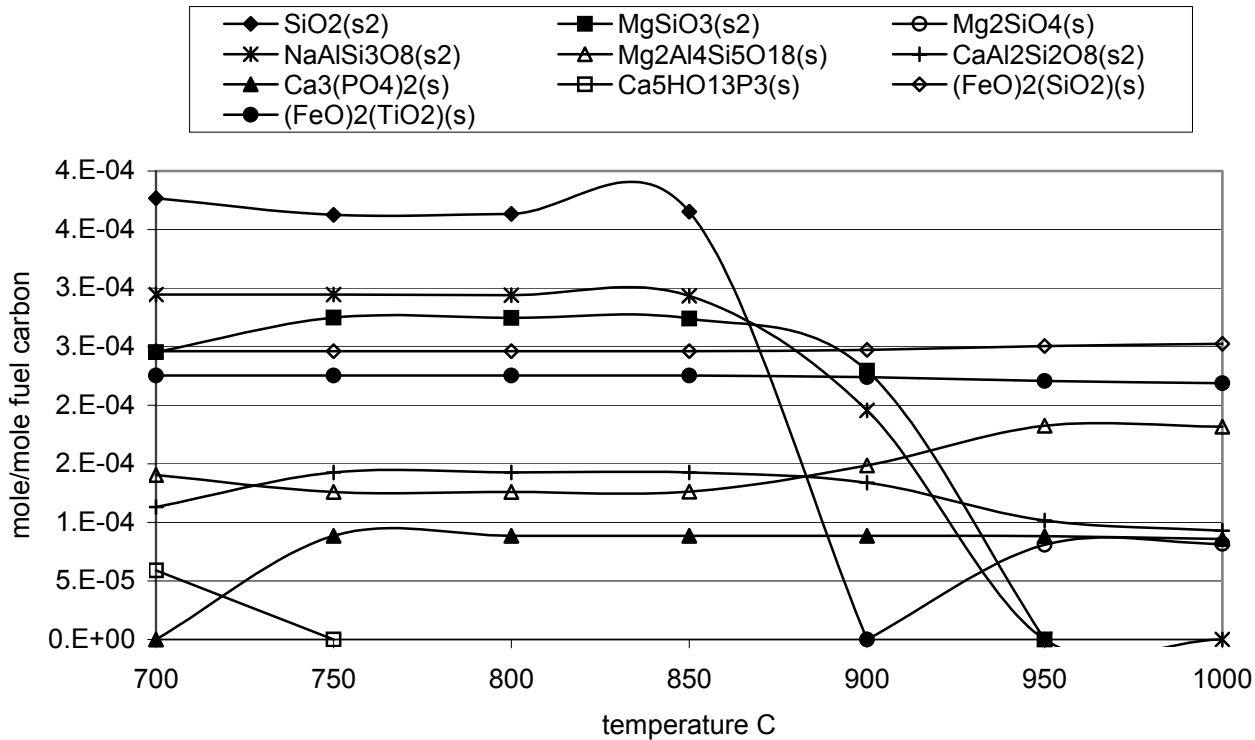
(a)



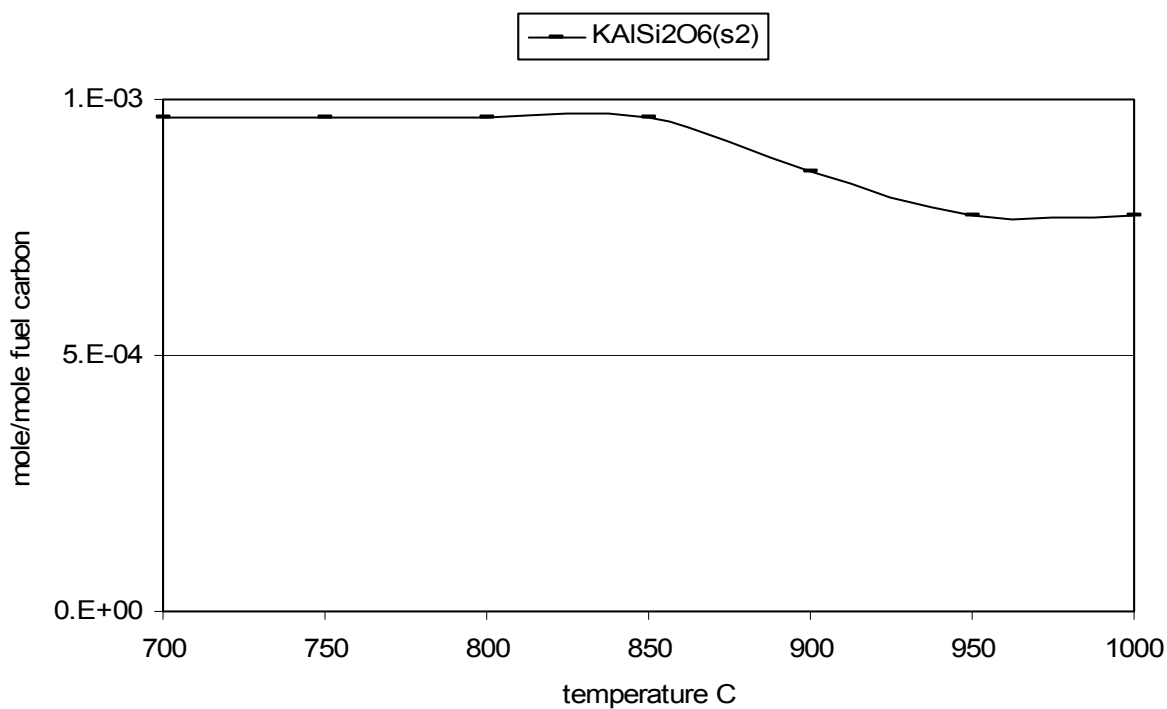
(b)

Figure A2.5. Equilibrium calculation of slag solution phase formed from gasification of clean bagasse (02/03 PSI Tests) (moisture content 10%) with an equivalence ratio of 0.3.



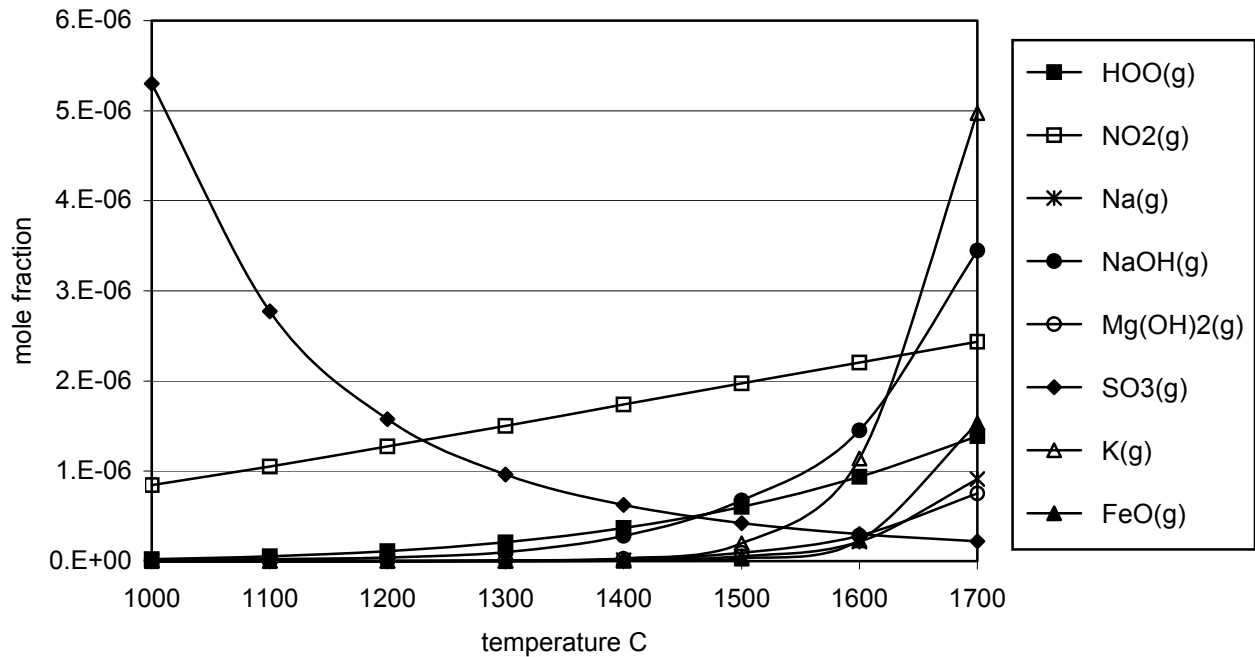


(a)

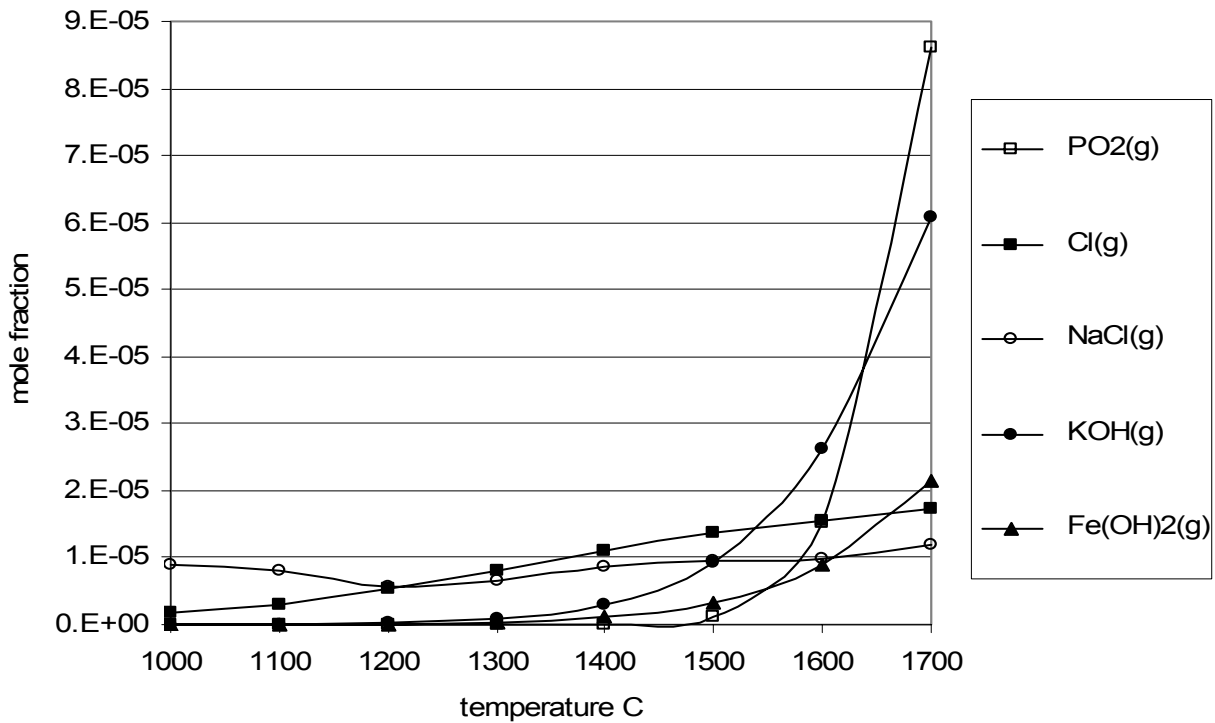


(b)

Figure A2.6. Equilibrium calculation of solid phase species formed from gasification of clean bagasse (02/03 PSI Tests) (moisture content 10%) with an equivalence ratio of 0.3.

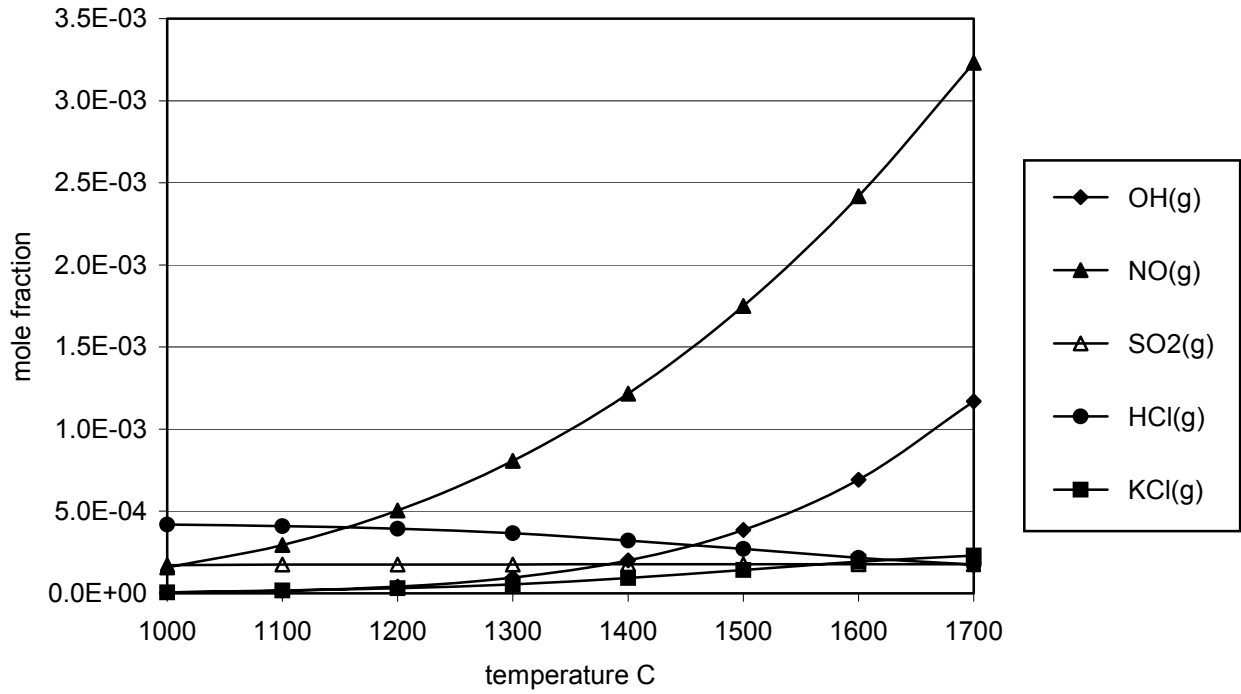


(a)



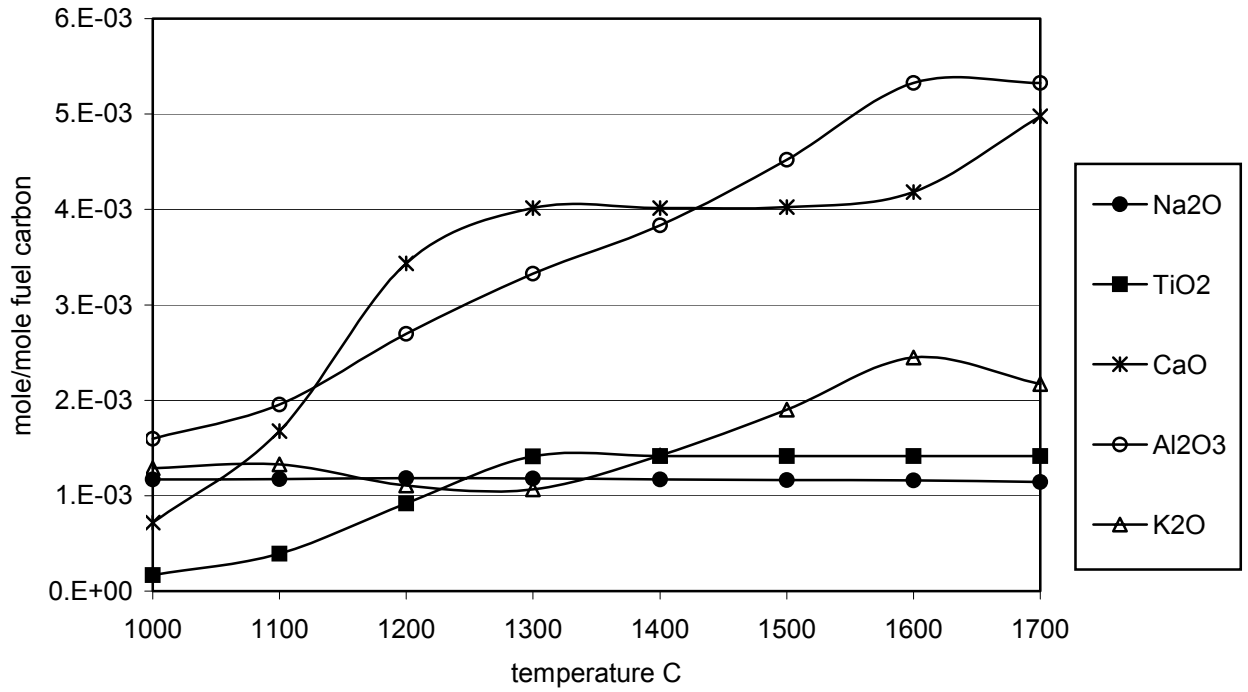
(b)

Figure A3.1. Equilibrium concentrations of gas species formed from combustion of fiber cane (01/02 Cofiring Tests) (moisture content 0%) with 26% excess air. Note: Mole fraction includes water vapor.

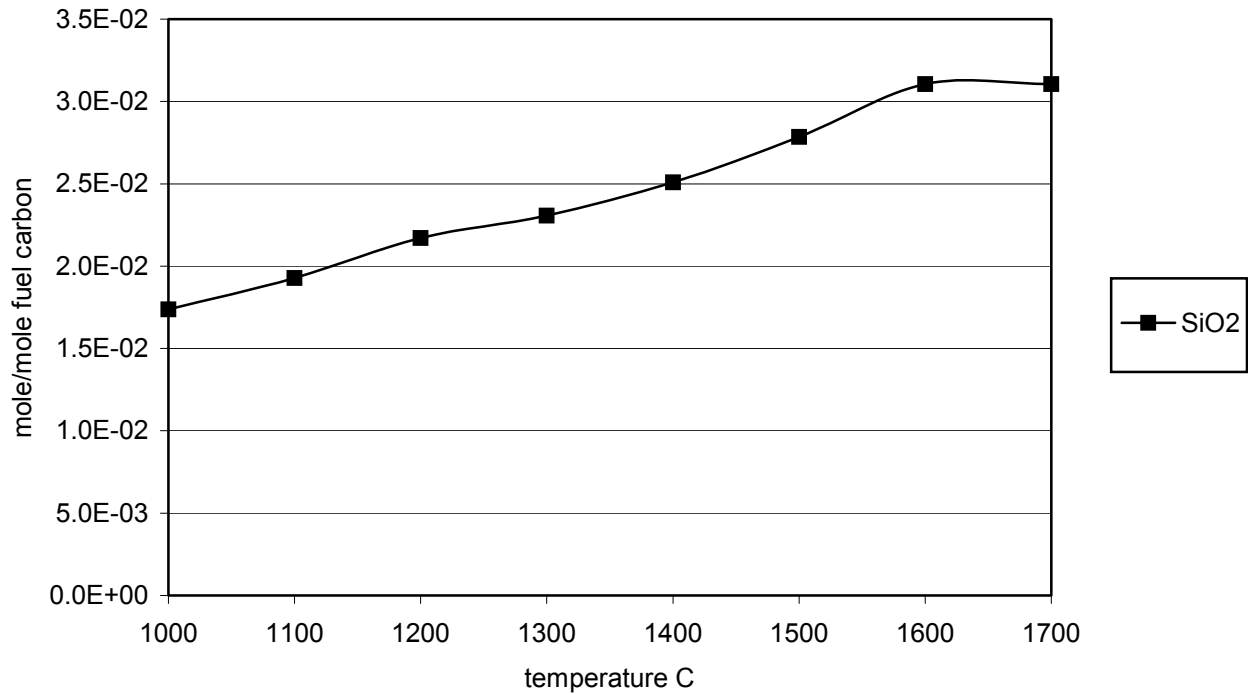


(c)

Figure A3.1. (continued) Equilibrium concentrations of gas species formed from combustion of fiber cane (01/02 Cofiring Tests) (moisture content 0%) with 26% excess air. Note: Mole fraction includes water vapor.



(a)



(b)

Figure A3.2. Equilibrium calculation of slag solution phase formed from combustion of fiber cane (01/02 Cofiring Tests) (moisture content 0%) with 26% excess air.

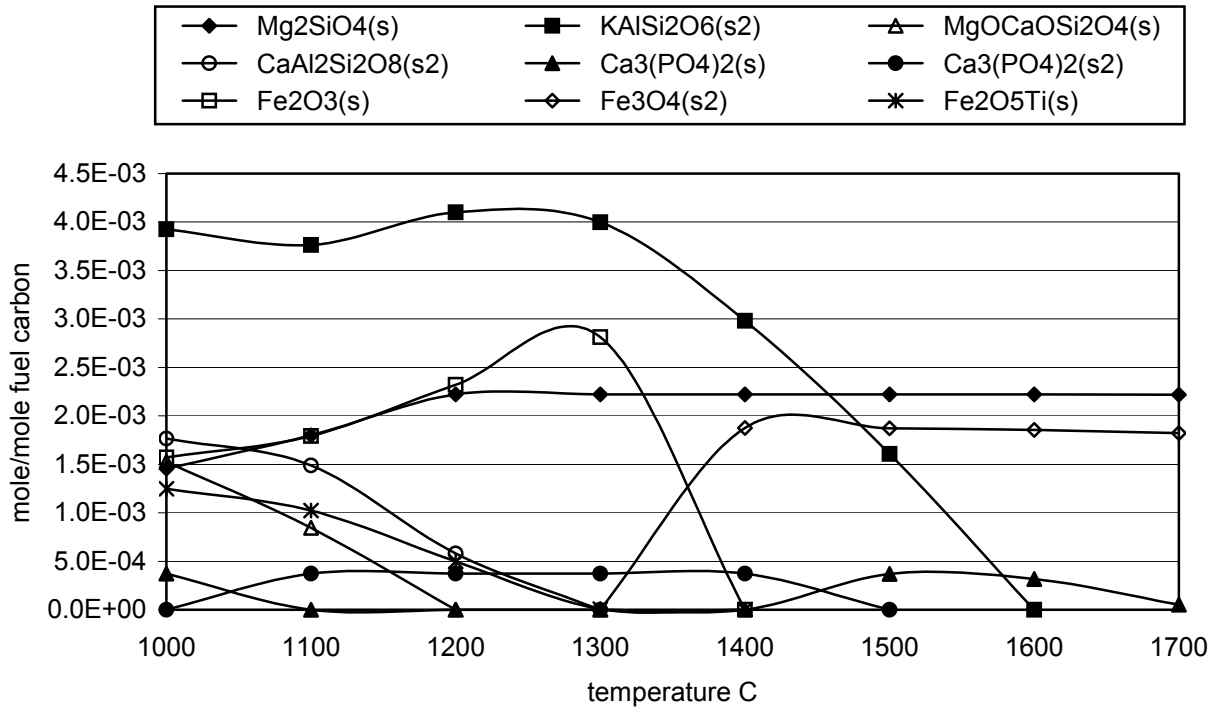
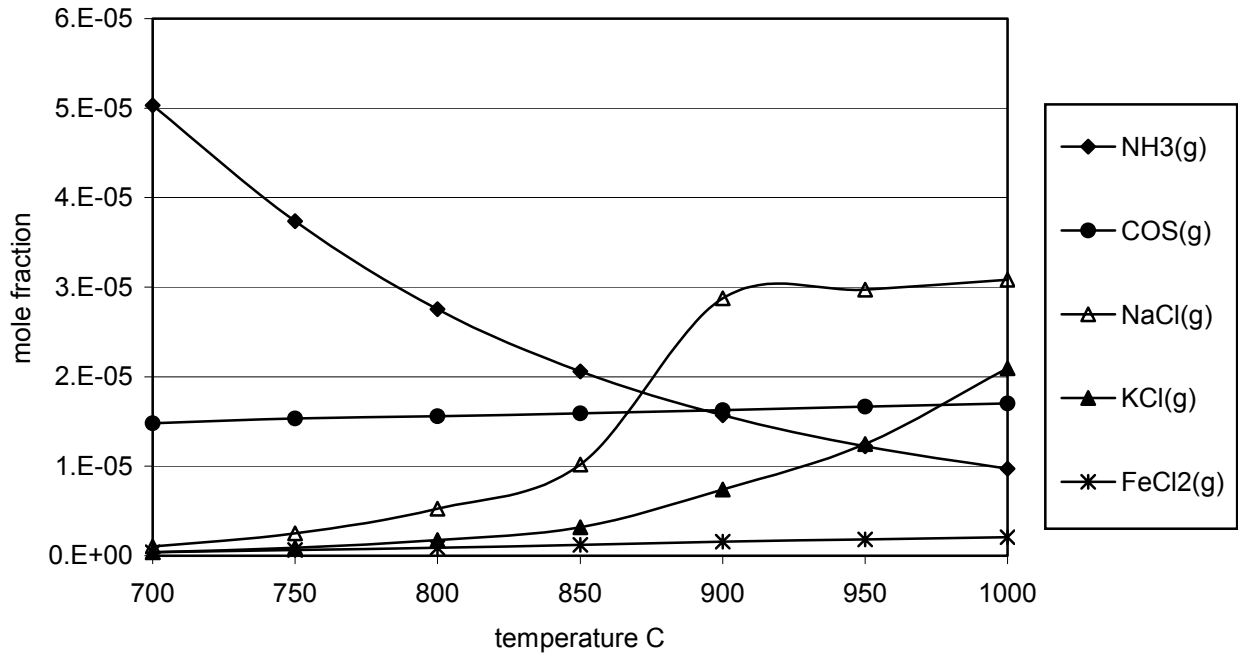
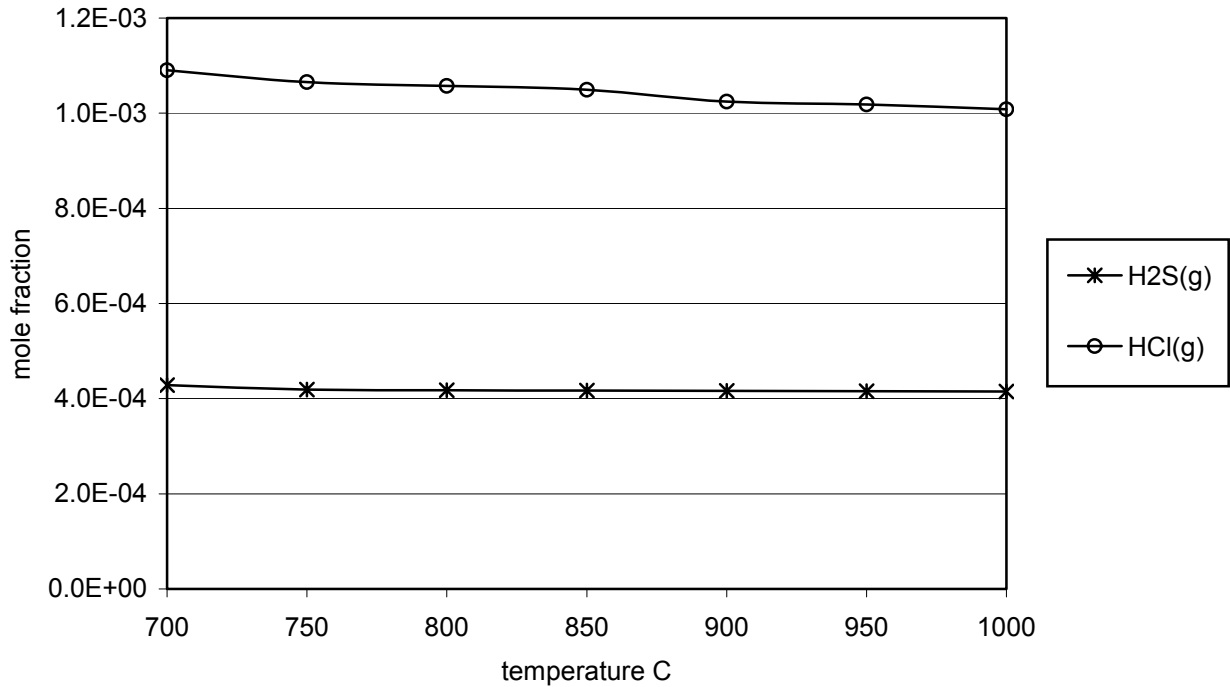


Figure A3.3. Equilibrium calculation of solid phase species formed from combustion of fiber cane (01/02 Cofiring Tests) (moisture content 0%) with 26% excess air.

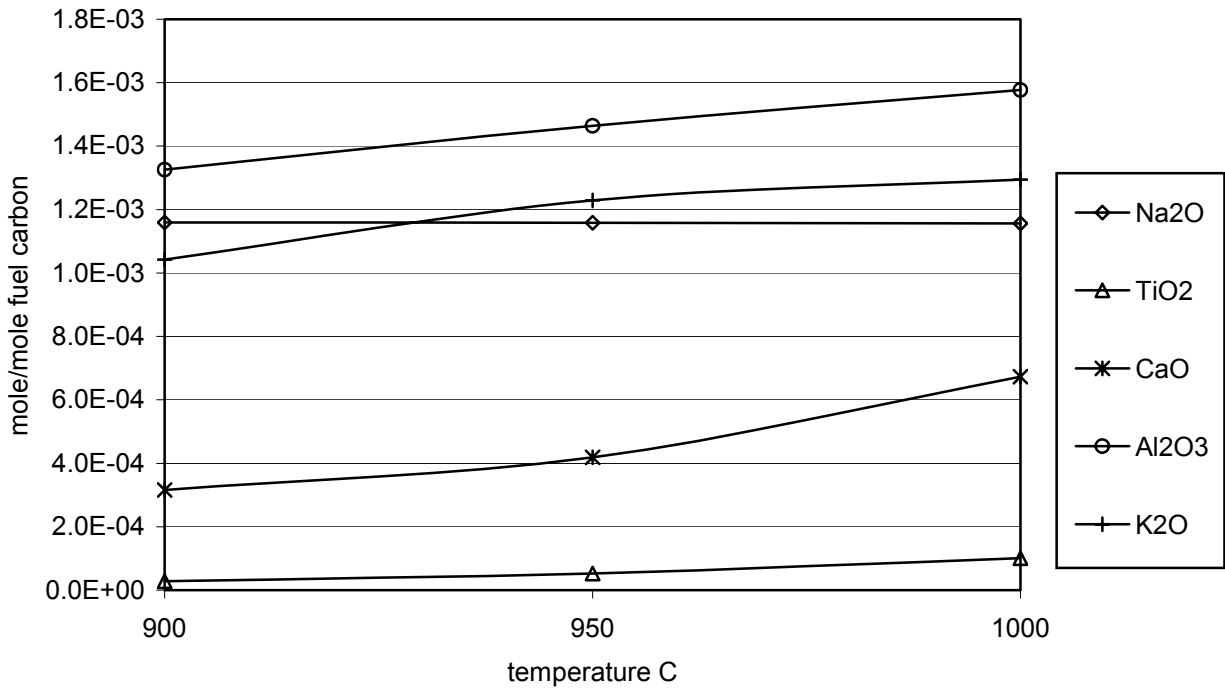


(a)

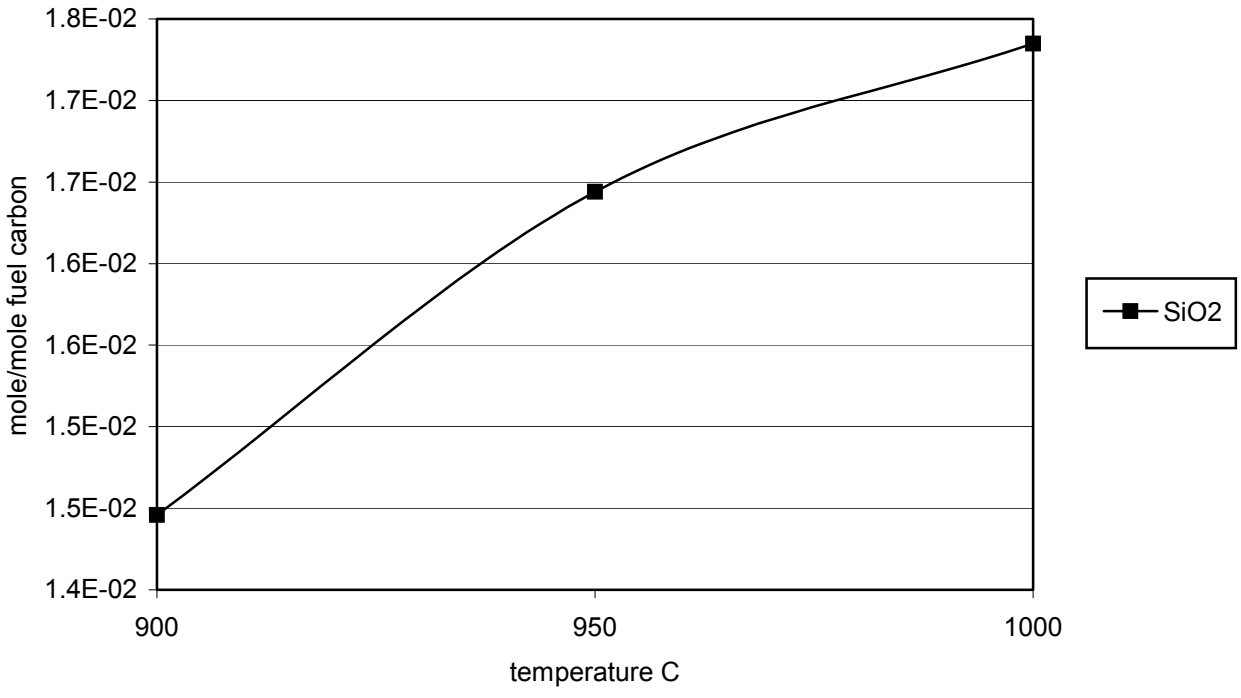


(b)

Figure A3.4. Equilibrium concentrations of gas species formed from gasifying fiber cane(01/02 Cofiring Tests) (moisture content 10%) with an equivalence ratio of 0.3. Note: Mole fraction includes water vapor.

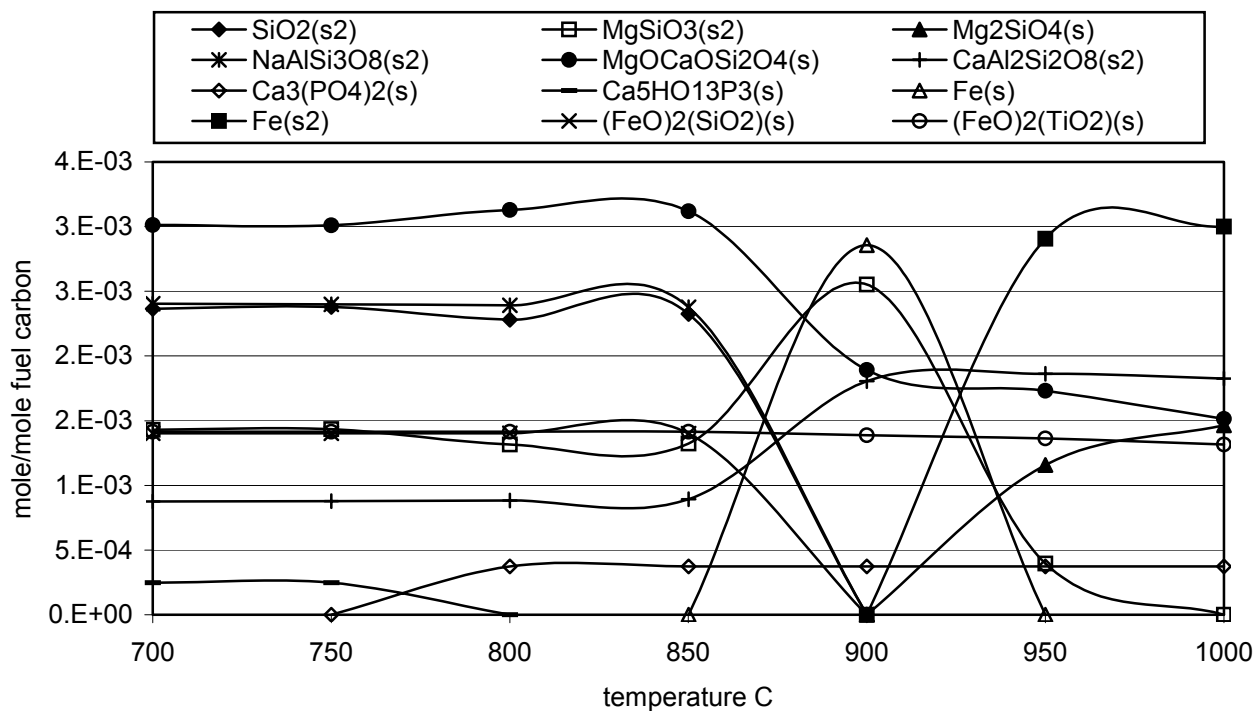


(a)

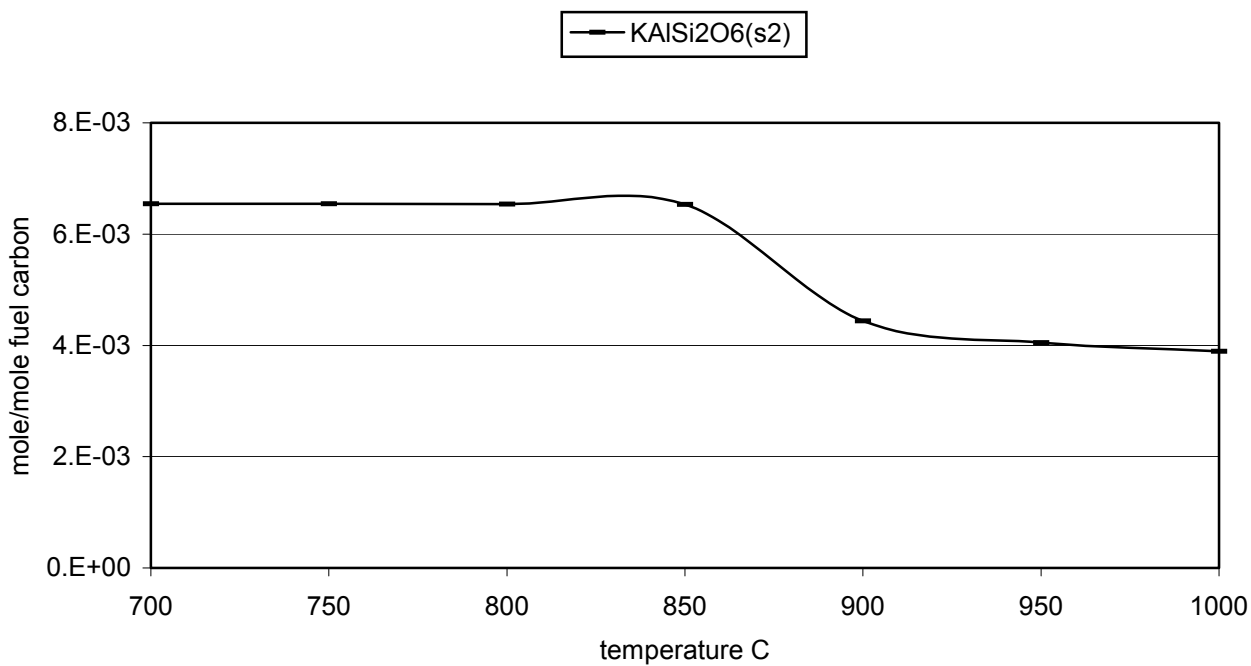


(b)

Figure A3.5. Equilibrium calculation of slag solution phase formed from gasification of fiber cane (01/02 Cofiring Tests) (moisture content 10%) with an equivalence ratio of 0.3.



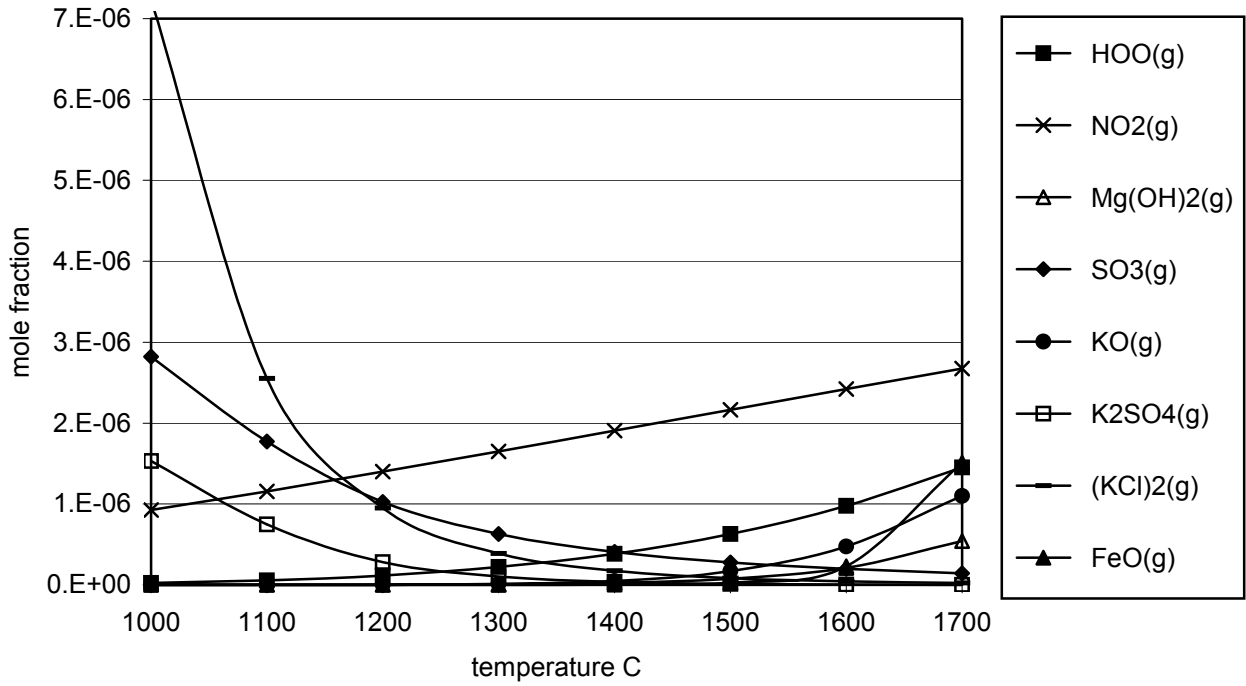
(a)



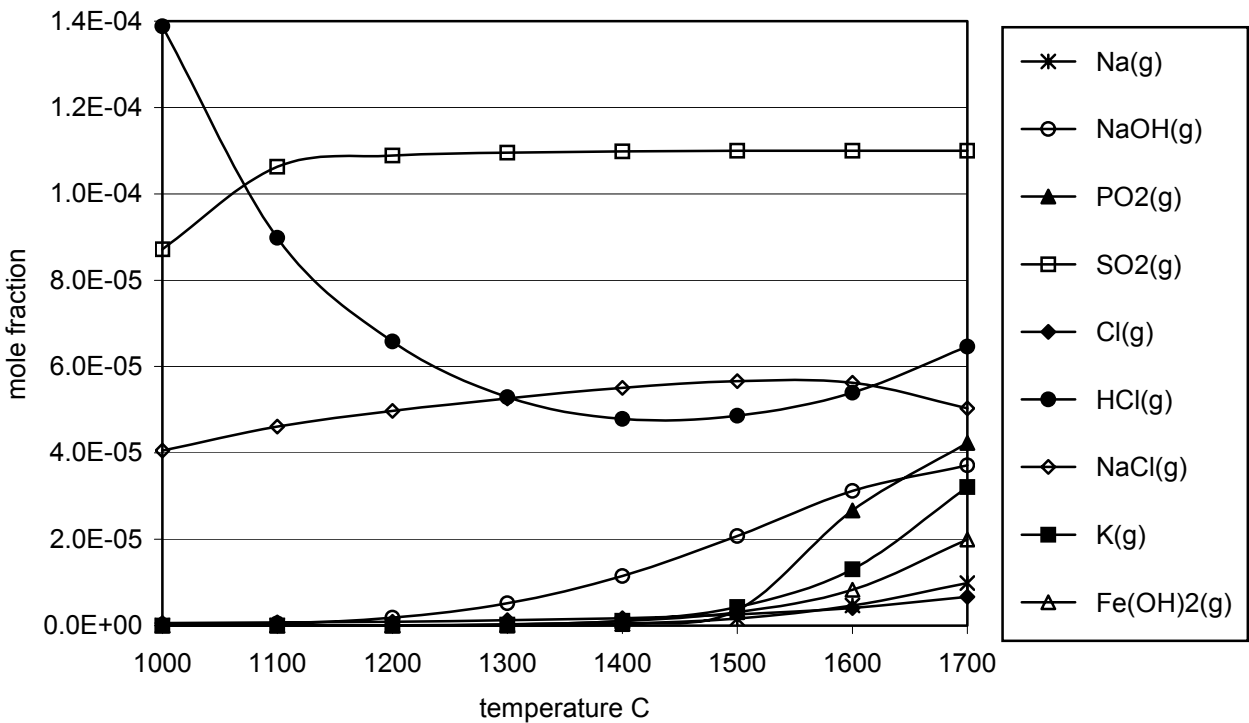
(b)

Figure A3.6. Equilibrium calculation of solid phase species formed from gasification of fiber cane (01/02 Cofiring Tests) (moisture content 10%) with an equivalence ratio of 0.3.



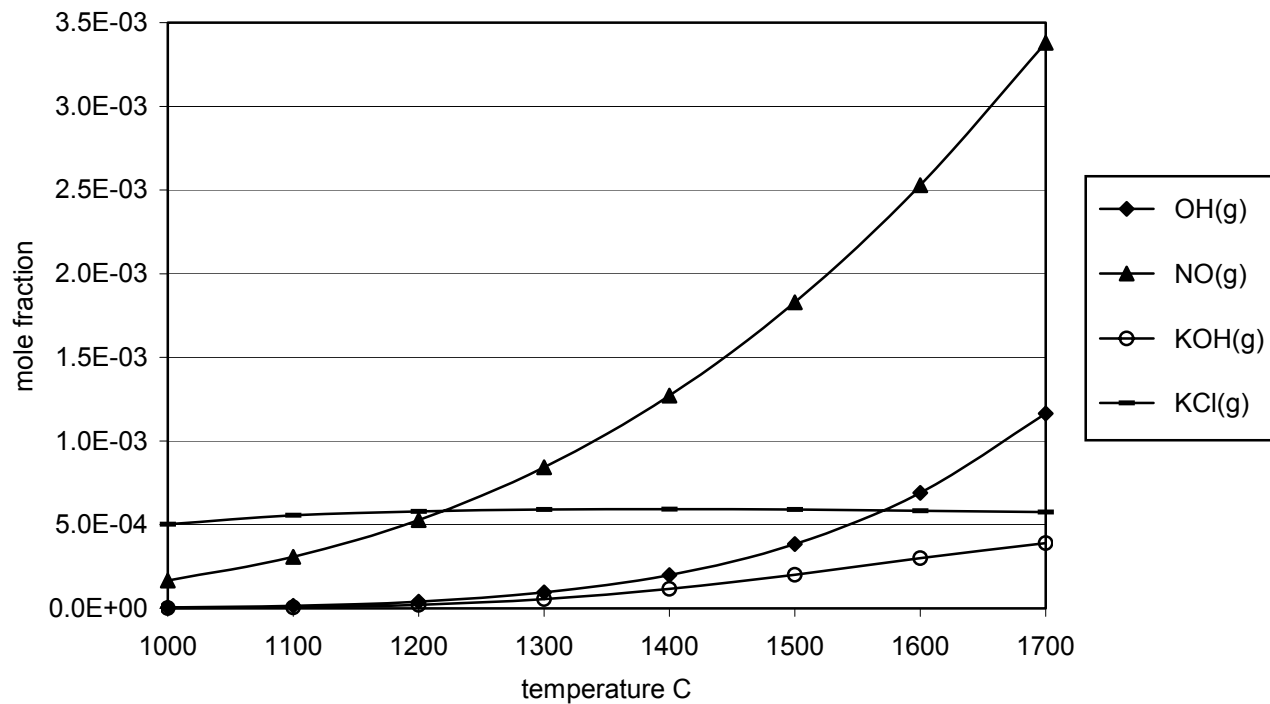


(a)



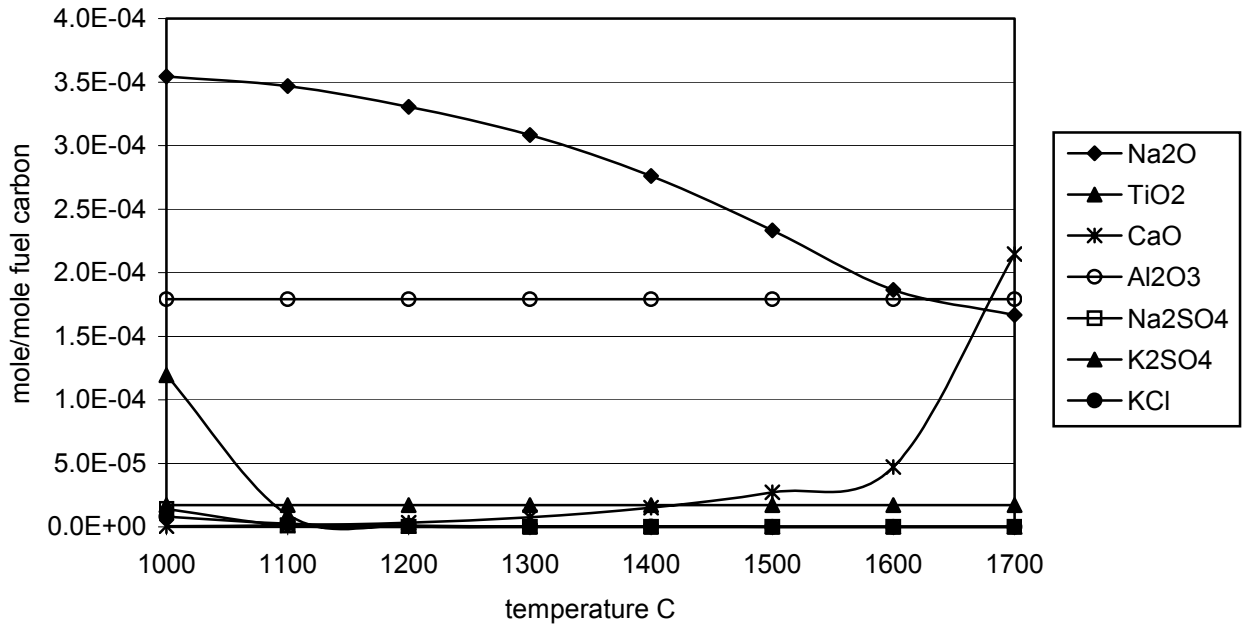
(b)

Figure A4.1. Equilibrium concentrations of gas species formed from combustion of banagrass (moisture content 0%) with 26% excess air. Note: Mole fraction includes water vapor.

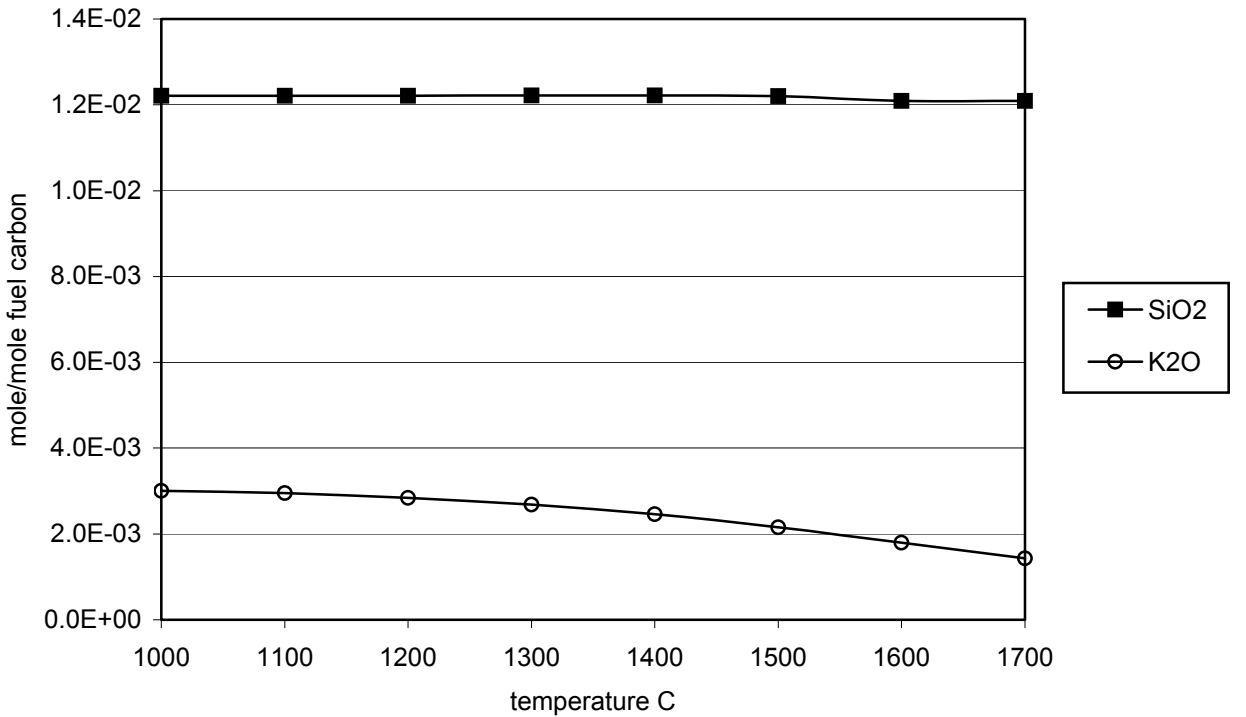


(c)

Figure A4.1. (continued) Equilibrium concentrations of gas species formed from combustion of banagrass (moisture content 0%) with 26% excess air. Note: Mole fraction includes water vapor.



(a)



(b)

Figure A4.2. Equilibrium calculation of slag solution phase formed from combustion of banagrass (moisture content 0%) with 26% excess air.

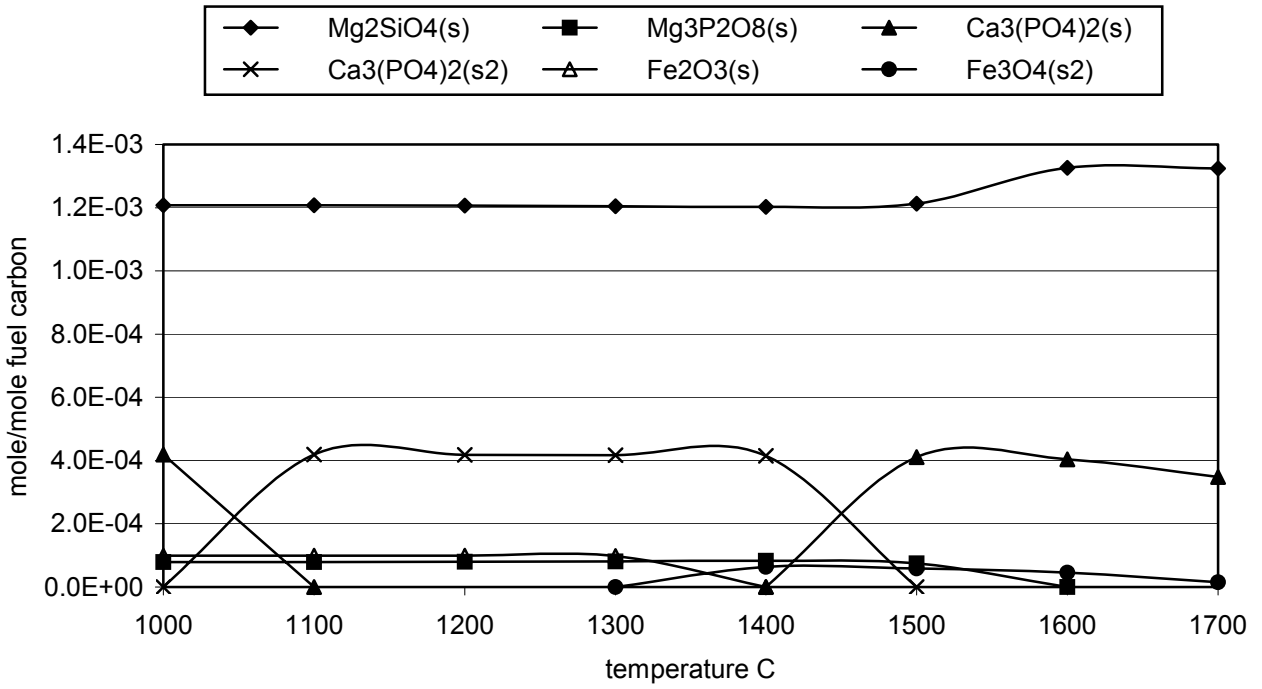
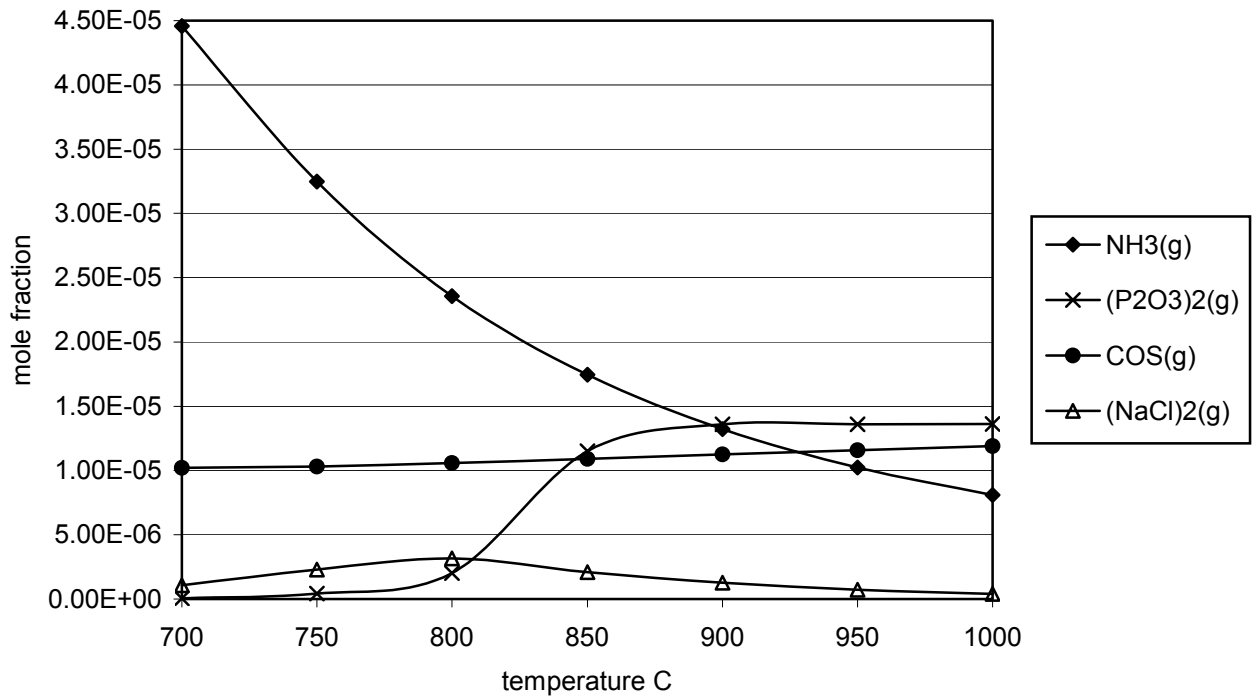
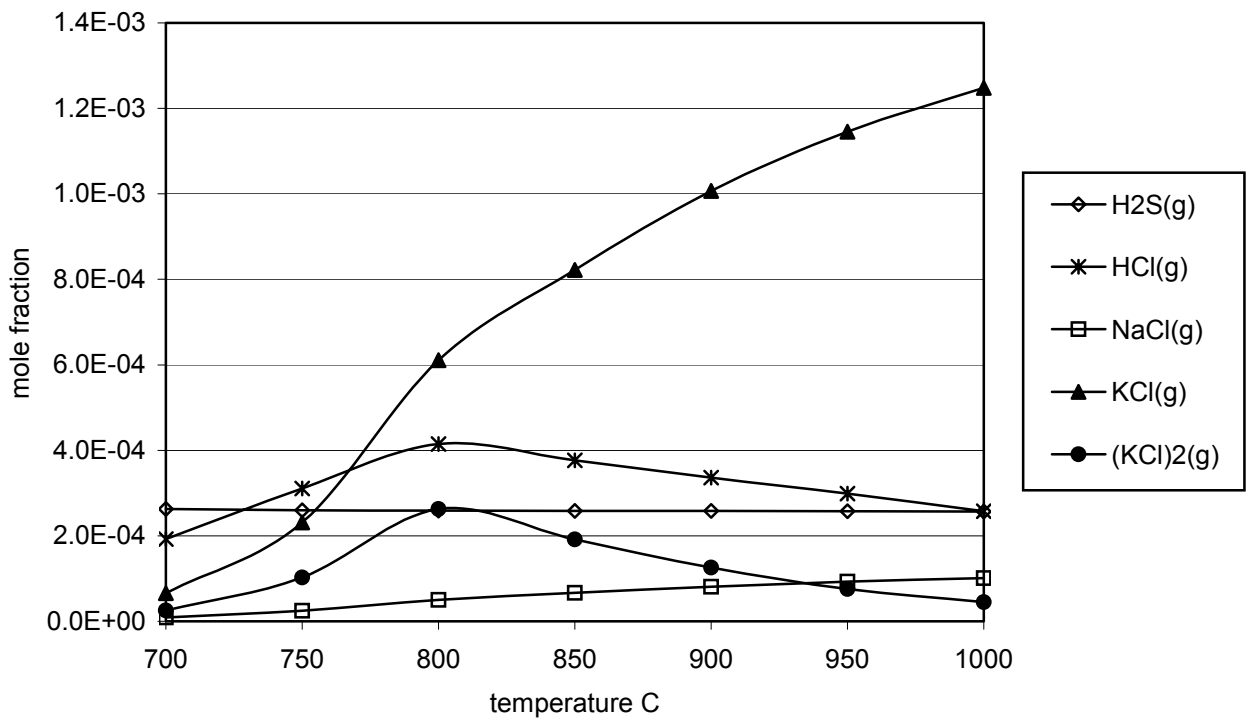


Figure A4.3. Equilibrium calculation of solid phase species formed from combustion of banagrass (moisture content 0%) with 26% excess air.

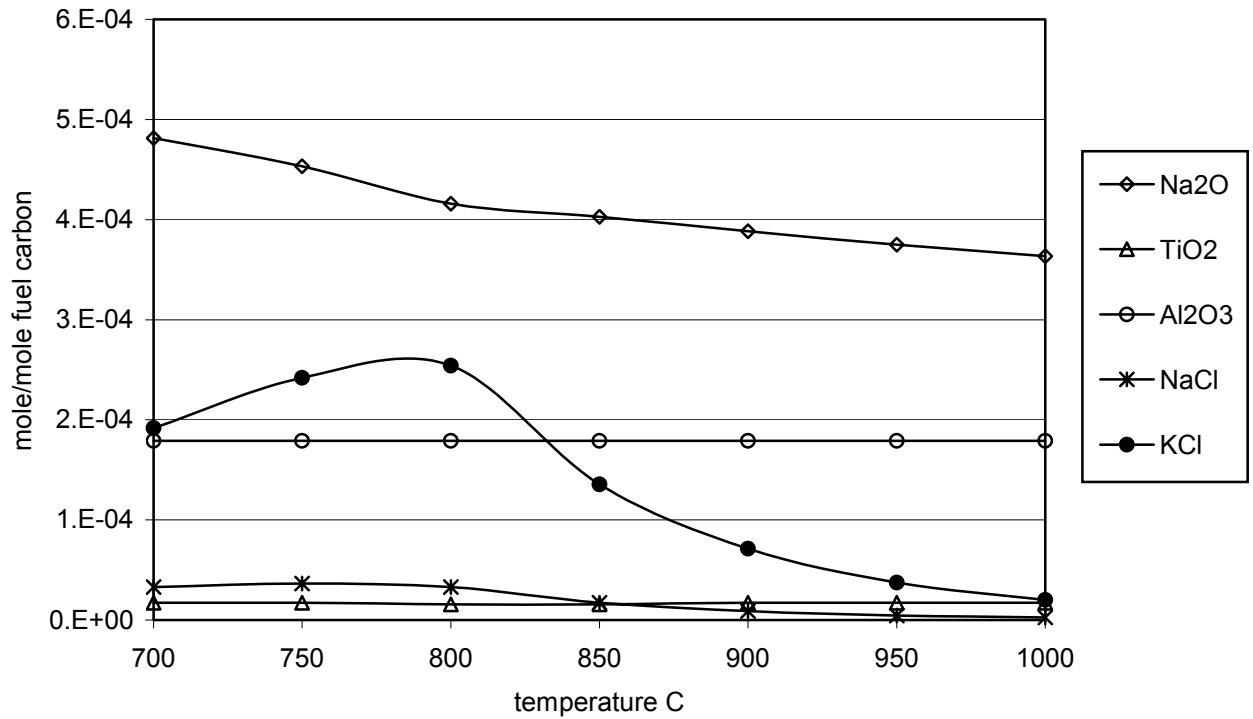


(a)

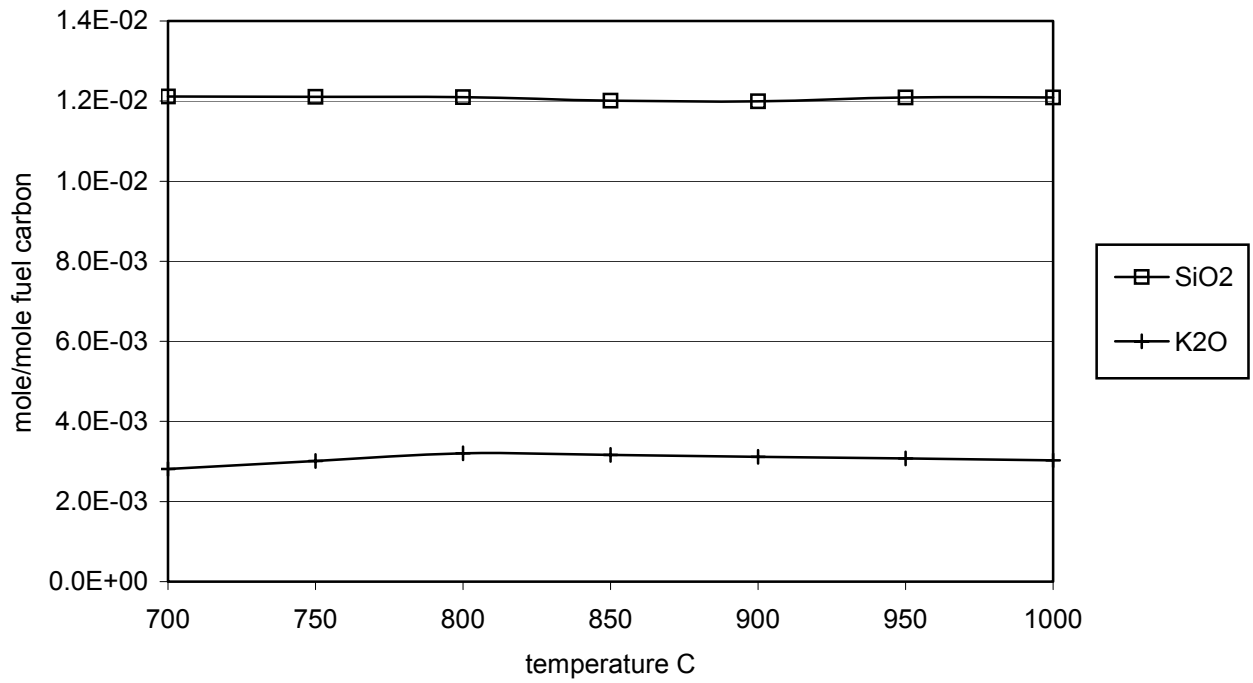


(b)

Figure A4.4. Equilibrium concentrations of gas species formed from gasifying banagrass (moisture content 10%) with an equivalence ratio of 0.3. Note: Mole fraction includes water vapor.

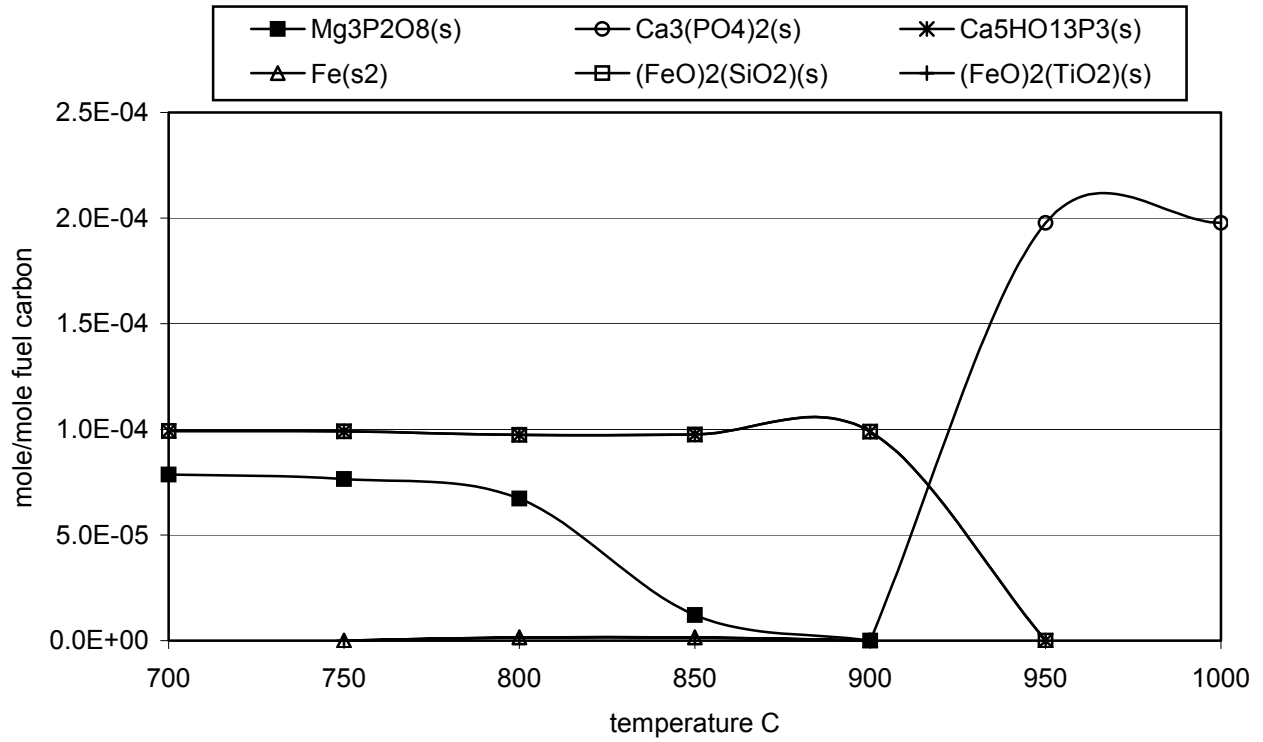


(a)

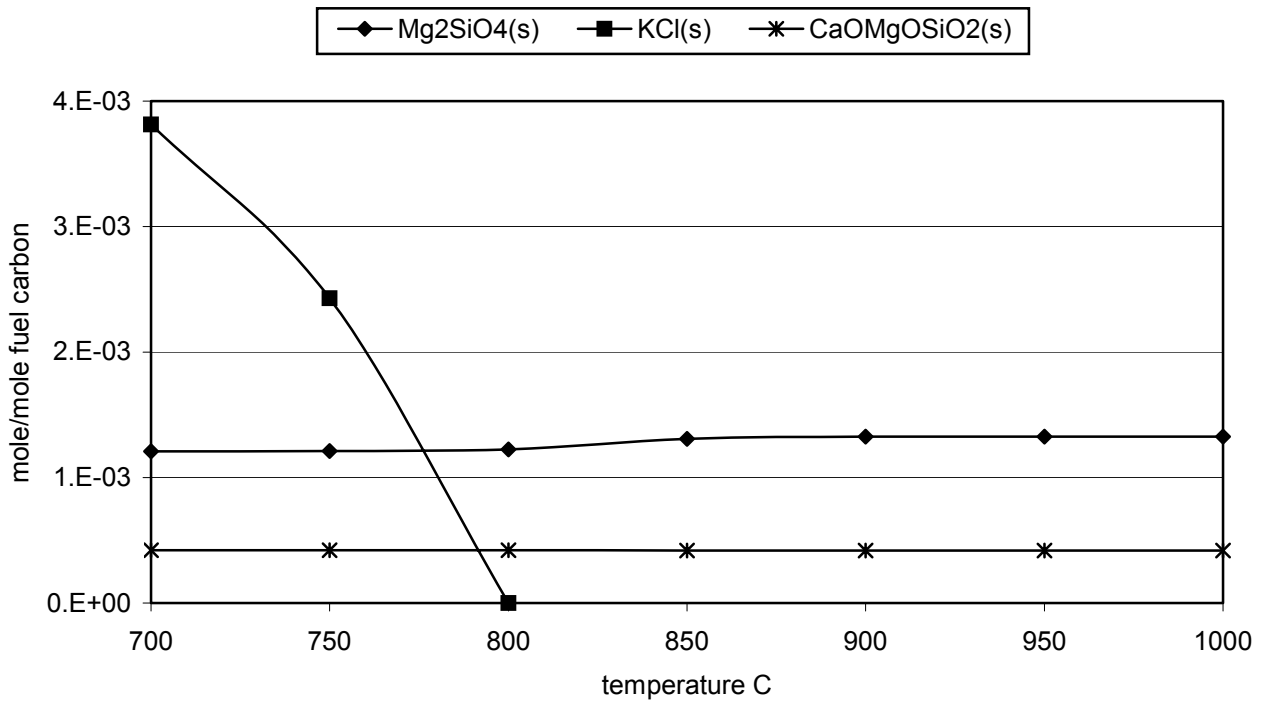


(b)

Figure A4.5. Equilibrium calculation of slag solution phase formed from gasification of banagrass (moisture content 10%) with an equivalence ratio of 0.3.

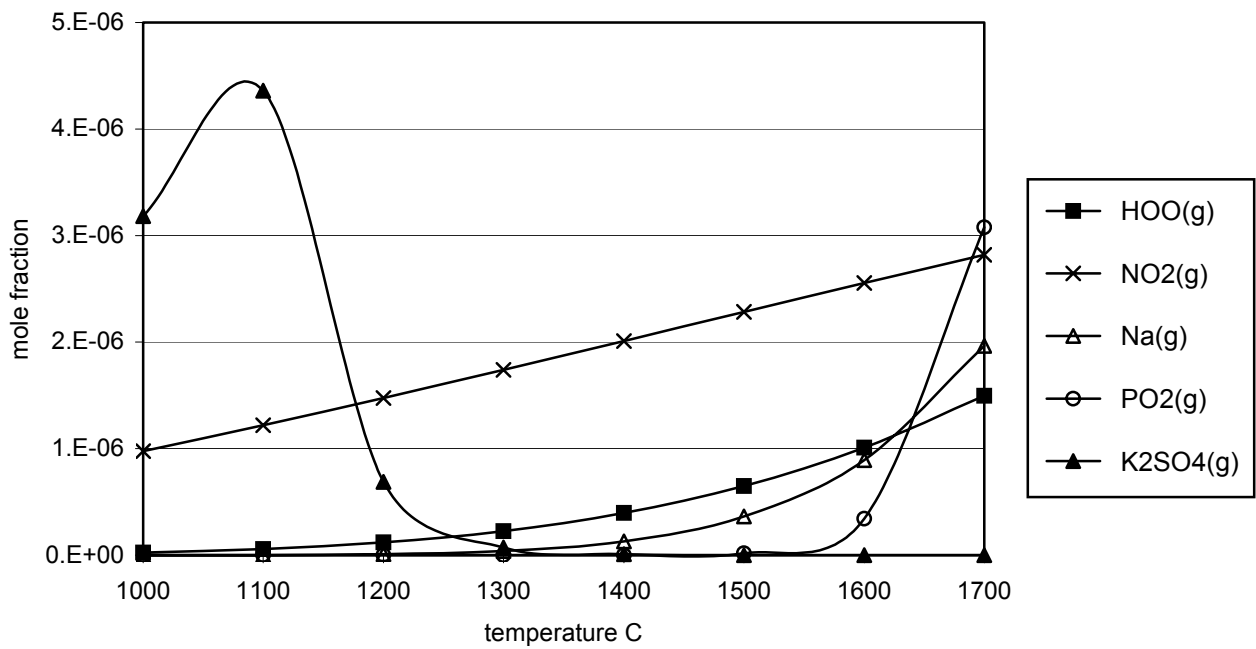


(a)

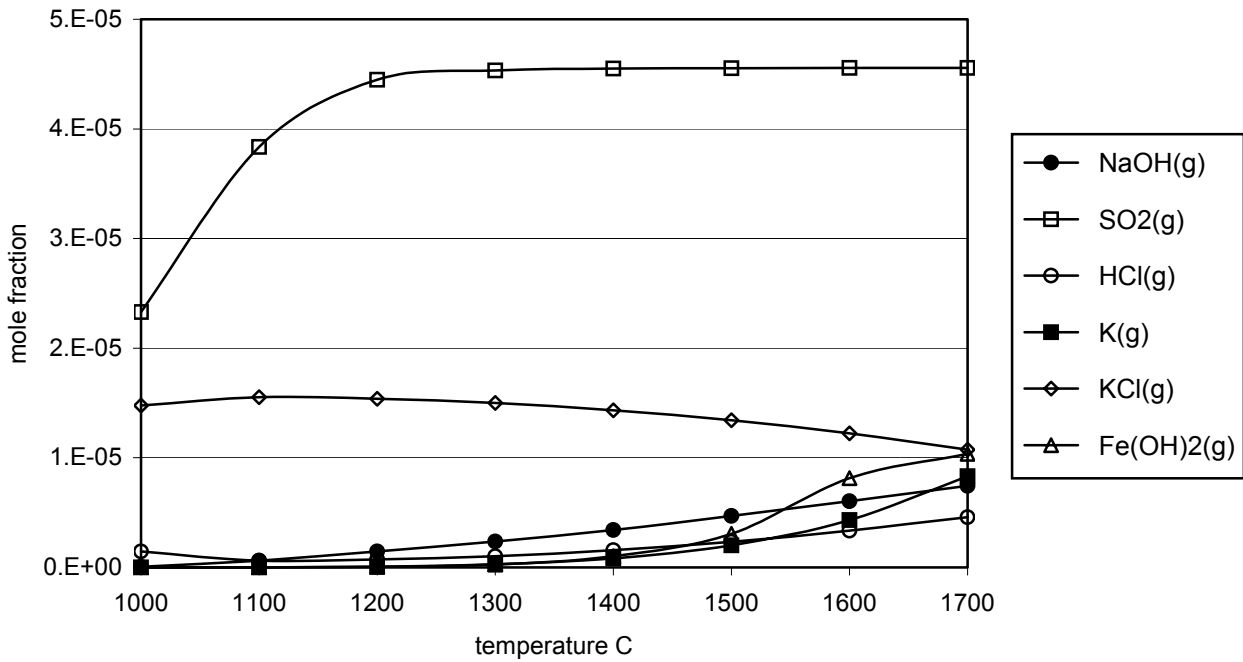


(b)

Figure A4.6. Equilibrium calculation of solid phase species formed from gasification of banagrass (moisture content 10%) with an equivalence ratio of 0.3.



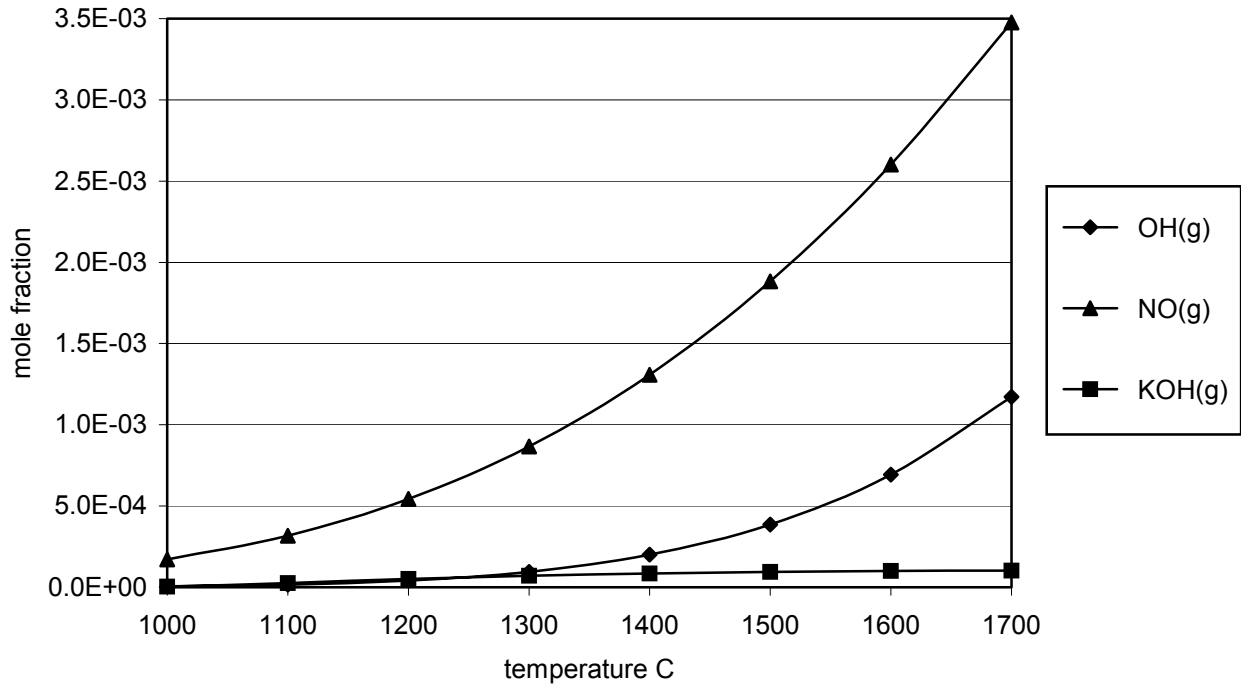
(a)



(b)

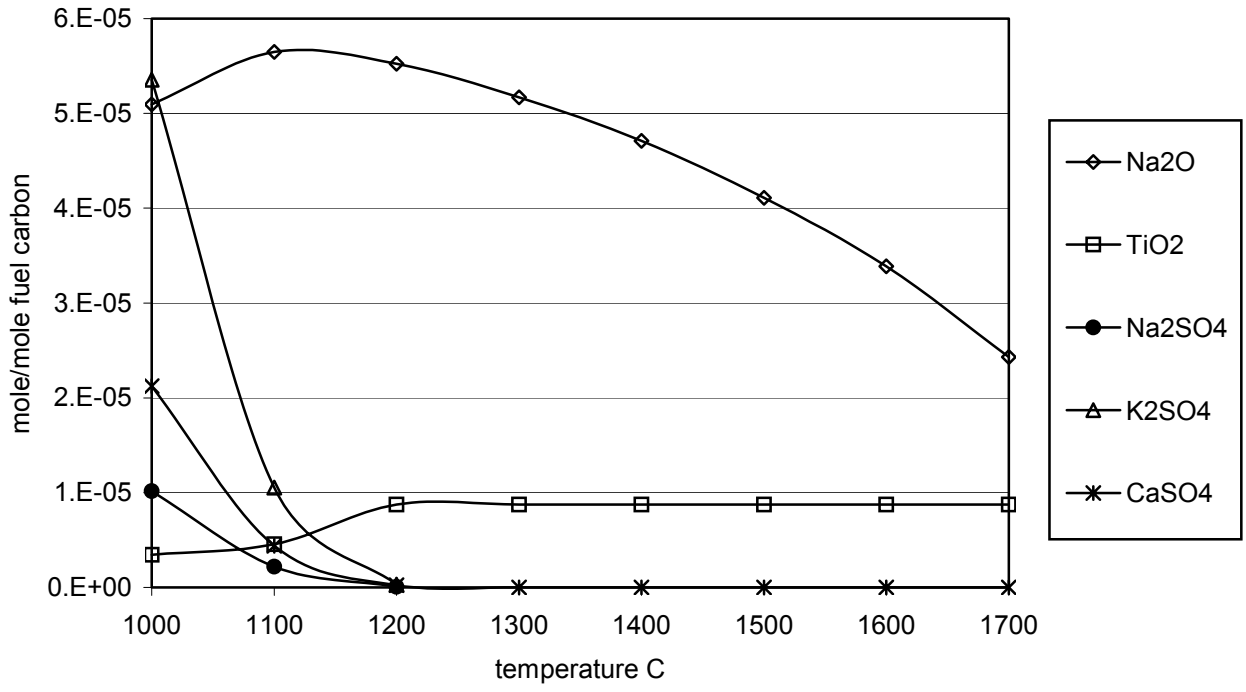
Figure A5.1. Equilibrium concentrations of gas species formed from combustion of macadamia nut shells (moisture content 0%) with 26% excess air. Note: Mole fraction includes water vapor.



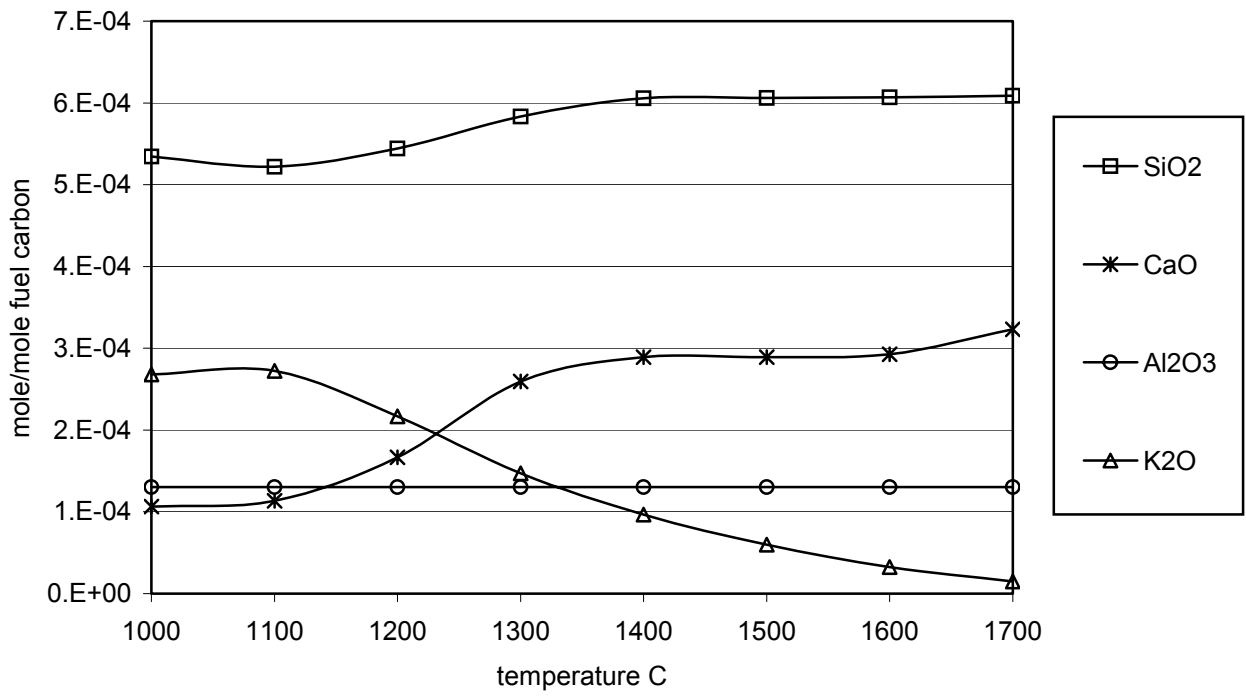


(c)

Figure A5.1.(continued) Equilibrium concentrations of gas species formed from combustion of macadamia nut shells (moisture content 0%) with 26% excess air. Note: Mole fraction includes water vapor.

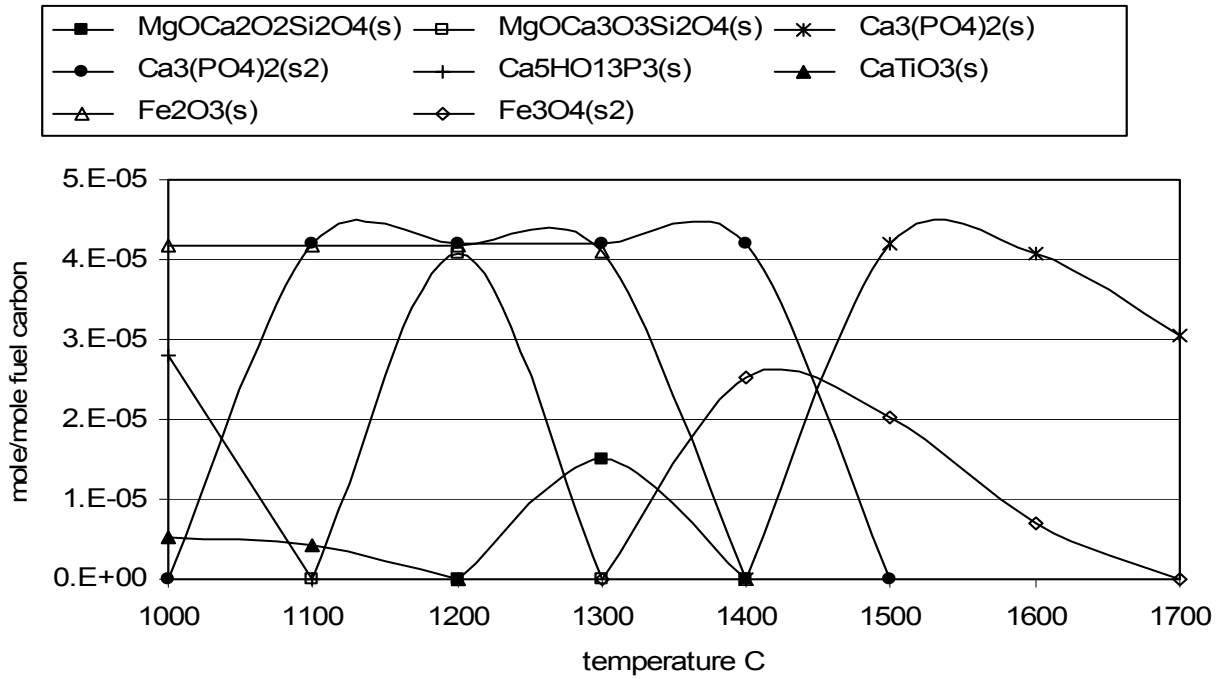


(a)

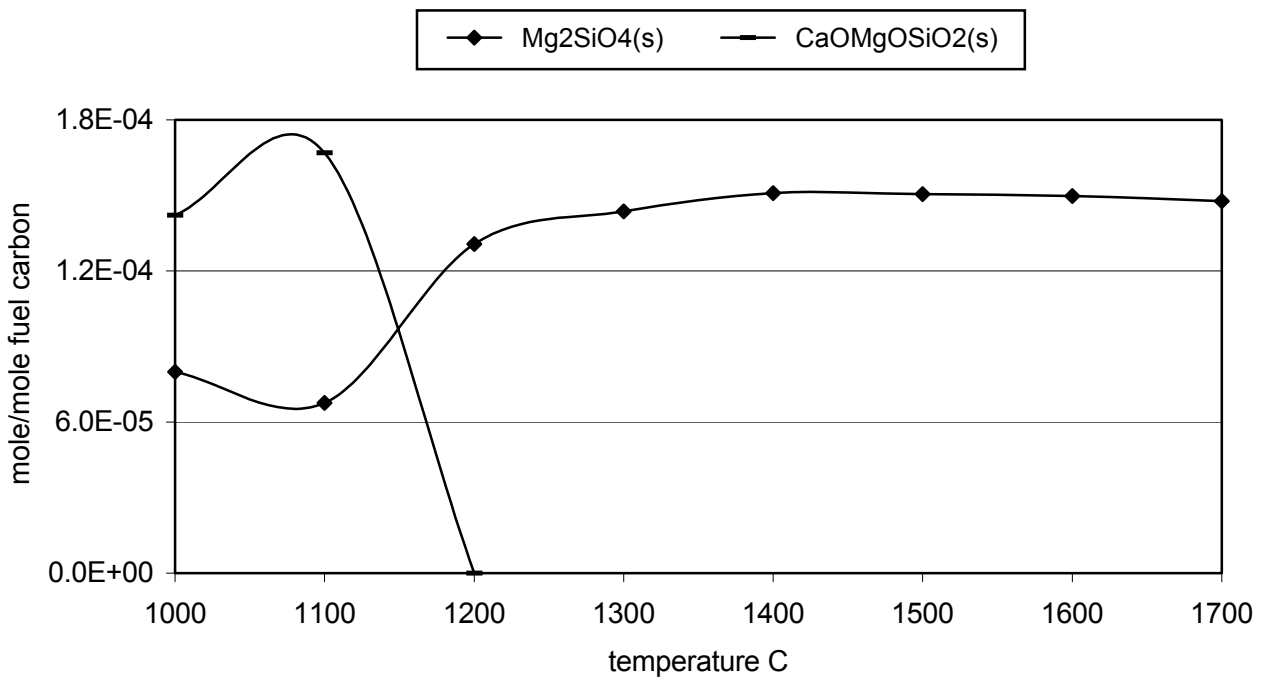


(b)

Figure A5.2. Equilibrium calculation of slag solution phase formed from combustion of macadamia nut shells (moisture content 0%) with 26% excess air.

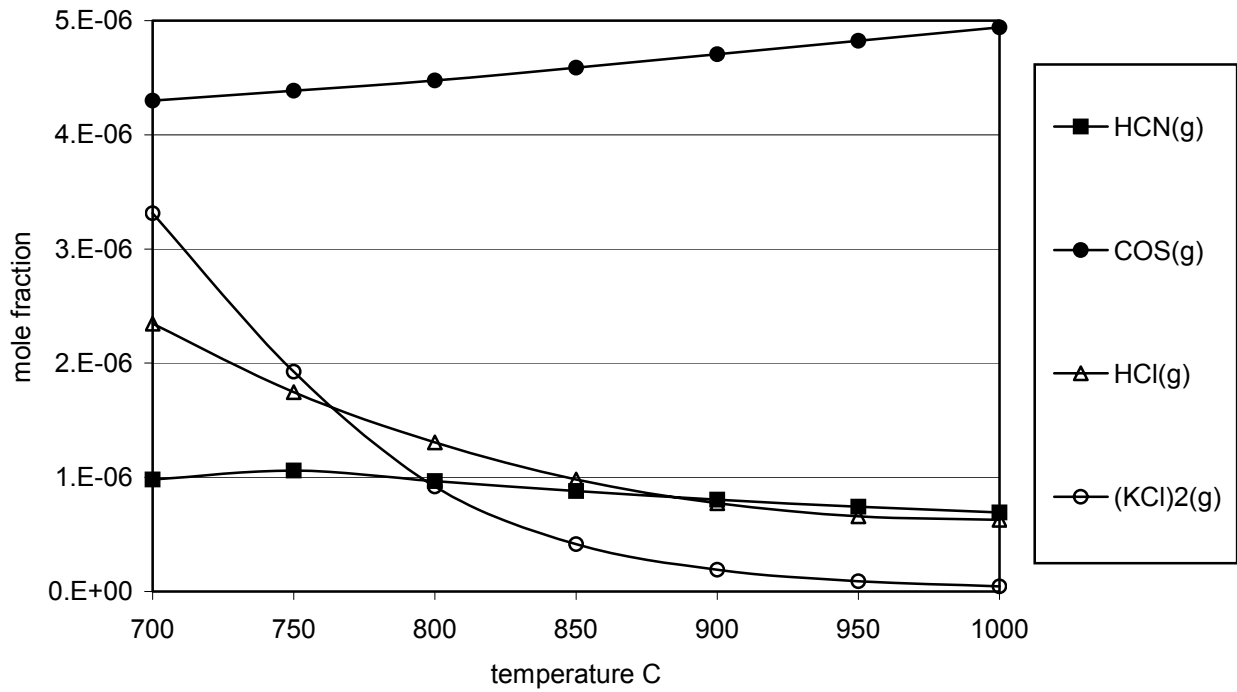


(a)

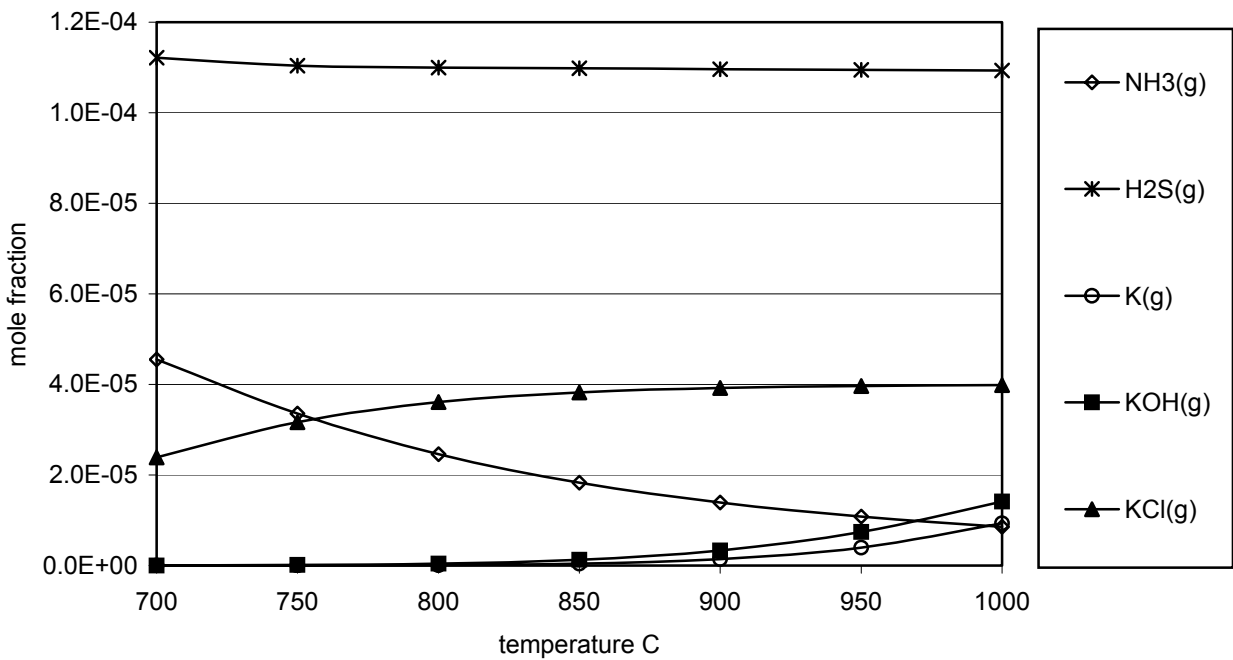


(b)

Figure A5.3. Equilibrium calculation of solid phase species formed from combustion of macadamia nut shells (moisture content 0%) with 26% excess air.

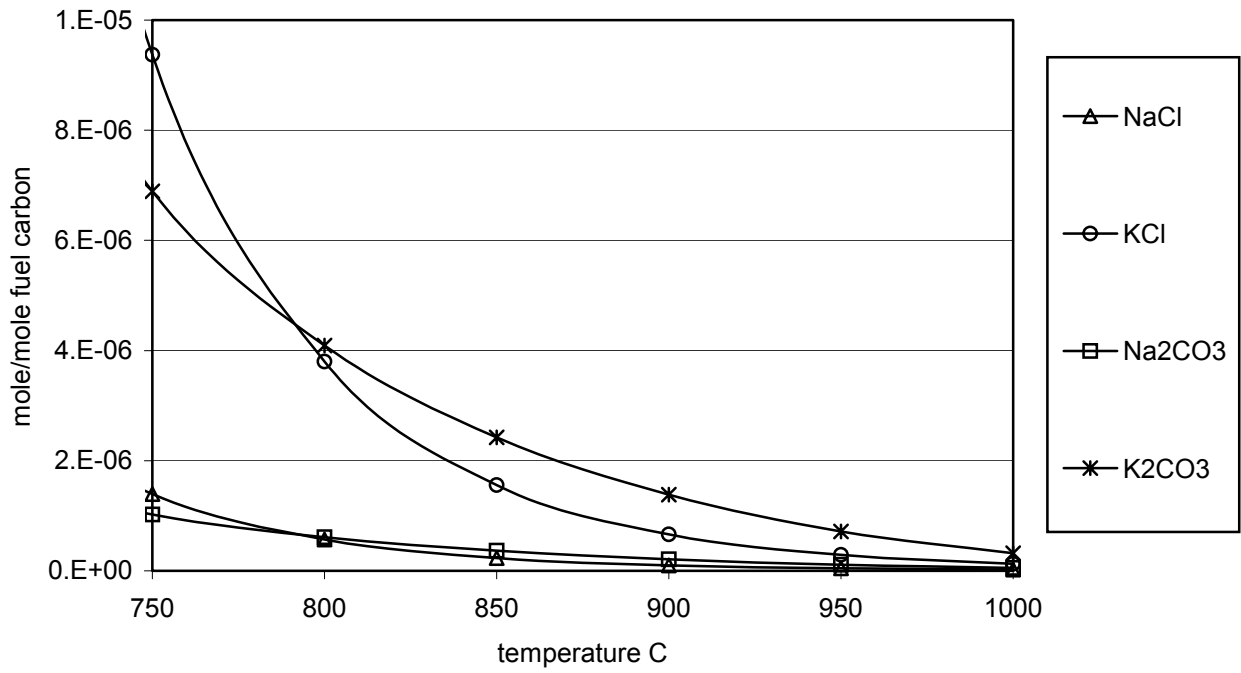


(a)

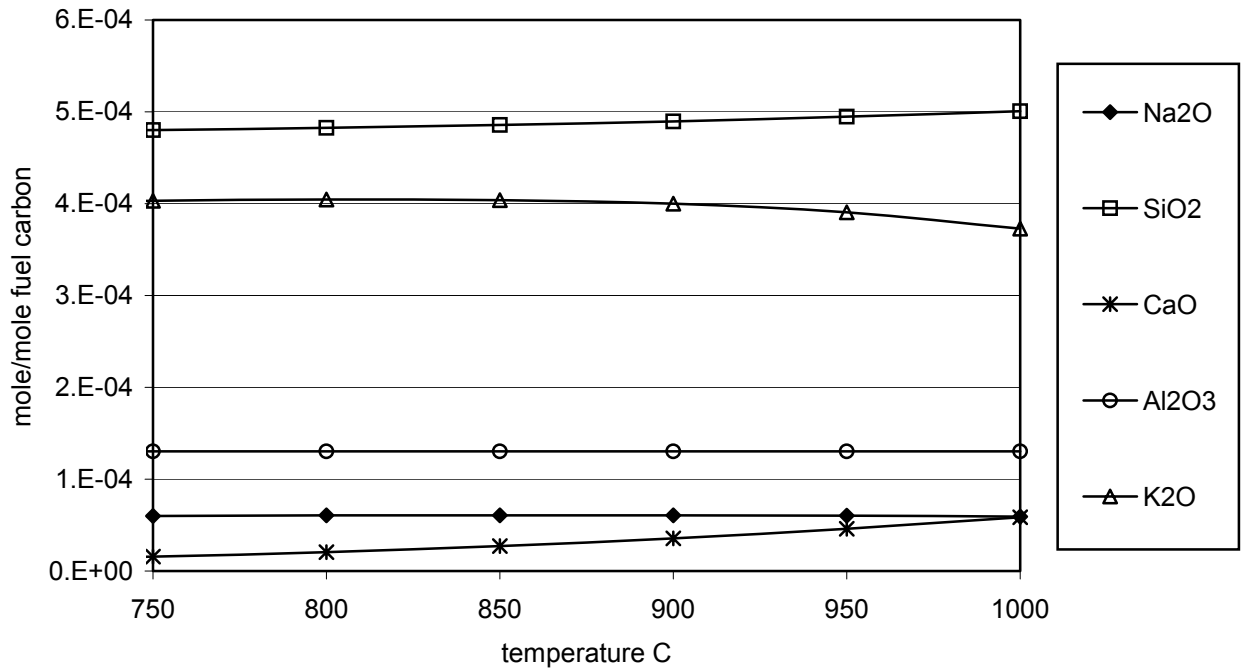


(b)

Figure A5.4. Equilibrium concentrations of gas species formed from gasifying macadamia nut shells (moisture content 10%) with an equivalence ratio of 0.3. Note: Mole fraction includes water vapor.



(a)



(b)

Figure A5.5. Equilibrium calculation of slag solution phase formed from gasification of macadamia nut shells (moisture content 10%) with an equivalence ratio of 0.3.

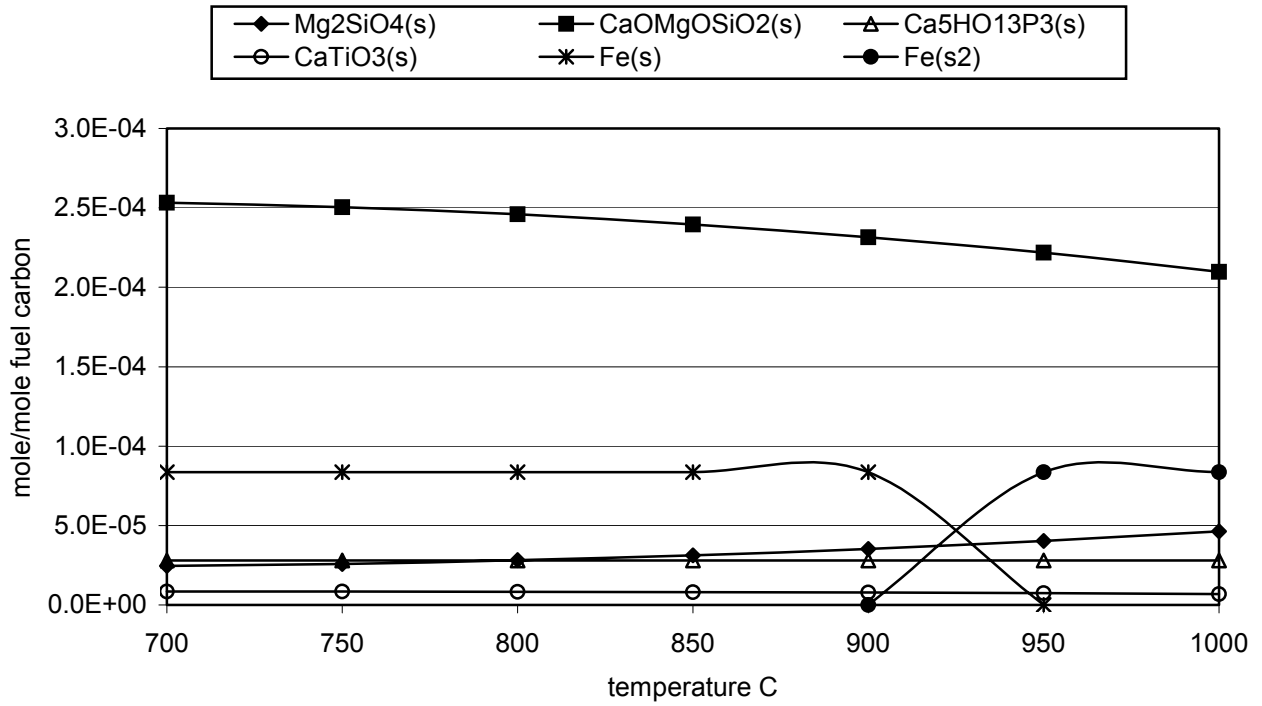
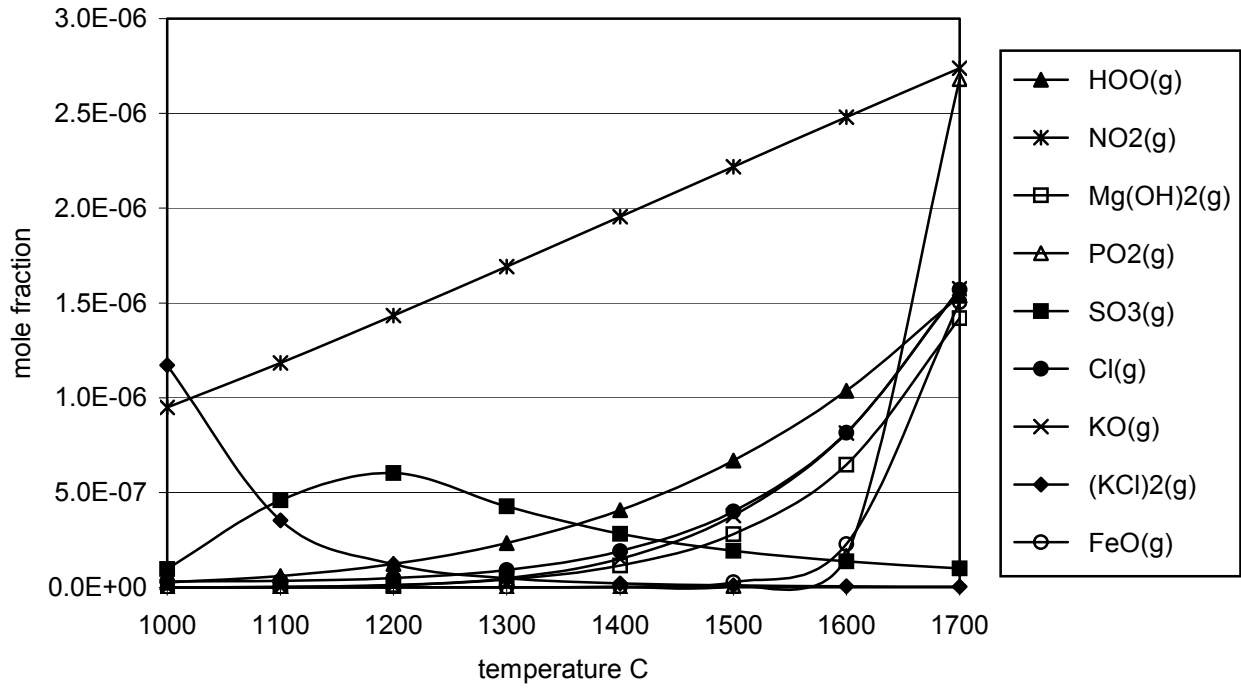
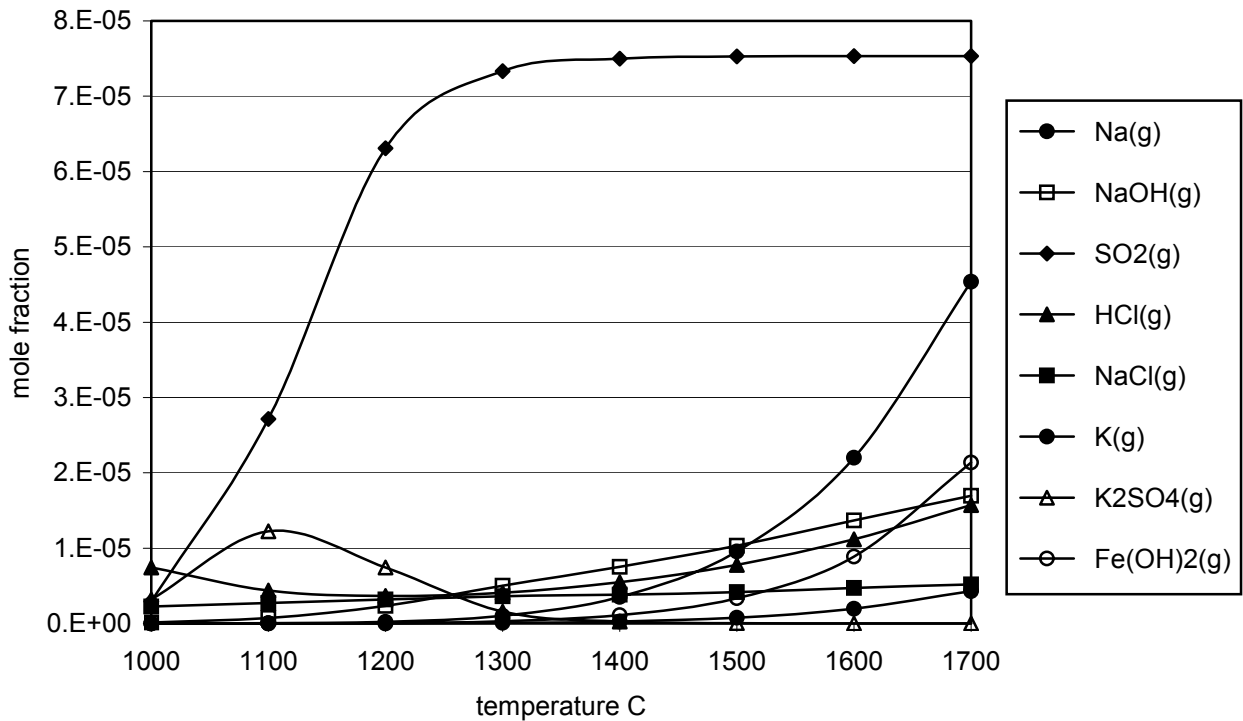


Figure A5.6. Equilibrium calculation of solid phase species formed from gasification of macadamia nut shells (moisture content 10%) with an equivalence ratio of 0.3.

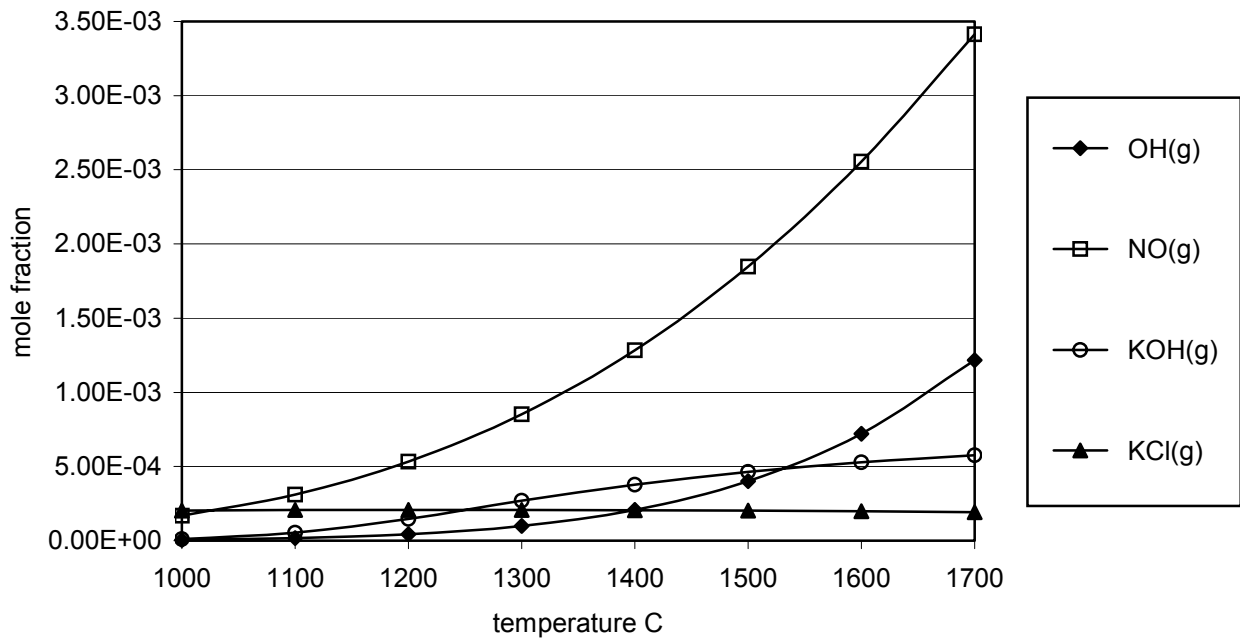


(a)



(b)

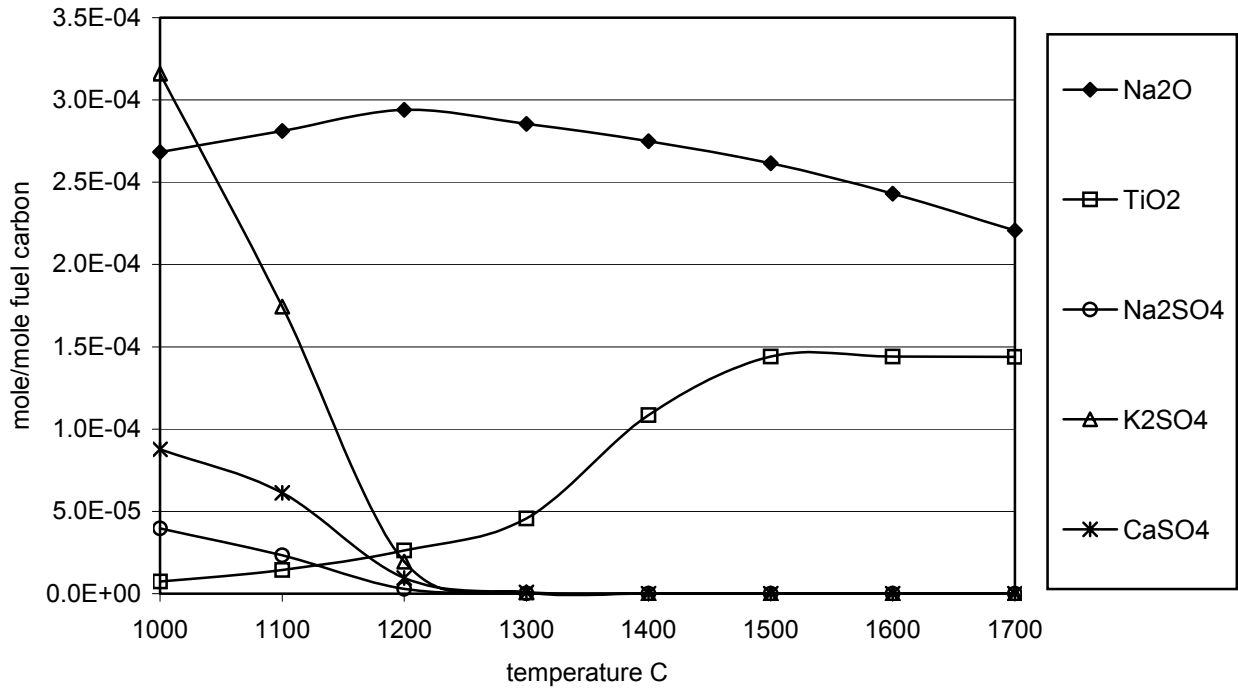
Figure A6.1. Equilibrium concentrations of gas species formed from combustion of hemp (moisture content 0%) with 26% excess air. Note: Mole fraction includes water vapor.



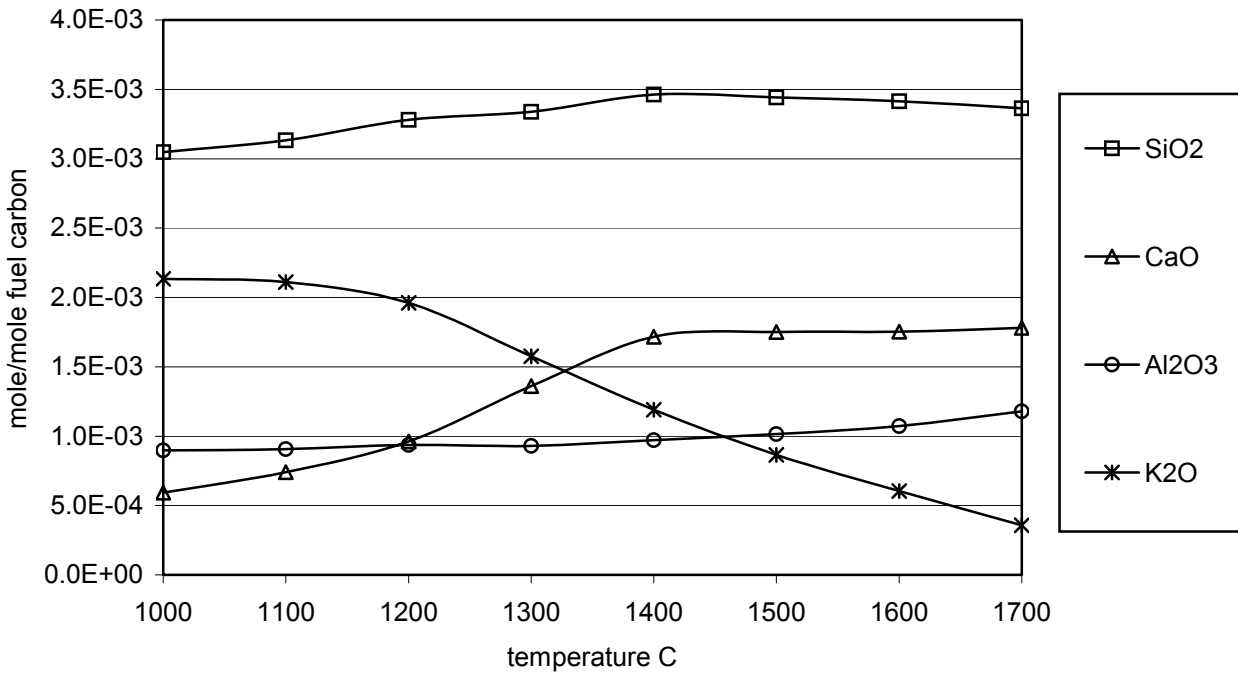
(c)

Figure A6.1. (continued) Equilibrium concentrations of gas species formed from combustion of hemp (moisture content 0%) with 26% excess air. Note: Mole fraction includes water vapor.





(a)



(b)

Figure A6.2. Equilibrium calculation of slag solution phase formed from combustion of hemp (moisture content 0%) with 26% excess air.

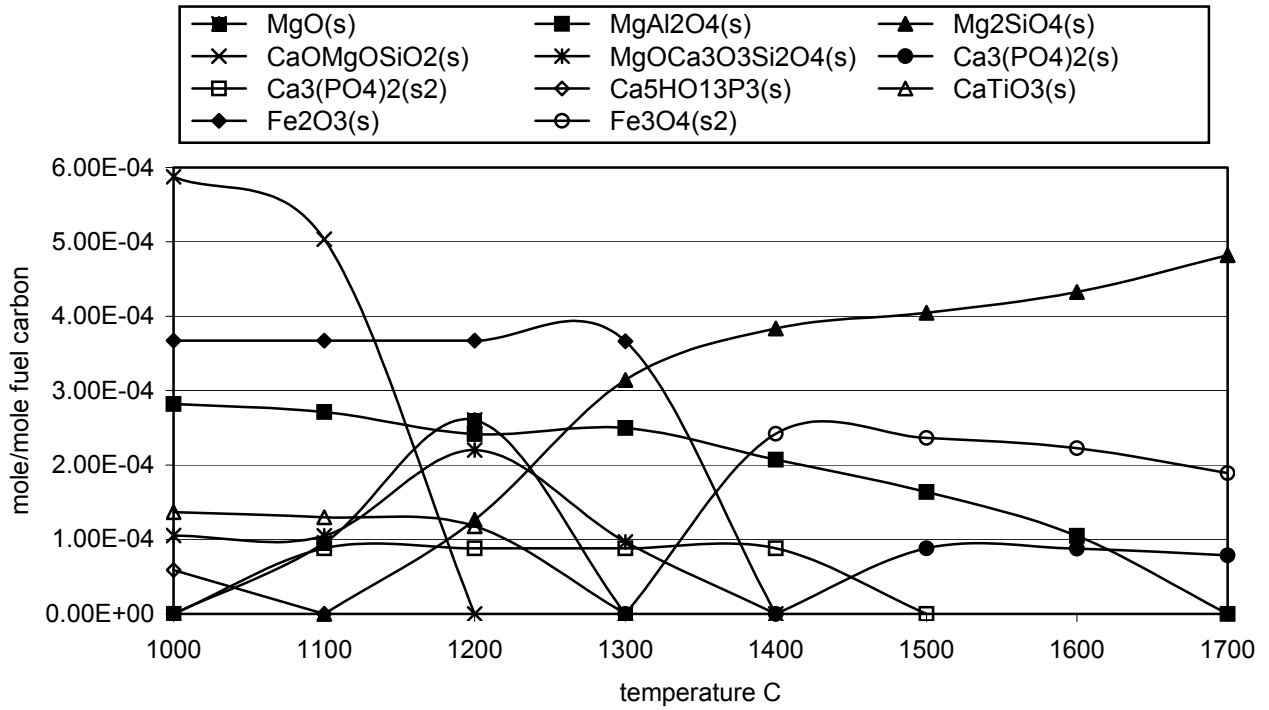
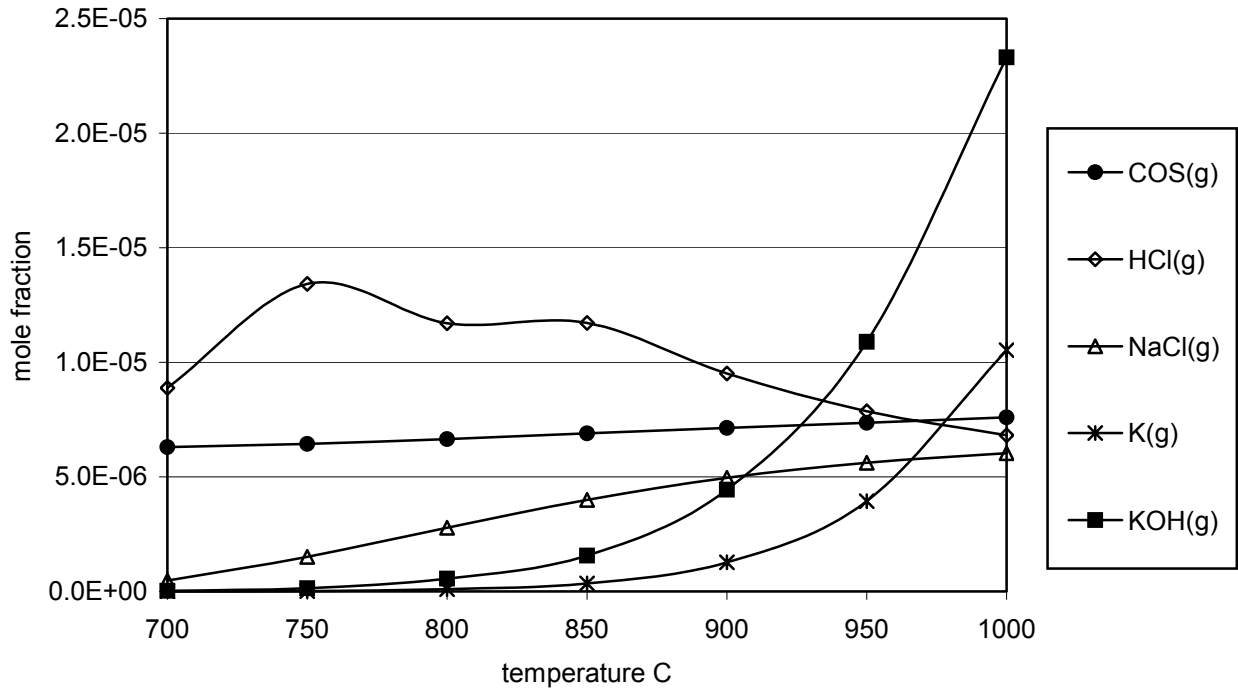
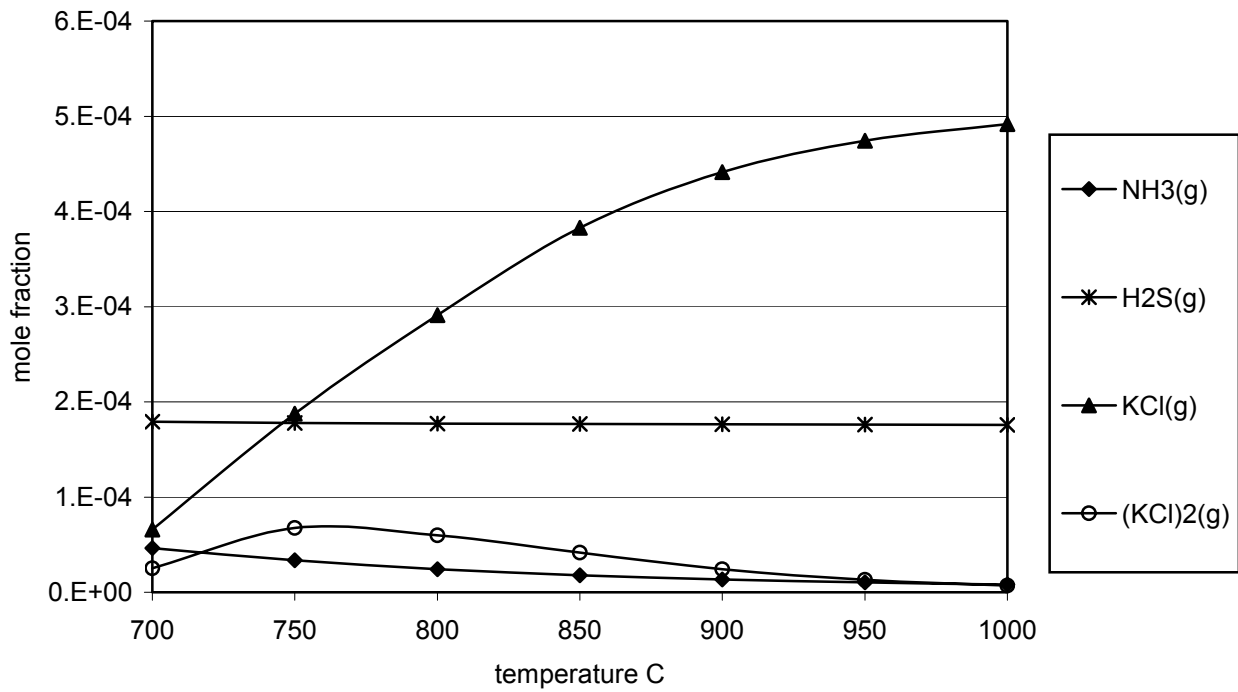


Figure A6.3. Equilibrium calculation of solid phase species formed from combustion of hemp (moisture content 0%) with 26% excess air.

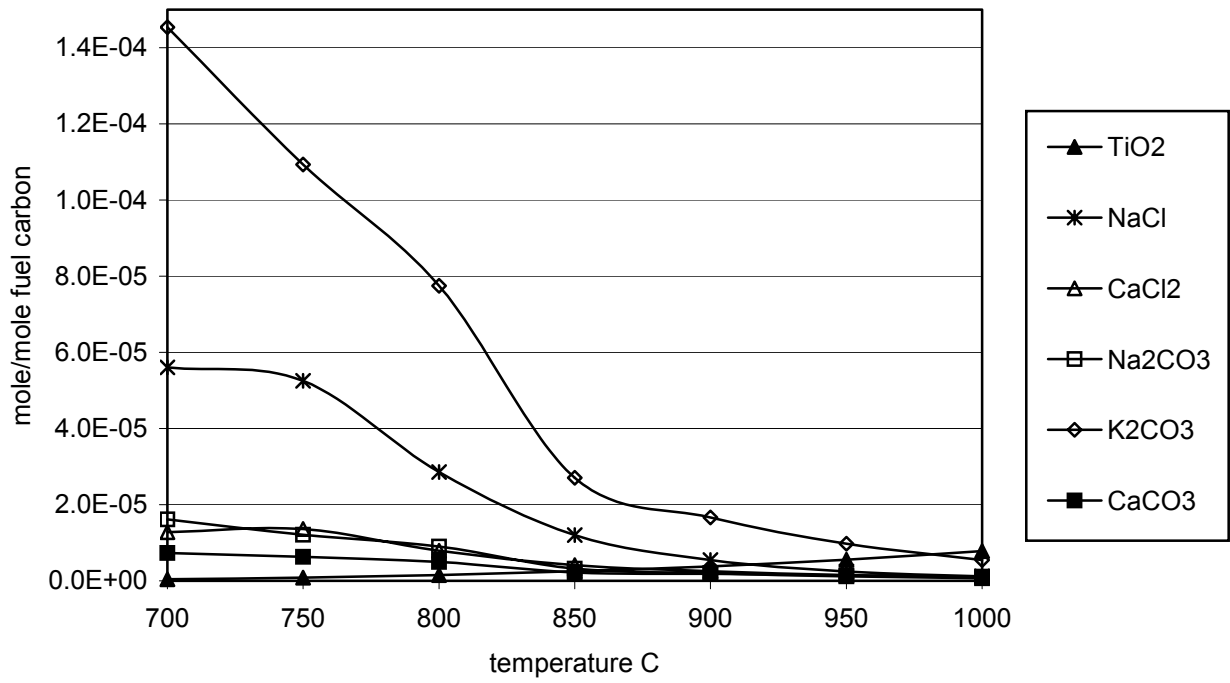


(a)

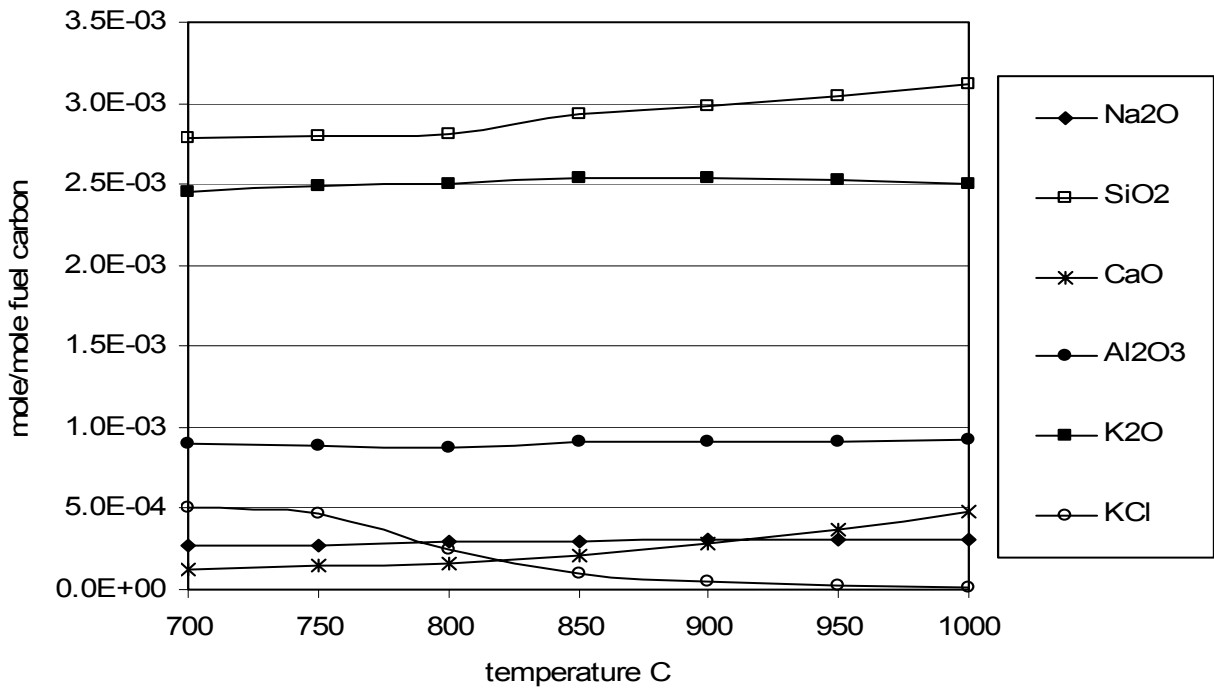


(b)

Figure A6.4. Equilibrium concentrations of gas species formed from gasifying hemp (moisture content 10%) with an equivalence ratio of 0.3. Note: Mole fraction includes water vapor.



(a)



(b)

Figure A6.5. Equilibrium calculation of slag solution phase formed from gasification of hemp (moisture content 10%) with an equivalence ratio of 0.3.

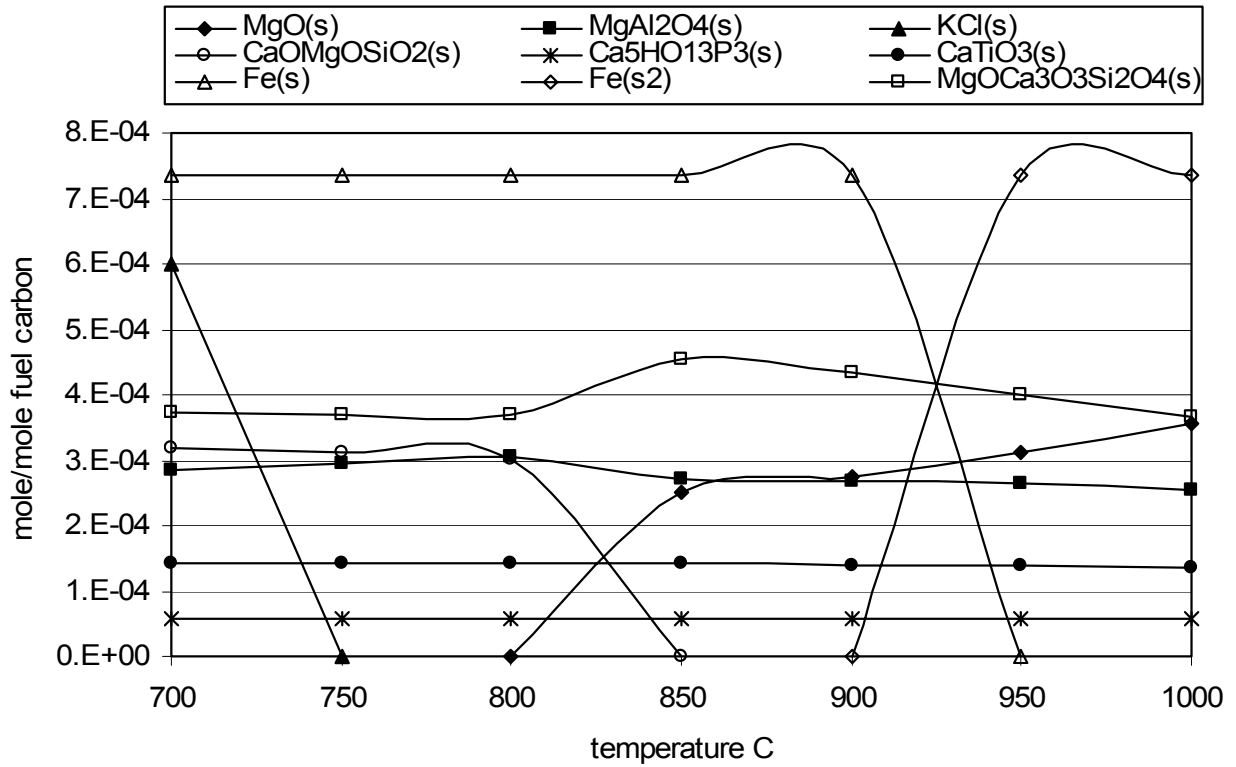
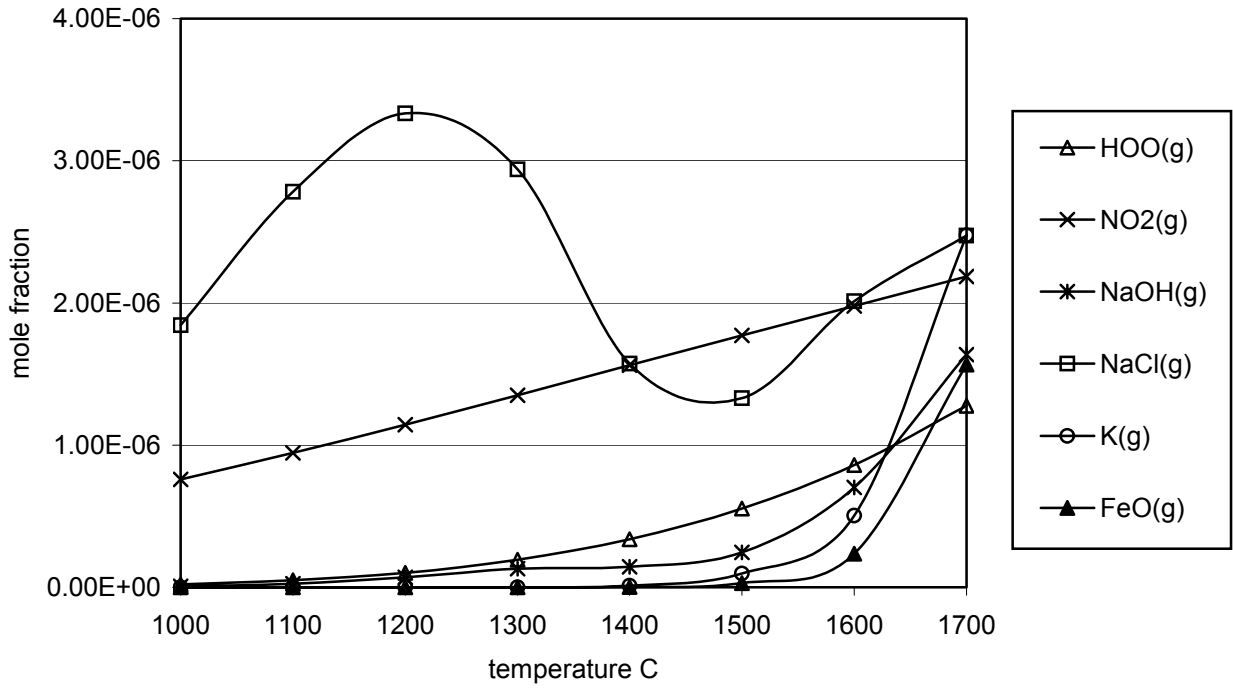
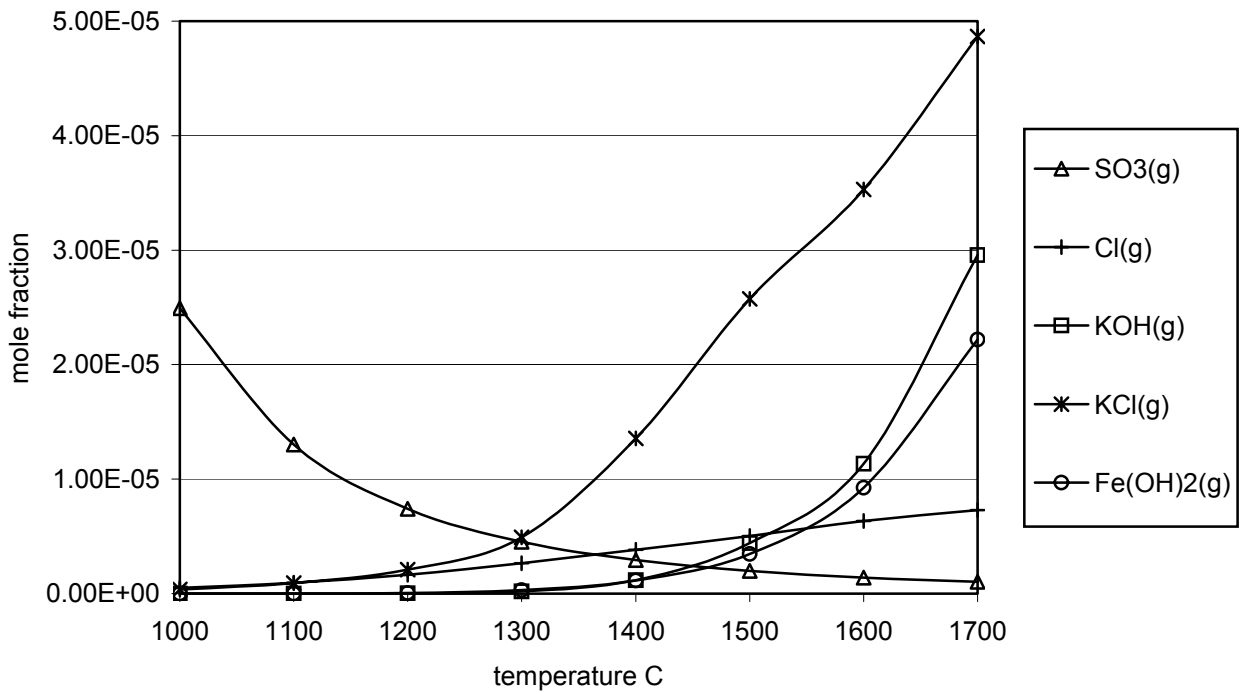


Figure A6.6. Equilibrium calculation of solid phase species formed from gasification of hemp (moisture content 10%) with an equivalence ratio of 0.3.

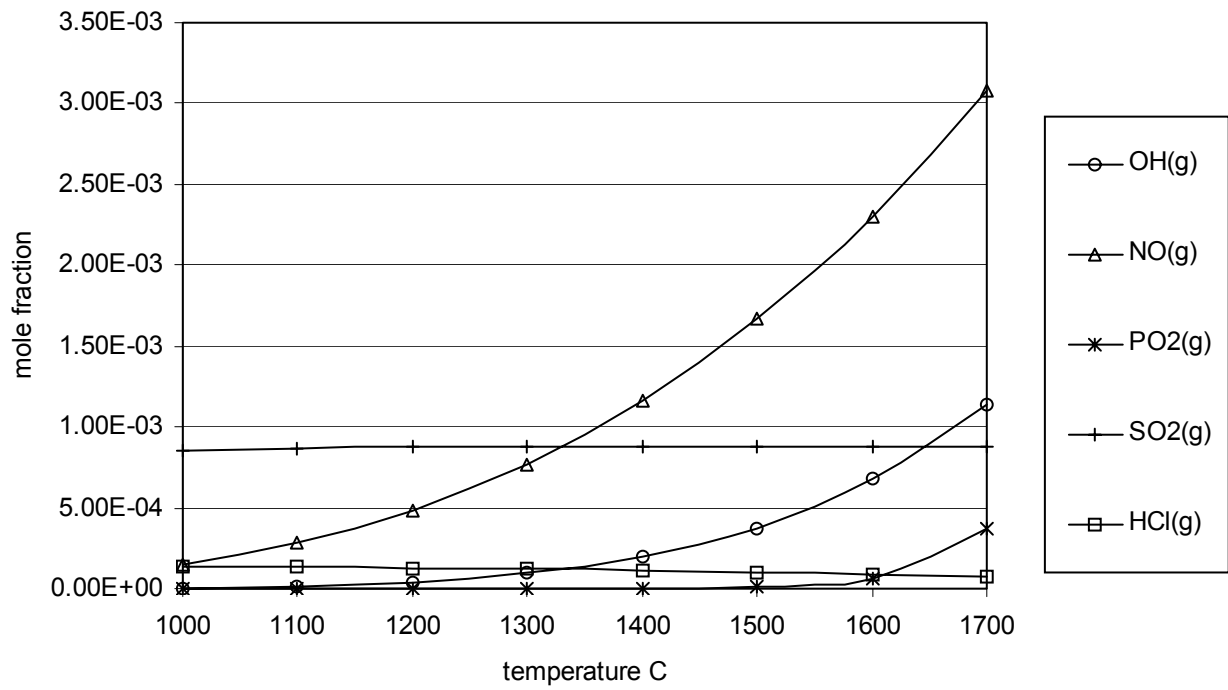


(a)



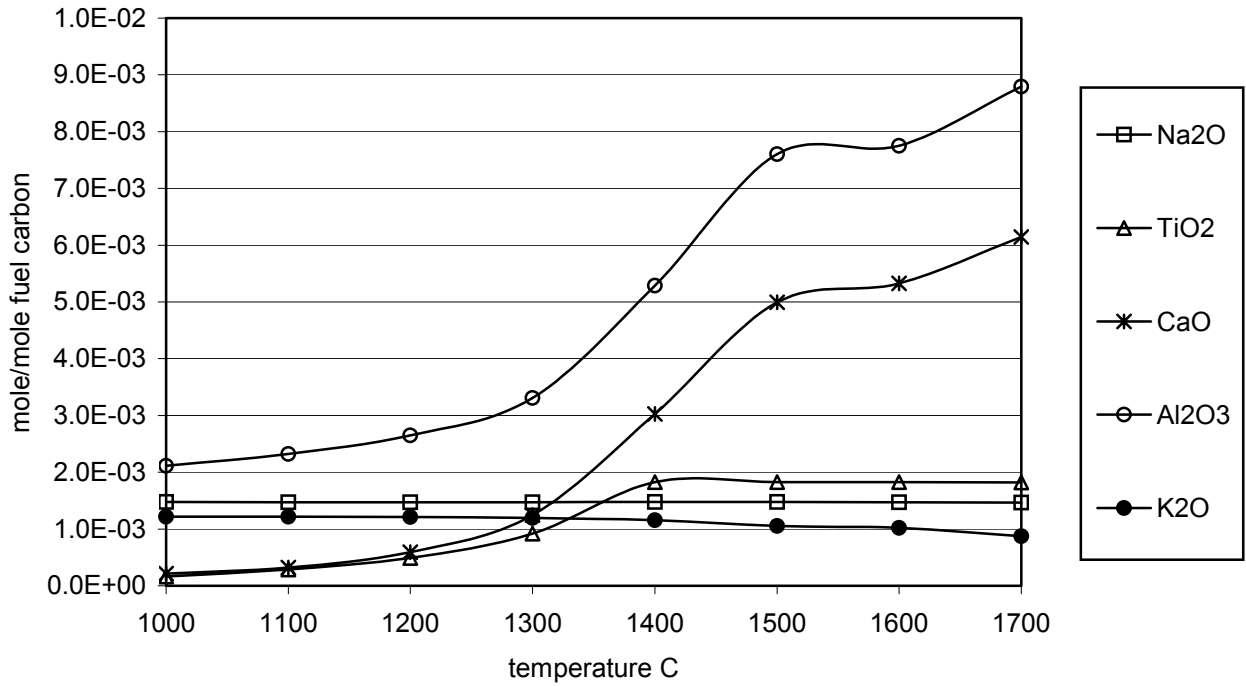
(b)

Figure A7.1. Equilibrium concentrations of gas species formed from combustion of Kahului WWTP sludge (moisture content 0%) with 26% excess air. Note: Mole fraction includes water vapor.

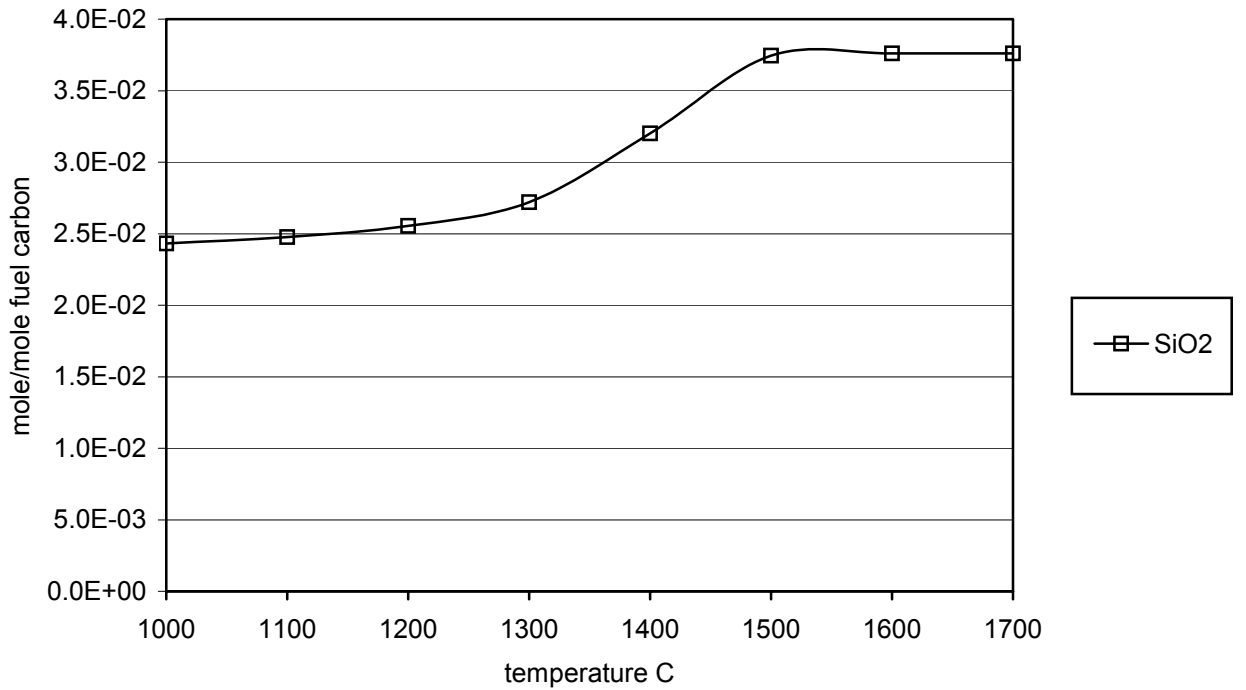


(c)

Figure A7.1. (continued) Equilibrium concentrations of gas species formed from combustion of Kahului WWTP sludge (moisture content 0%) with 26% excess air. Note: Mole fraction includes water vapor.



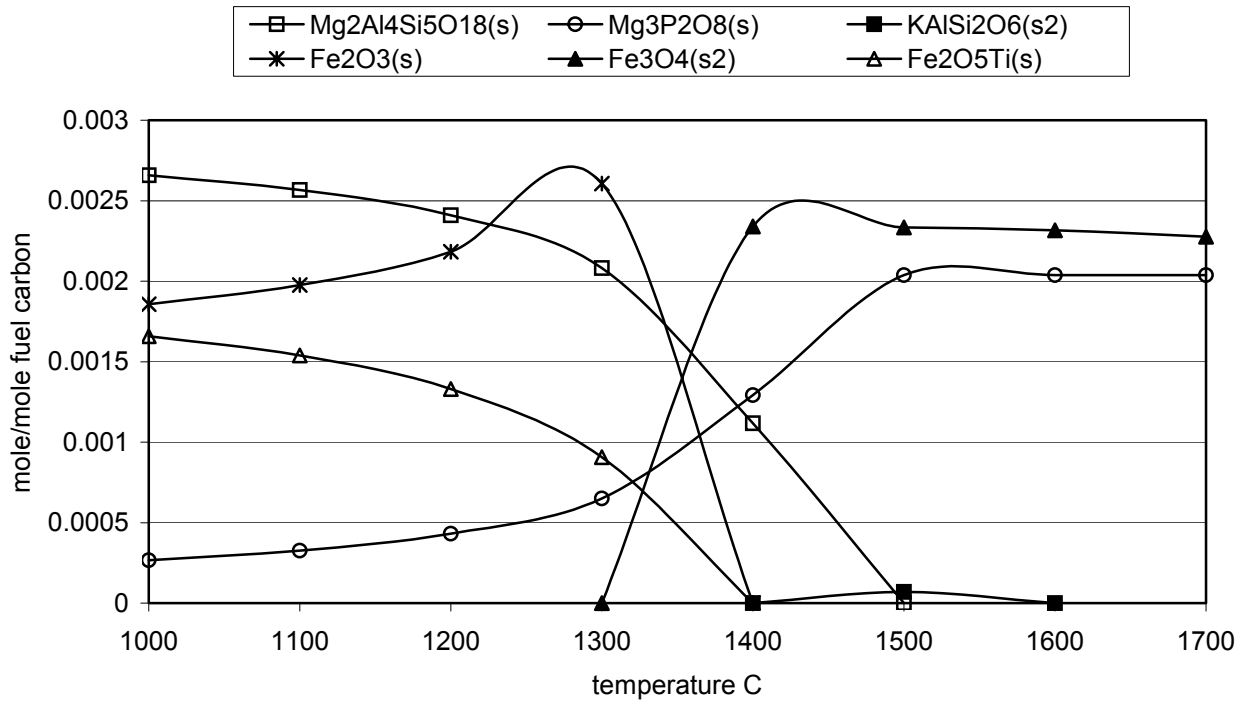
(a)



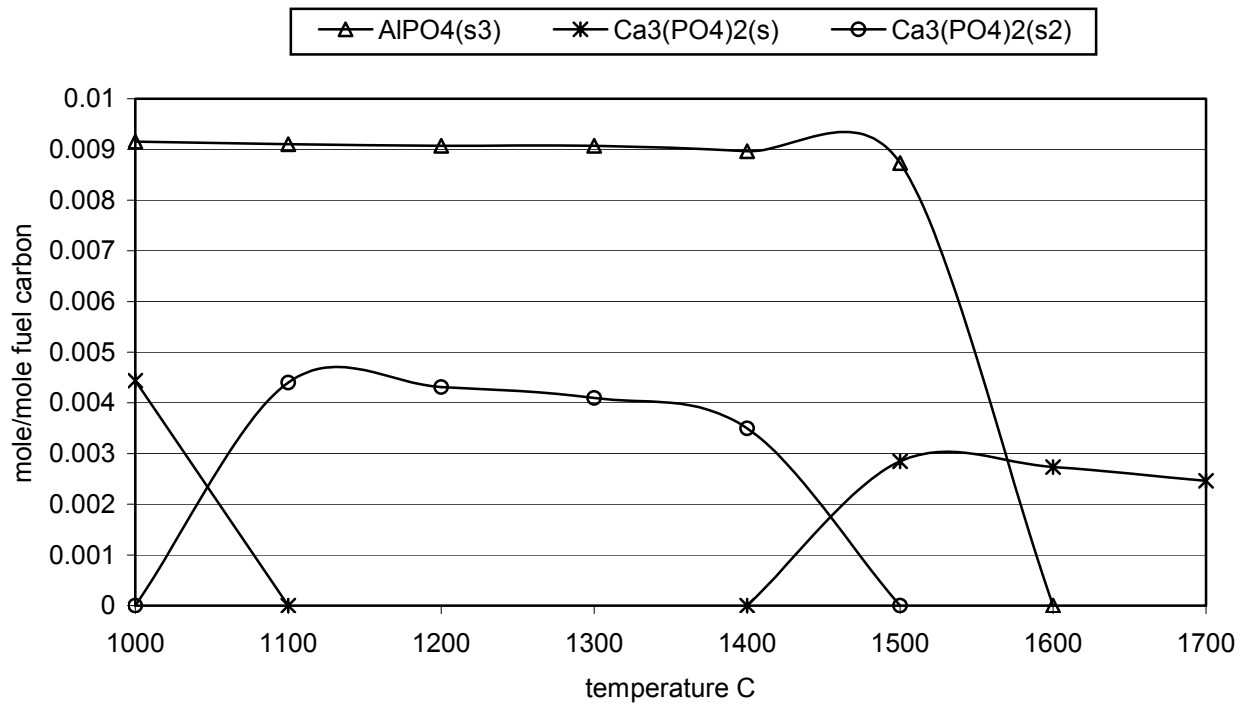
(b)

Figure A7.2. Equilibrium calculation of slag solution phase formed from combustion of Kahului WWTP sludge (moisture content 0%) with 26% excess air.



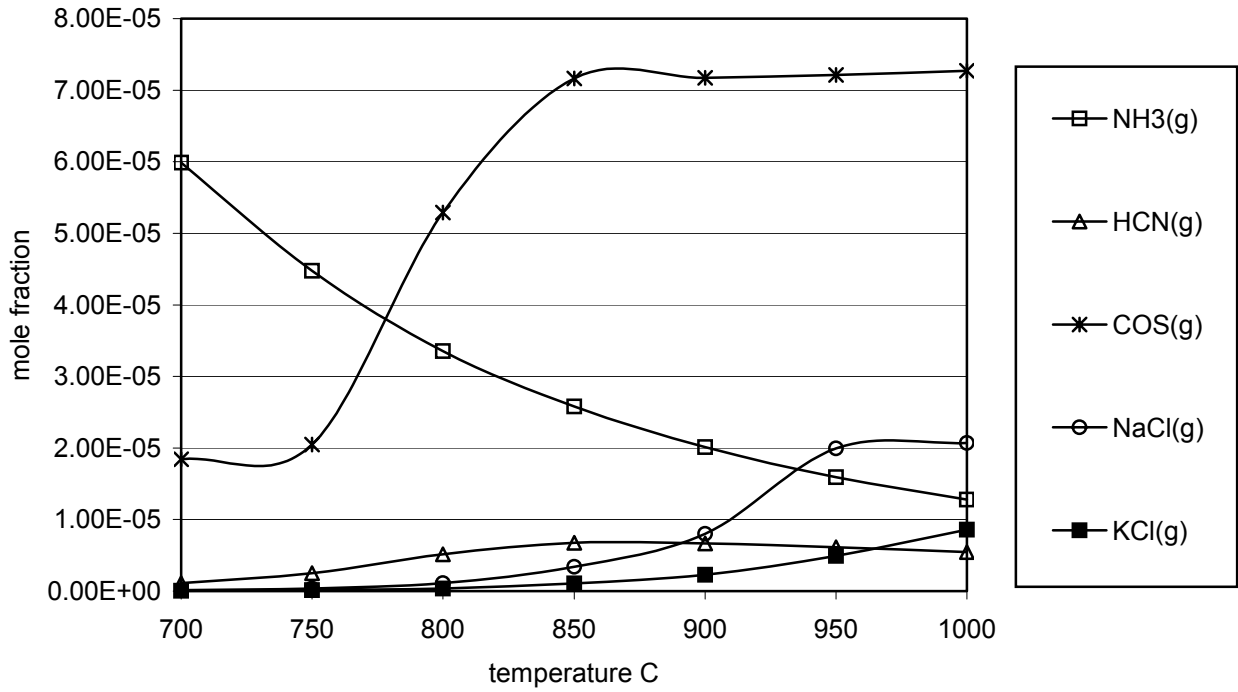


(a)

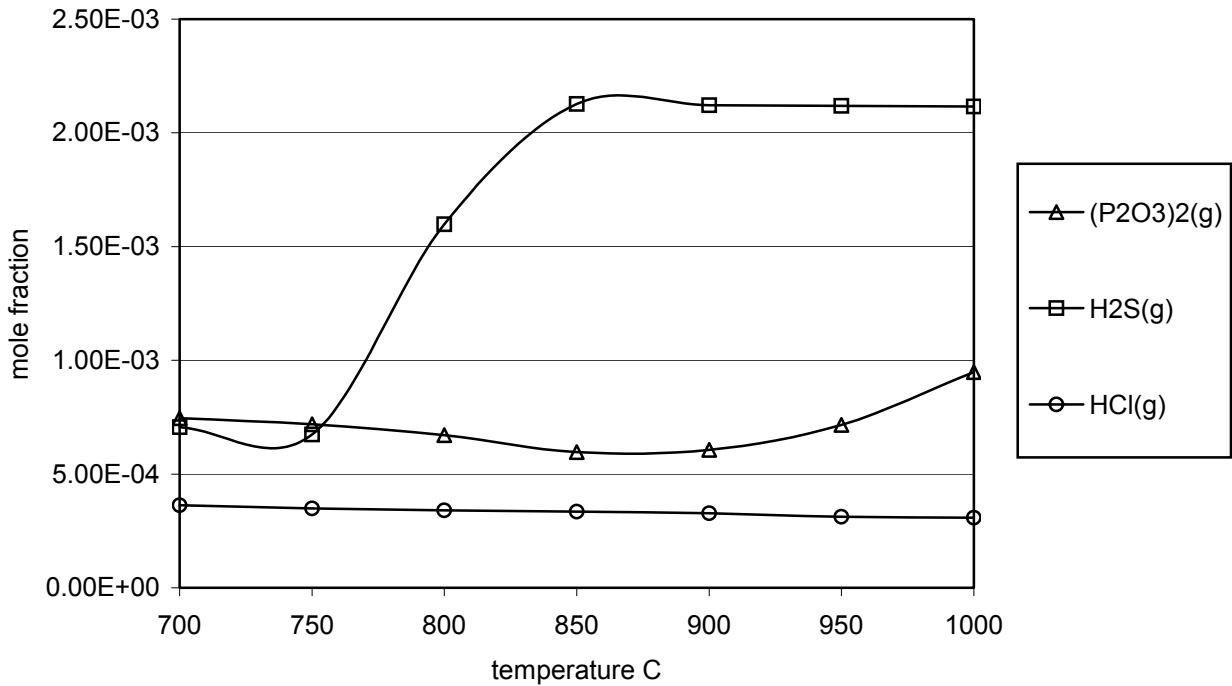


(b)

Figure A7.3. Equilibrium calculation of solid phase species formed from combustion of Kahului WWTP sludge (moisture content 0%) with 26% excess air.

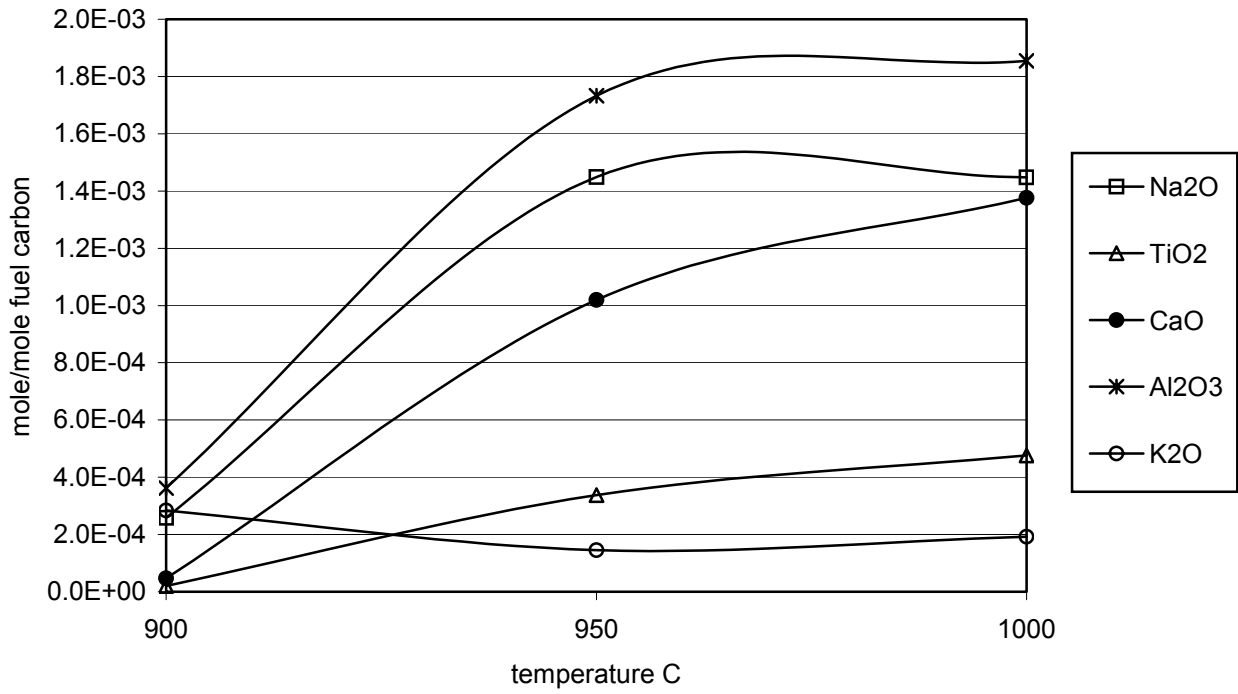


(a)

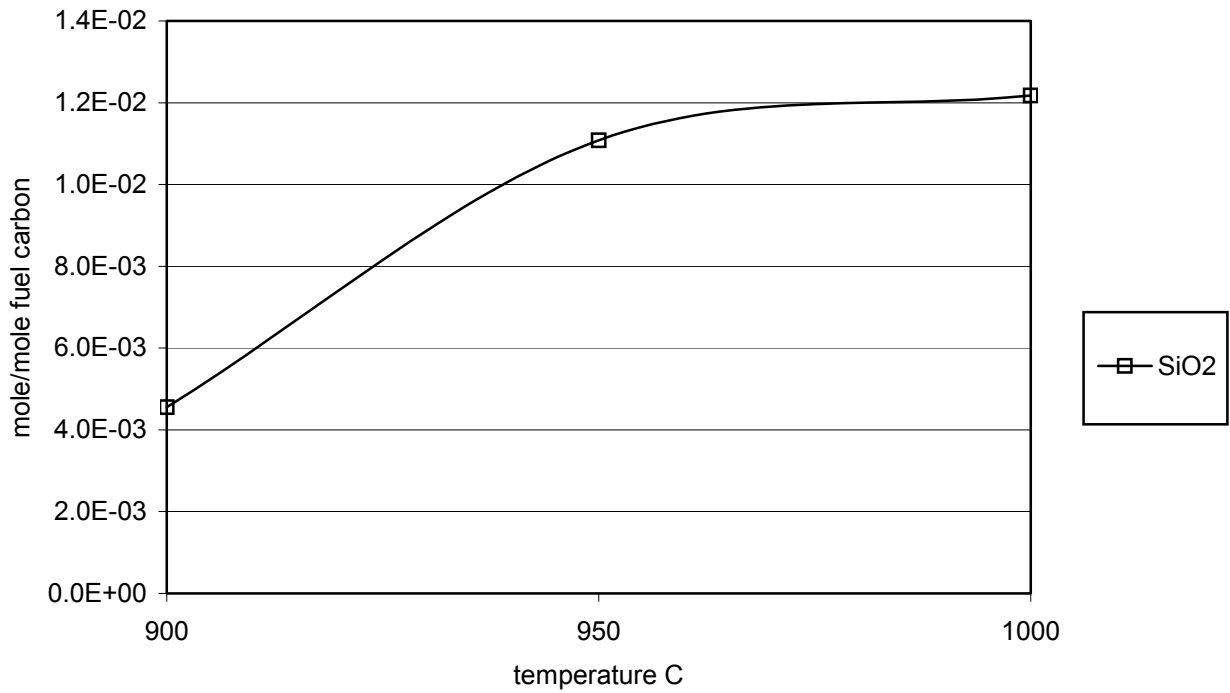


(b)

Figure A7.4. Equilibrium concentrations of gas species formed from gasifying Kahului WWTP sludge (moisture content 10%) with an equivalence ratio of 0.3. Note: Mole fraction includes water vapor.

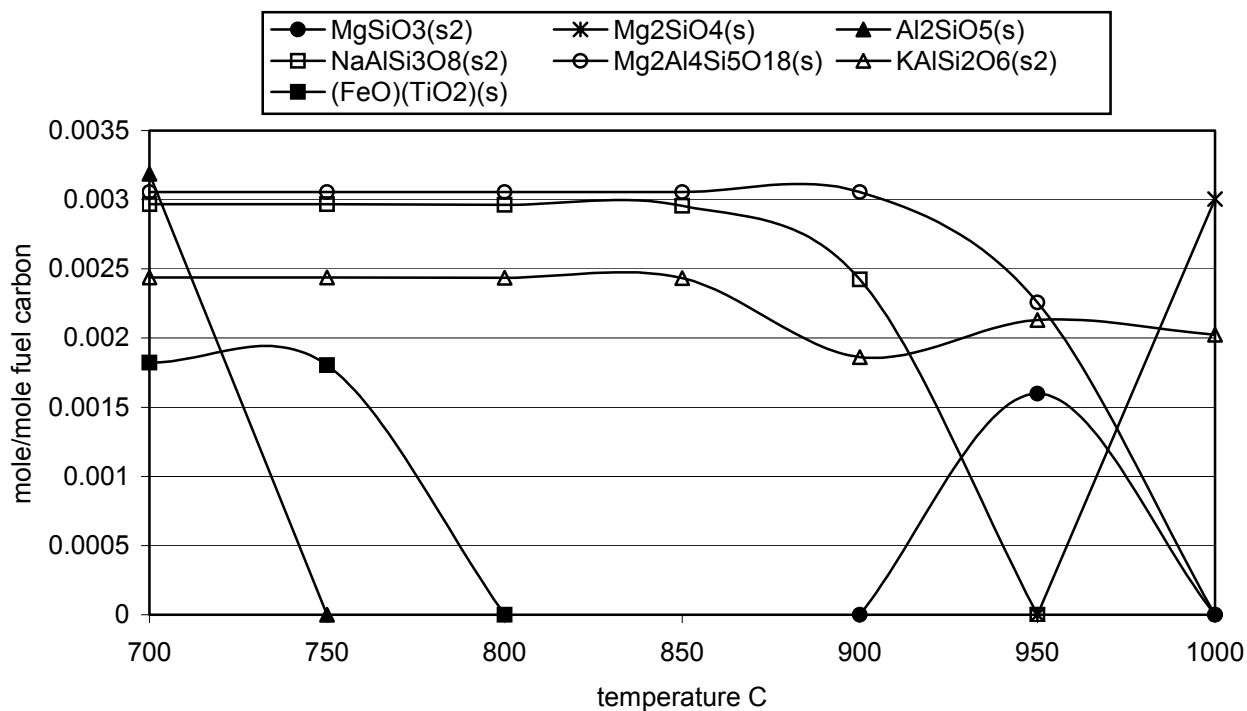


(a)

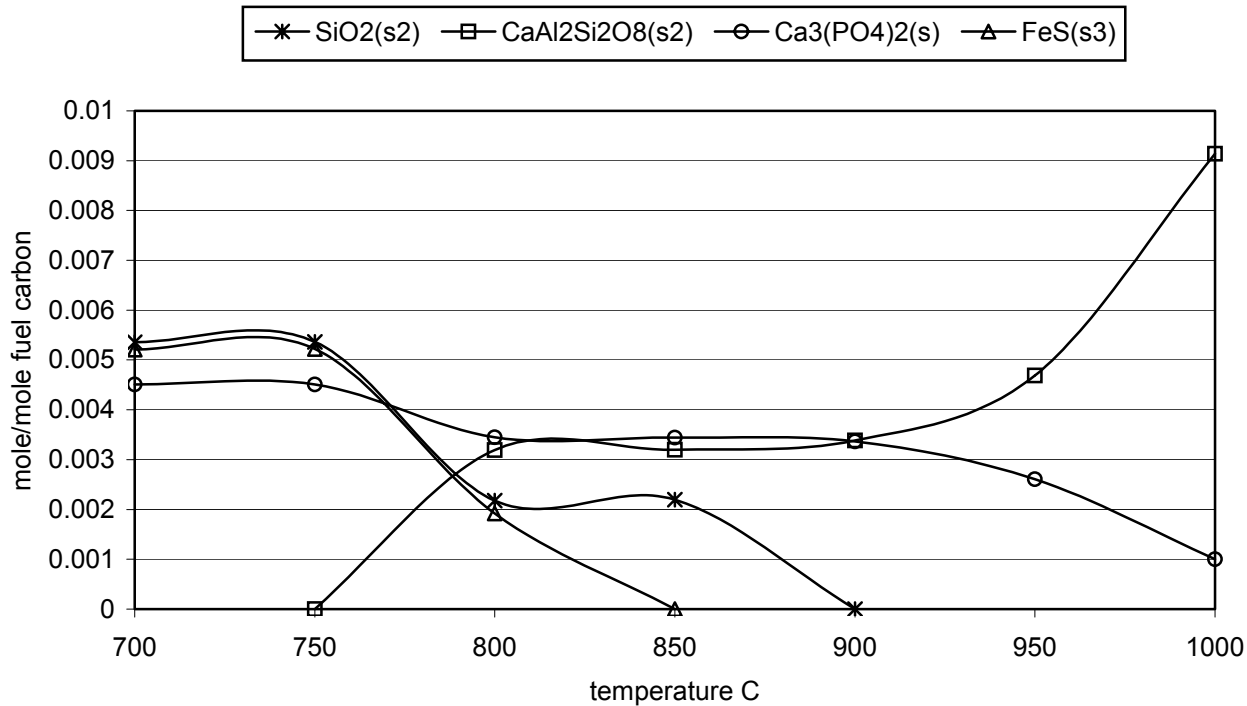


(b)

Figure A7.5. Equilibrium calculation of slag solution phase formed from gasification of Kahului WWTP sludge (moisture content 10%) with an equivalence ratio of 0.3.



(a)



(b)

Figure A7.6. Equilibrium calculation of solid phase species formed from gasification of Kahului WWTP sludge (moisture content 10%) with an equivalence ratio of 0.3.