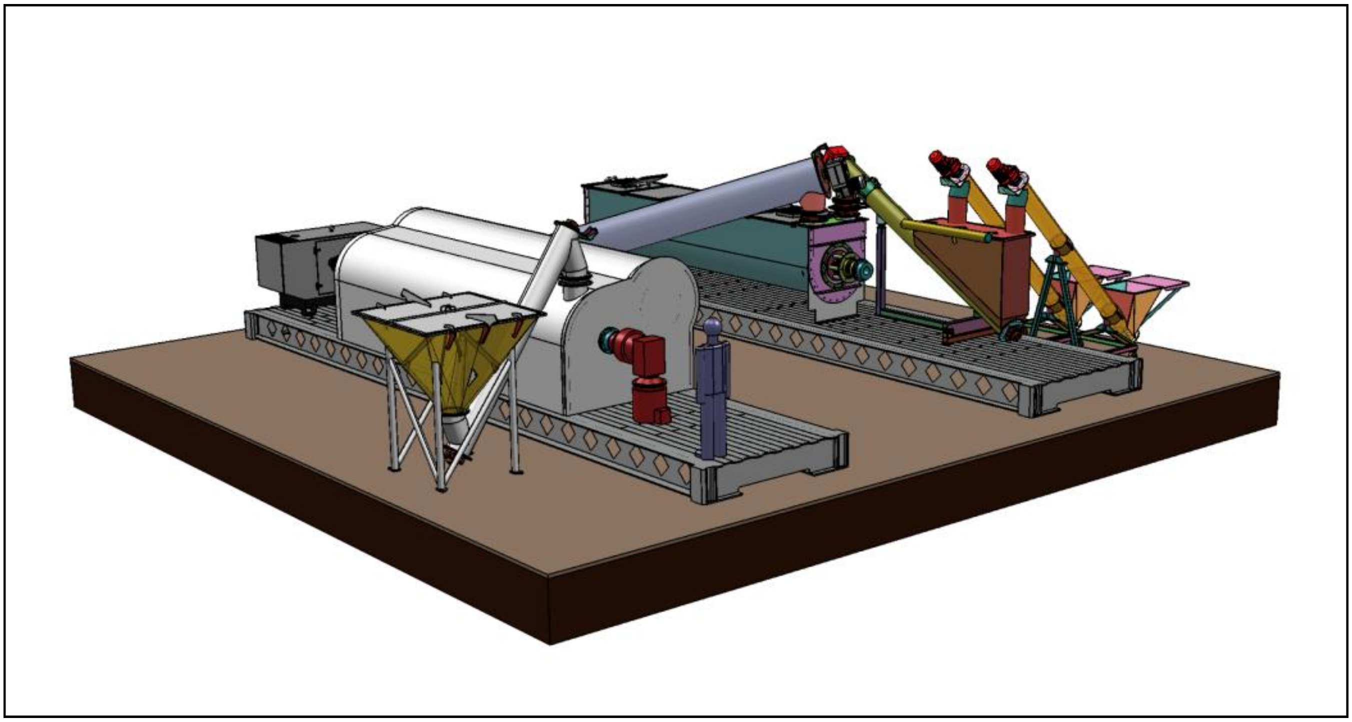
Guidelines for the Development and Testing of Pyrolysis Plants to Produce Biochar



Jane Lynch
Technology Extension Director
International Biochar Initiative

Stephen Joseph
Technical Director
International Biochar Initiative

International Biochar Initiative

www.biochar-international.org

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Disclaimer: *This document has been produced as a guideline to provide advice on equipment design and testing and biochar application. It is not an exhaustive guideline and does not provide comprehensive evaluation of the potential hazards possible in the design and testing of pyrolysis plants. The International Biochar Initiative accepts no responsibility and recommends the use of professional engineers for proper system design.*

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1. INTRODUCTION

This document was produced to assist in the development and testing of small pyrolysis plants and provides advice on equipment design and testing as well as the specification and testing of the biochar product.

The International Biochar Initiative encourages innovation and development of biochar production technologies at all scales. Because there are personal and environmental health and safety risks inherent in producing biochar, IBI has developed these Guidelines to assist in the safe and effective development and testing of biochar production technologies. The top concerns are to:

- Ensure the safety of equipment operators and the general public
- Minimise emissions of atmospheric contaminants
- Produce biochar that is suitable for soil application (refer to documentation of International Biochar Initiative's Characterisation Workgroup for parameters).

IBI seeks to promote biochar for environmental management and biochar production methods which are safe and beneficial for people and the environment. You can find more information about the IBI and about biochar at the IBI website:

www.biochar-international.org

1.1 Components of Pyrolysis Plants

Pyrolysis is the thermal degradation of biomass under the absence of oxygen. Pyrolysis results in three products: biochar, non-condensable gases and condensate (tars and water). The proportion of each is a strong function of the feedstock and the operating conditions of the pyrolyser. Some systems (slow pyrolysers) focus on biochar production with syngas as the major co-product, while other systems (fast pyrolysers) focus on bio-oil (condensate) production with biochar as the major co-product. These guidelines focus on slow pyrolysers.

Depending on the size and complexity of the pyrolysis plant, the main components of a pyrolysis plants include: pre-processing equipment (e.g. grinding, drying, chipping, sieves or screens), materials handling (belt conveyors, storage bins) and feeding equipment (feed screws, lock hoppers, feed belts), dryer (as required), biochar kiln, burners including syngas burners, gas cleaning, cooling and/or quenching equipment, instrumentation, and electrical equipment including generators.

The outline of a Functional Specification for Pyrolysis Plant in 2.1.1.1 provides an example of the scope of components which may be part of a plant. The Process Flow Diagram in 2.2 and the Process and Instrumentation Diagram in 2.4 provide illustrations of different pyrolysis plants.

2. THE DESIGN PHASE – SAFE, EFFICIENT, APPROPRIATE

Good quality biochar manufactured safely and efficiently starts with good equipment design.

The biochar community is growing every day. There are people and resources available to assist with the design process. Others may have experienced similar design issues and be able to share commonly experienced pitfalls, problems and solutions. The potential designer of a plant should be acutely aware that there is a range of pyrolysis companies operating world-wide, with a variety of experience and technologies. As much use as possible should be made of prior projects, information and publications before starting a design.

A good place to start connecting to others interested in development of biochar technologies is through internet groups such as:

http://tech.groups.yahoo.com/group/biochar-production/

Using the following guidelines on sound engineering design practice will greatly assist in the development of safe, efficient and appropriate pyrolysis plants.

2.1 Sound Engineering Design Practice

The design process involves the following main steps that will result in a series of documents that together constitute the complete design including design review and documentation:

- Functional Specifications for the pyrolysis plant and the biochar product
- Process Flow Diagram
- Process Instrumentation Diagram
- HAZOP (Hazard and Operability Study)
- Detailed Design and Costing
- Design Review
- Documentation

2.1.1 Functional Specifications

A Functional Specification is the documentation that describes the requested behaviour of an engineered system. The documentation typically describes what is needed by the system user as well as requested properties of inputs and outputs. It should be a coherent document, which allows the reader to appreciate how the entire process works and how it is integrated (if appropriate) and which demonstrates what each major unit operation does and how the material flows from the start to the end. In this case we need to develop

Functional Specifications for both the plant and the biochar product itself.

2.1.1.1 Functional Specification for Pyrolysis Plant

The table of contents of a functional specification could include the following:

1. *Introduction*

   This defines the general philosophy behind the overall process, the objectives of plant performance and product quality the plant must reach and the standards that will be used in the design of the plant. Separate functional specifications, in the form of specification sheets will elaborate in more detail the functions of the unit operations that comprise the overall process. This allows the designer, or design team to focus on issues particular to each unit operation. A process flow diagram with all major process streams should be drafted at this time.

2. *Process Description*

   This may be a simple description or a more detailed analysis of all of the flows of materials and energy through the plant (for more details see Section 2.1.2). The process description is essential for environmental permitting and to help regulatory authorities to understand the nature and objectives of the process.

3. *Major Components (Unit Operations)*

   This will include a detailed specification of the principal unit operations – the plant items that comprise the overall process, from feed reception to discharge of products and wastes from the process.

4. *Components Supplied by Other Manufacturers*

   - Materials Handling Equipment (including the equipment to size, clean and possibly dry the feedstock).
   - Burners (startup, secondary, flare)
   - Instruments
   - Controls

5. *Detailed Component Specification*

   Each of the major components will have a number of sub-components that need detailed specification. For the kiln this could include such things as chimneys, emergency vent, char exit screw, steam injection system.

6. *Control and Electrical System*

7. *Commissioning Plan*

8. *Operating Procedures and Manuals*

2.1.1.2 Functional Specification for the Biochar

As part of preparing a functional specification it is important to first define the desired qualities/properties of the biochar, including:

- Average particle size and true and bulk density
- Water holding capacity, surface area and pore volume
- Surface properties such as degree of hydrophobicity, oxygenated functional groups, concentration of acid and base sites, cation exchange capacity
- Labile and recalcitrant carbon content
- Ash constituent and relative solubility of the minerals
- Acid neutralising ability, pH, available N, P, K

These desired properties then help to define the process conditions in the pyrolysis reactor and the biomass pre-treatment. It is important to recognise that the interactions between the process parameters cannot be treated as independent variables and that the definition of the process conditions will most likely be based on prior art, or laboratory R&D. Designers therefore need to be fully aware of the complexity and trade-offs required in the design of pyrolysis systems and that all may not be achievable in any particular pyrolysis plant. It may be necessary to prioritise desired properties of the end product.

2.1.1.3 Meeting Sustainability and Fit For Purpose Guidelines

IBI and various national biochar groups are promoting the adoption of sustainability standards for biochar production and use. The biochar produced should provide measurable benefits, whether environmental, economic, or social and should be 'fit for purpose'.

Table 2.1 provides a list of potential results from biochar production and use that should be analysed for their impacts and evaluated for sustainability. In addition, the Australian New Zealand Biochar Researchers Network, (2009) provides the following examples of sustainability principles that apply to biochar:

- Soil quality should always be maintained or improved, but never degraded.
- Biochar production should always be able to demonstrate the sustainability of supply for the biomass (and mineral) resources applied.
- Biochar production processes should always be able to demonstrate a genuine "community licence to operate" in addition to any statutory approvals necessary from the prevailing jurisdictions.
- The proposed application of biochar to soil/land should demonstrate, on the balance of probabilities, after seeking appropriate scientific advice and opinions, that the receiving soils and the proposed land use will benefit as anticipated by the application (quantum and characteristics) of the particular biochar materials presented. As an absolute minimum it should be demonstrated that soil quality will not be degraded by the activity.

Table 2.1. Benefits and Disadvantages of Biochar Manufacture and Application

Biochar (and the energy by-products) manufacture and application can:-	Which can present as benefits…	Or as Disadvantages/negative impacts…
(i) Reduce atmospheric Carbon levels	If generated, processed and applied sustainably and efficiently	If sourced unsustainably, processed inefficiently and/or applied inappropriately
(ii) Provide essential ecosystem services as a collateral outcome	If sourced as sustainable yields from appropriate land use allocations	If sourced as a result of inappropriate land use or prioritisation
(iii) Provide sustainable economic opportunities for regional and rural industries	If value is added to residues, uses found for by-products or if symbiotic land use activities are created	Where land use is inappropriately allocated or higher net resource value materials are directed away from food, fibre or higher value applications
(iv) Impact soil quality, fertility, erosion and production	If the activity is conducted so as to improve soil quality, fertility, retention and production	If the activity is conducted so as to deliver negative soil impacts (over-harvesting, intensive monocultures etc.)
(v) Facilitate the remediation of degraded lands	Where the production of biomass yields is from land quite unsuitable for food production	If conducted inappropriately
(vi) Provide local, catchment and global water cycle and management outcomes	If conducted sensitively and with due regard to the prevailing water cycle issues	Where inappropriate planting and over-harvesting etc. deliver any or all of the outcomes as disadvantages
(vii) Deliver net biodiversity outcomes in the soil and above ground	Where such issues are duly considered in the selection of plantings and the conduct of the specific management plan relevant for each locale	Where intensive planting (monocultures) and harvesting deliver negative biodiversity outcomes
(viii) Provide an intensive bioremediation opportunity for certain urban and industrial waste materials	Where the conversion processes have a "community licence to operate" and are conducted with minimal Impact in relation to value achieved	Where collateral Impacts are disproportionately negative with regard to Value achieved
(ix) Improve, maintain or remediate soil quality	Where applied with due regard to demonstrable fitness for purpose	If applied without due regard to actual local needs or receiving soil characteristics

(Adapted from Sustainability Guide for Bioenergy (https://rirdc.infoservices.com.au/items/05-190))

2.1.2 Develop a Process Flow Diagram and Mass and Energy Balances

A process flow diagram specifies all of the inputs and outputs for the plant. Energy and mass balances are useful, if not essential tools to analyse the material flows and energy efficiency of the entire process.

Figure 2.1 illustrates the process flow categories (or unit operations) of the biochar production process from acquisition of the biomass to the application of biochar to soil (including transport (T)). This is only indicative and not definitive for all pyrolysis processes.

Each of the streams into and out of a particular unit operation should have a line number and a detailed description of the amount [in mass flow] units and properties of the input.

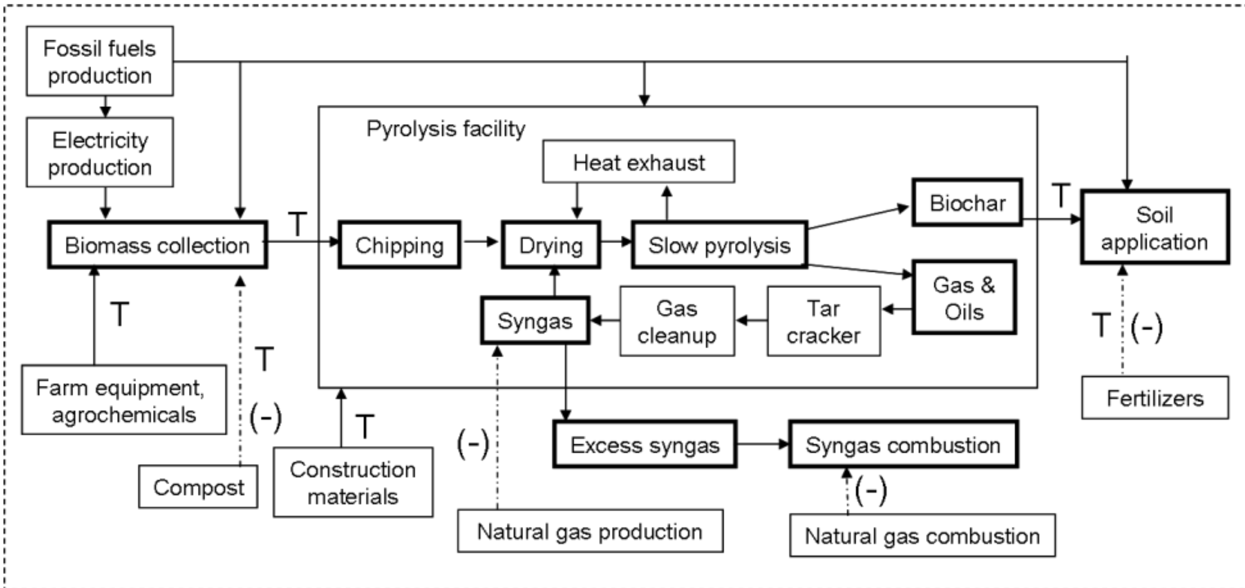


Figure 2.1: Process Flow Diagram for Biochar Production Process ((Roberts et al, 2009)

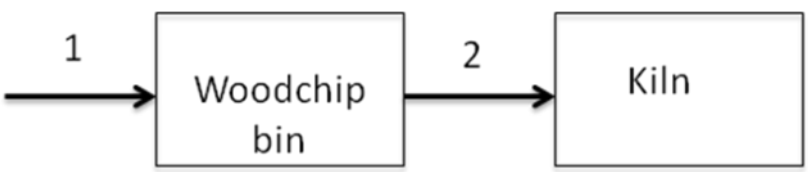


Figure 2.2: Process Flow Diagram for Biochar Production Process

Table 2.2 is an example of a simple method for specifying the amount and properties of the input and output flows to a unit operation. The unit operation illustrated (see Figure 2.2) is for the flow of clean wood into a bin flowing out to the pyrolysis kiln.

A Sankey diagram can be used to help visualise the energy flows through the plant. The Sankey diagram below (Figure 2.3) illustrates the energy balance of a biochar system for corn stover.

A Life Cycle Assessment of the system provides useful analysis of the energy, greenhouse gas and economic aspects of the system. There are several free LCA programmes available, which are specific to bio-energy and these can be tailored to meet specific process requirements, e.g. GEMIS (Global Emission Model for Integrated Systems).

The process flows for each line/stream are then typically summarised on an overall mass balance sheet so that checks can be made on the mass balance and errors/discrepancies found.

Table 2.2. Input and Output Flows for Woodchips to Kiln

Description	Woodchip into Feed Bin (Bobcat)	Woodchips into Kiln
Stream No.	**1**	**2**
Mass Flows		
Feed/Mixture(dry basis), kg/hr	600	600
Water, kg/hr	82	82
Syngas (dry), kg/hr		
LPG, kg/hr		
Char, kg/hr		
Air, kg/hr		
Particulates, kg/hr		
Steam, kg/hr		
Flue (dry basis), kg/hr		
Other, kg/hr		
Total, kg/hr	**682**	**682**
Properties		
Moisture, %wt (wet basis)	12%	12%
Temperature, °C	20	20
Sensible Heat + Latent, kW-h	0	0
Chemical Energy kW-h	3163	3163
Total Energy kW-h	**3163**	**3163**

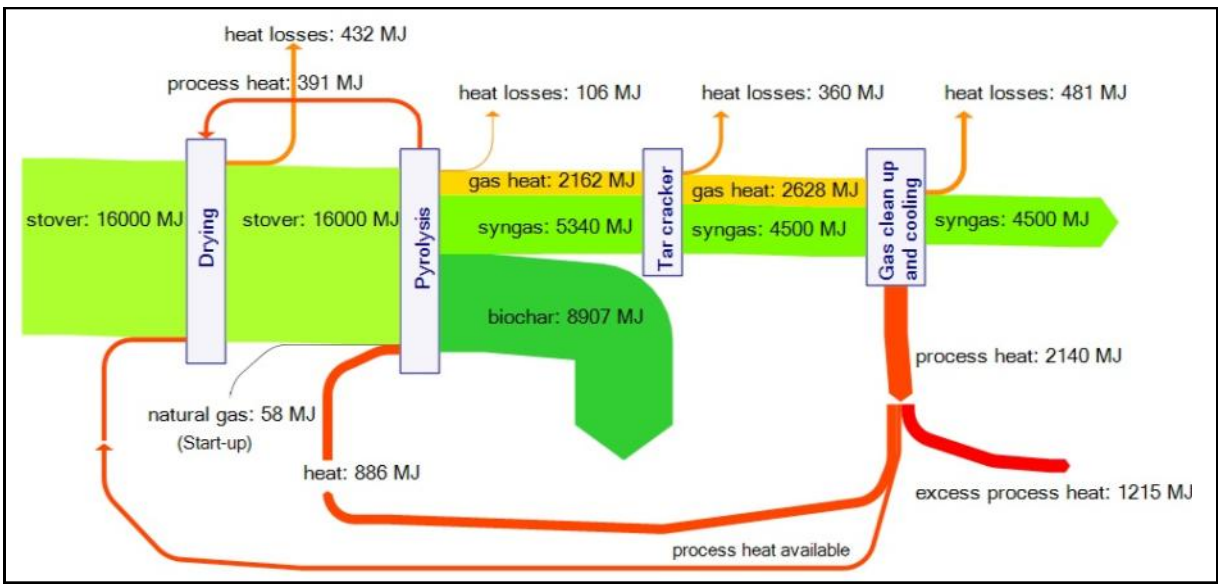


Figure 2.3: Sankey Diagram for Corn Stover (Roberts et al, 2009)

2.1.3 Process and Instrumentation Diagram (PID)

A PID needs to show enough detail that there is sufficient monitoring and control to ensure that the plant is operating to the requirements of the functional specification and is meeting relevant emissions standards. There should be enough instrumentation for safety (see HAZOP) and data collection purposes, but over-instrumentation only adds unnecessary costs to the plant.

Care also needs to given to the provision of certified monitoring equipment for permit compliance in certain areas and the recording of this data on a Programmable Logic Circuit (PLC).

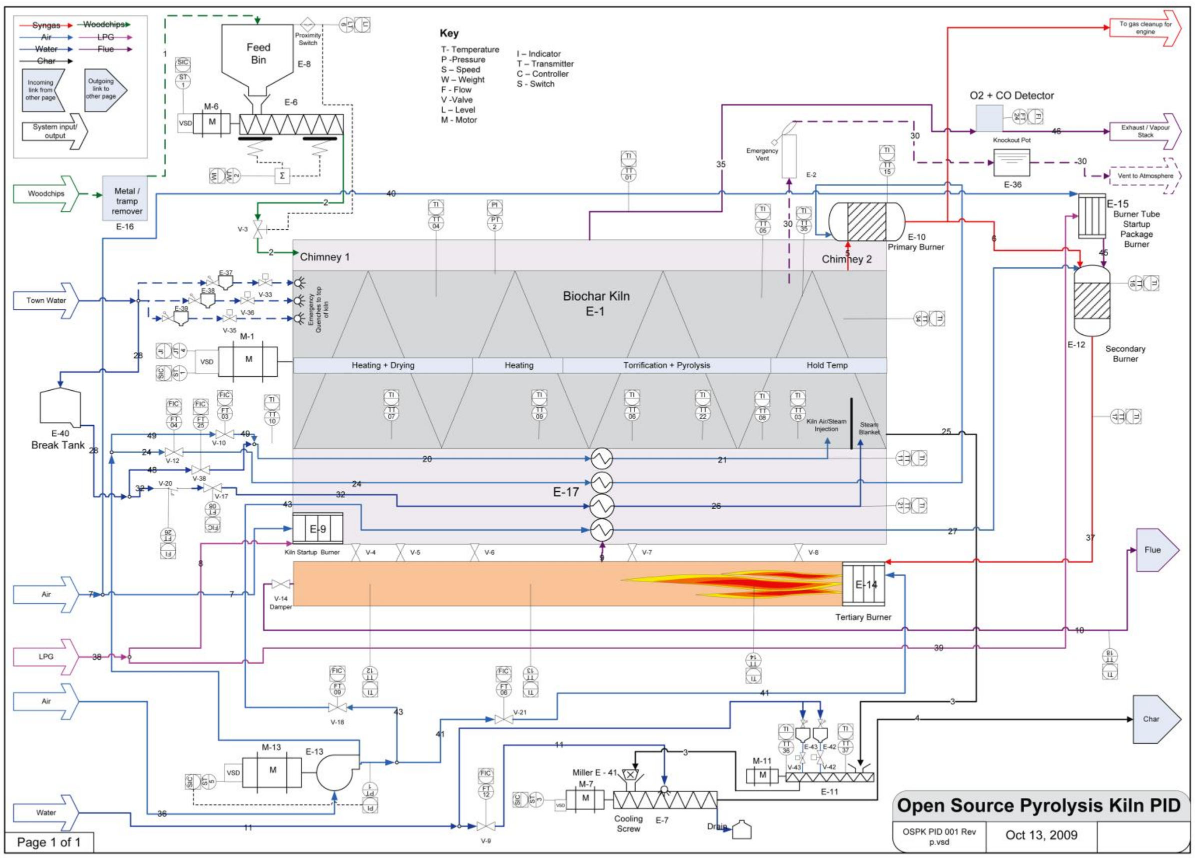


Figure 2.4. Open Source Pyrolysis Kiln Process and Instrumentation Diagram (Joseph, S., 2009) See Appendix D for larger version.

2.1.4 HAZOP Methodology

A HAZard and OPerability study (HAZOP) is a methodology for identifying and managing potential problems in industrial processes, particularly those problems which have the potential to create a hazardous situation. HAZOPs are usefully undertaken by a group of people involved in the design process or with particular expertise, to increase the potential for identifying and discussing issues. It is useful to include at least some people with electrical and mechanical expertise who have not been involved in the design process, who are able to see the design with a fresh perspective.

There are many examples of HAZOPs on the internet and references can be found at http://en.wikipedia.org/wiki/Hazop. There are international and national standards for HAZOPs which can be obtained from the standards regulatory body in each country. An example of a HAZOP process is outlined below in Figure 2.5.

Parameter / Guide Word	More	Less	None	Reverse	As well as	Part of	Other than
Flow	high flow	low flow	no flow	reverse flow	deviating concentration	contamination	deviating material
Pressure	high pressure	low pressure	Vacuum		delta-p		explosion
Tempera-ture	high tempera-ture	low tempera-ture					
Level	high level	low level	no level		different level		
Time	too long / too late	too short / too soon	sequence step skipped	backwards	missing ac-tions	extra actions	wrong time
Agitation	fast mixing	slow mixing	no mixing				
Reaction	fast reaction / runaway	slow reaction	no reaction				unwanted reaction
Start-up / Shut-down	too fast	too slow			actions missed		wrong recipe
Draining / Venting	too long	too short	None		deviating pressure	wrong timing	
Inertising	high pressure	low pressure	None			contamination	wrong mate-rial
Utility fail-ure (instrument air, power)			Failure				
DCS failure			Failure				
Mainte-nance			None				

Figure 2.5. HAZOP Table used to guide a HAZOP identification process. (Wikipedia)

Results of the HAZOP need a detailed record that includes actions to be taken and a log to document that the relevant actions are completed. A responsible person must be nominated to ensure all measures are taken to complete the actions.

It may also be pertinent to carry out other assessments. IBI is working on a separate document that will detail appropriate safety guidelines for biochar production and handling. Once this document is available, it should be consulted as part of the design process as health and safety considerations may change the design of some elements of the process or its operability.

2.1.5 Detailed Design and Costing

Following the HAZOP, in which all hazard and operability concerns should have been addressed, a detailed plant design and costing should be undertaken by a professional engineer.

2.1.6 Design Review

A review of the detailed design and costing is recommended to be conducted by independent experts if possible.

2.1.7 Documentation

All appropriate documentation should be produced. Examples include a Commissioning Manual and an Operation and Maintenance Manual. The operational manuals should use input from the HAZOP and any other safety assessments to ensure that the operation of the system is safe and compliant.

2.2 Design Checklists

Before signing off on a final design, it will be helpful to go over a series of checklists to make sure that all the important factors have been considered. Checklists for health and safety, environmental, technical and economic considerations, and training and staffing needs are give below.

2.2.1 Health and Safety Considerations Checklist

☐ A risk assessment/HAZOP (hazard and operability analysis) should be conducted as an essential part of the design phase of the project. Refer to example HAZOP that was provided in *2.1.4*. A more detailed analysis of risk and safety assessment requirements will be dealt with in a separate document currently in production.

☐ During all phases of the process – loading, start-up, operation, shut-down, unloading and storage – the following risks for operators and the public should be considered, and any relevant regulations adhered to:

- Fire and explosion (including dust explosion on hot surfaces, combustion during storage)
- Particulate and gaseous emissions
- Gas leakage (particularly CO)
- Noise pollution

2.2.2 Environmental Considerations Checklist

☐ Can the equipment operate effectively at design throughputs in a steady state? Does the system require full PLC (programmable logic circuit) control or other intermediate control system?

☐ Does the equipment meet gaseous and particulate emissions standards (or equivalent)? These can be obtained from the local, State or National Environmental Protection Agency (or equivalent). Appendix A lists some regulatory agencies along with their corresponding standards legislation or regulation.

☐ Does the equipment meet relevant standards for noise and odour beyond the site boundary?

☐ Are air, water and soil quality directives complied with?

☐ Are there any specific risks associated with a particular feedstock? For example carcinogens may be produced when pyrolysing certain feedstocks under certain conditions.

☐ Does the feedstock come from a sustainably produced source? This is not directly related to the process and is an indirect consideration in terms of environmental compliance of the process/system.

☐ Does obtaining the use of a particular feedstock have any other negative environmental implications (on humans, animals, plants, biodiversity, water)? This is not directly related to the process and is an indirect consideration in terms of environmental compliance of the process/system.

☐ Is the equipment able to produce biochar with suitable quality and soil amendment characteristics? Does the biochar have any components which are toxic to certain organisms or plants growing in the soil?

☐ Does the plant instrumentation provide sufficient data on the process so that a life cycle analysis may be performed to measure the energy, greenhouse gas and economic benefits of the process?

☐ Are there any solid or liquid (e.g., tar) wastes to be disposed of? What are the relevant regulations and how will this/these material/materials be effectively dealt with?

2.2.3 Technical Considerations Checklist

☐ Have the materials, components and manufacturing process been appropriately selected such that they can withstand temperature, pressure and weight stresses during operation?

☐ Have all relevant manufacturing standards [e.g., EU Machinery Directive] been complied with? Does the equipment have the appropriate rating for certain area classifications such as the ATEX rating for explosive atmospheres in the EU?

☐ What pressure relief system provision is there to prevent/minimise deflagrations?

☐ Is the equipment suitable for locally available feedstocks, providing they meet the defined specifications? What deviation from the specification is permissible without causing problems?

☐ Is the equipment able to be manufactured and repaired appropriately and economically under local conditions?

☐ What warranties are offered on sub-contracted items and what level of support can be expected and for how long?

☐ How will the syngas (gas produced from pyrolysis of feedstock) be treated? Does it meet emissions standards if emitted untreated? Will it be flared, utilised for pyrolysis or as an energy source?

☐ What pre- or post-processing of feedstock/biochar is needed? For example pre-processing could involve grinding or sieving the material and post-processing could involve the mixing of biochar with other materials to form a biochar mineral complex.

2.2.4 Economic Considerations Checklist

☐ What is the cost of the feedstock (or economic gain through avoidance of paying for waste disposal)?

☐ How much does the pyrolysis equipment cost?

☐ How much does operating the equipment cost?

☐ What other costs or benefits should be taken into account? What are the boundaries of the biochar 'system' being analysed (for example costs and benefits outside of the actual production and application of biochar such as transport reduction in fertiliser use, etc.)?

☐ Is there an overall economic benefit?

2.2.5 Training and staffing Checklist

☐ What level of training is required for plant operation?

☐ How many shifts will the plant require to operate it?

☐ How will staff be trained and what proof can be provided or certificated that they are proficient in its operation?

☐ Are all staff fully aware of the nature of the process, operating conditions, safety considerations and potential hazards?

☐ Who is responsible for plant commissioning, start-up and handover?

☐ Are long term operation and maintenance contracts available from the plant provider (if purchased)?

3. THE SETUP PHASE - BEFORE TESTING STARTS

Looking forward to commencing plant operations, it will be useful to consider site specific and local restrictions that you may encounter during setup. Some of these are listed below.

3.1 Test Location

The following would be part of risk assessment and site assessment surveys:

☐ Are there any zoning restrictions in the area? For example such equipment may only be able to be tested in areas zoned industrial rather than residential or commercial. Are any permits required to install and operate the equipment? This should be checked with the relevant local government authority.

☐ Review noise, dust, odour and air pollution requirements, as addressed during the design phase.

☐ Ensure you are working in an outdoor or well ventilated area.

☐ Check for fire hazards such as trees, grasses or buildings close by to the test site.

3.2 Occupational Health and Safety

☐ Refer to relevant occupational health and safety regulations to ensure compliance. Provide personal safety equipment for the operator or others in the immediate vicinity, such as:

- Eye protection (safety glasses, goggles)
- Lung protection (mask, ventilator)
- Ear protection (ear plugs, ear muffs)
- Heat protection (appropriate gloves, clothing)
- Foot protection (steel capped boots)

☐ Protect the public. For example, restrict access to the test area by fences and signs.

☐ Provide for CO leakage detection.

☐ Make sure evacuation procedures are in place according to relevant safety regulations.

☐ Provide fire fighting equipment and training according to relevant safety regulations

☐ Make available emergency equipment, e.g., first aid, shower/eyewash.

☐ Make sure there is adequate local ventilation.

3.3 Storage and Handling of Feedstock and Biochar

☐ Ensure proper storage and handling equipment and procedures as per *5.1 Feedstock Preparation, Storage, Handling and Loading* and *5.4 Unloading, Storage and Handling of Biochar.*

☐ Special issues involved with handling and storing biomass include spontaneous combustion and pest infestation. Appropriate measures should be taken to avoid these.

3.4 Preparation of Equipment Required for Testing

Make sure that all of the following are at hand before you begin testing:

- Storage and handling equipment (e.g. bins, shovels, machinery, etc).
- Quenching water sprayer.
- Data collection measurement equipment as per *6.1 Measurement Equipment Required.*

4. TESTING THE PLANT - WHAT DO WE WANT TO KNOW?

While the equipment has been designed around certain process parameters, it is likely that only through experimentation and testing is it possible to ascertain the actual capabilities. It is advisable to determine in advance what parameters are most important to measure so that the proper measurement protocols can be developed.

Note: This does not apply to commercial plants with performance guarantees.

4.1 Optimal feedstock characteristics

Begin with the feedstock. These are the feedstock parameters you need to know:

- The types of feedstock that the equipment can reliably pyrolyse

- The quantity or feed rate (kg, lb or tonne/hr)
- Particle size range
- Moisture content range
- Ash content (and possibly composition)

4.2 Operating procedures that produce desired product characteristics

Below are the operating conditions that will determine the product characteristics:

- Heating rates for each of the phases (see below)
- Time held at intermediate and final temperatures
- Reactor temperature profile and limits on temperatures
- Addition of reagents to the process or specific atmosphere in the process

The pyrolysis process can be divided into the following phases:

1. **Drying**—Drying occurs as the biomass feedstock is heated up to approximately 120-150°C and the moisture evaporates.
2. **Torrefaction**—Torrefaction involves heating the biomass until it starts to depolymerise, giving off a range of low molecular weight compounds. This occurs between approximately 150°C and 250°C.
3. **Pyrolysis**—Pyrolysis begins around 250°C and can be initiated either in the absence of air or with small amounts of air. Some pyrolysis units use the syngas (gas produced during the pyrolysis of biomass) to torrefy and then pyrolyse the biomass. Manufacturers of equipment specify heating rates and holding temperatures and times (in some cases). Such information for similar units may assist with estimating these parameters for the particular unit being tested.

4.3 Biochar produced

You will want to measure the quantity of biochar produced; along with various properties of the biochar produced, for example:

- Beneficial properties as a soil amendment
- Chemical, physical and nutrient properties that can be measured
- Recalcitrance for carbon sequestration
- Ability to hold moisture
- Particle size (handling implications if very dusty)

Refer to documentation of the International Biochar Initiative's Characterisation Workgroup for more detailed information.

4.4. Gas produced

For purposes of use as an energy source and for meeting emissions standards, you will want to measure the following properties of the pyrolysis gas:

- Composition (CO, CO_2, CH_4, H_2, N_2O, NO, NO_2, H_2S), VOC and acid gases. Note that the analysis of these gases may need to be undertaken by specialists
- Quantity
- Water content of the gas may also be important
- Energy value

5. OPERATING THE PLANT SAFELY AND EFFICIENTLY

Most accidents occur in combustion and pyrolysis plants during start-up and shut-down, but it is important to remain vigilant during all phases of the production process. Development of a standard operating procedure or manual for the equipment is a good way to minimise risks for operators.

Following are some guidelines for operating procedures which can be adapted to your particular plant. See also *Appendix B: Gasifier Testing* for further test procedures which can be adapted.

5.1 Feedstock preparation, storage, handling and loading

☐ Biomass feedstocks may contain dust, bacteria or moulds. Handlers should use appropriate lung, nose and eye protection.

☐ Feedstocks should be protected from getting wet, as this may lead to rotting as well as increasing the amount of energy required to dry the biomass prior to pyrolysis. It is possible for dust explosions to occur on hot surfaces so dust should be minimised and any dust control regulations adhered to.

5.2 Start-up and Shut-down

☐ It is desirable to purge the system with nitrogen, exhaust gas from an engine or steam before start-up to remove the oxygen so that no flammable gases are remaining which could lead to explosion on start-up.

☐ Operators should remain aware that most accidents occur during start-up and shut-down.

☐ Emergency shut-down procedure should be developed in case of incident, for example shutting down any external heat/flame source (e.g. burners), flaring flue gases.

☐ An auxiliary source of heat is needed to warm up the unit during start-up (e.g. biomass, LPG, natural gas, kerosene).

☐ During shutdown, and while pyrolysis is ongoing, an auxiliary source of heat may be required to ensure unburnt syngas is not polluting, i.e. in a thermal oxidiser or flare.

5.3 Operation and Monitoring

☐ In the early stages of operation the initial gases should be sent to a flare or thermal oxidiser.

☐ The feedstock should be heated at appropriate rates and held for the time and temperatures specified in the design.

☐ Times, temperatures and emissions can be monitored as per *Section 6. Data Collection.*

☐ Plants should preferably be PLC controlled.

☐ The operator(s) should be monitoring the plant operation at all times.

☐ Safety advice will dictate a minimum number of staff required to work on a plant at any time.

5.4 Unloading, Storage and Handling of Biochar

☐ Care should be taken when opening and unloading the plant as the addition of air can cause combustion or explosion, depending on the exact nature of the product and the conditions of exposure. Testing of char samples by a recognised authority should be carried out to assess its pyrophoricity, especially if the material is to be transported to another site. This will also impact on other safety/handling requirements.

☐ Appropriate safety equipment for heat and dust (eye, nose, lung, gloves, clothing, etc) should be worn during unloading of the biochar.

☐ Biochar may be quenched by spraying a small amount of water on it or mixing with a clay slurry to avoid combustion. Again, this depends on the condition of the char, as cold chars from wood are generally not pyrophoric.

☐ Biochar should be stored in sealed containers or vessels and stored in a covered area, protected from wind and rain, and far from fire hazards in case of combustion.

5.5 Maintenance

☐ Ensure regular maintenance of the plant, including cleaning, testing of valves, electrical equipment, etc. as per manufacturers/suppliers schedules.

☐ Make sure instruments are calibrated on a regular schedule.

6. DATA COLLECTION

Data collection from your pyrolysis unit is valuable in assisting with:

- Understanding how the pyrolysis process is working and the effect it has on the biochar produced
- Providing quantitative data for an iterative engineering design process leading to improvements in plant design and operation and subsequent biochar quality
- Calculating fuel consumption, biomass feedstock consumption, biochar yield, heat transfer, efficiency
- Calculating greenhouse gas and energy benefits
- Measuring emissions in order to meet environmental and health regulations
- Contributing to the knowledge and development of the biochar industry as a whole

6.1 Measurement Equipment Required

- Thermocouples (to measure temperatures inside pyrolysis equipment and flue gas) connected to data logger for continuous temperature measurement if possible
- Gas analysis equipment (to measure CO, CO_2, H_2, CH_4, NO_x, N_2O. Emissions can be measured using a personal monitor or a hood attached to a gas chromatograph or portable gas analyser
- Gas flow meters (to measure flow rate of output gas)
- Scales (to measure mass of feedstock and biochar produced)
- Oven (to dry feedstock in order to calculate moisture content)
- Pressure measurement equipment to alert of blockages in pipes (for example due to tar condensation)

Note: It is imperative that calibration of all instruments according to their operation manuals is carried out at the recommended intervals.

6.2 Data Collection: Inputs

Table 6.1 lists the properties of the feedstock and other process inputs that are important to measure.

Table 6.1 Data to Be Collected on Feedstock and Other Process Inputs

	Feedstock characteristics	**Units**
(a)	Type of material	e.g. wood, bagasse, corn stover, etc
(b)	Moisture content	%
(c)	Initial mass of feedstock	kg
(d)	Average particle size	mm
(e)	Feedstock analysis (laboratory)	% C, O, H, N, ash
(f)	Ash (mineral) content	% K, P, Ca, Mg, Na, Fe, Cl, S, etc
	External inputs	
(g)	Auxiliary power (from engine or mains power (kW) or heat from gas burner(MJ/hr))	MJ/hr
(h)	Air, steam (if any)	m^3/hr
	Other	
(i)	Feed rate if continuous feed equipment	kg/hr

6.3 Running the Equipment: Conditions and Variables

Temperature and time held at temperature will influence the quality of biochar produced. Therefore it is recommended that different conditions be methodically trialled. In order to be successful in determining the results from different process conditions, you will need to insert thermocouples inside the reactor and also in the outlet gas stream. See *Appendix C: Process and Instrumentation Diagram*, for one possible distribution of thermocouples in a pyrolysis plant.

Record temperature with a continuous data logger if possible, or at regular intervals to determine heating rate. See Table 6.2 for a guide to the parameters and conditions that should be measured

6.4 Data Collection: Outputs

It is recommended that gaseous emissions be measured anywhere there is a point source. It is recommended that dioxin and furan emissions be measured if municipal solid waste (MSW) is being pyrolysed, according to government regulations. IBI recommends a full set of emissions tests and comparison to local emissions regulations to ensure compliance. See Table 6.2 for a list of output measurements.

Table 6.2 Process Conditions and Parameters

	Initial conditions	Units
(a)	t_0 (time at start of heating)	°C
(b)	T_{int} (internal temperature)	°C
(c)	T_{out} (outlet/flue gas temperature)	°C
(d)	Flue gas composition	%CO, CO_2, H_2, CH_4, N_2, NO_x
(e)	m_{out} (mass of flue gas) NB: measuring the mass of flue gas is difficult unless you have access to pitot tubes or annubars. The alternative is to use the mass balance equations to calculate the mass, based on flue gas composition and mass balance on the input feed and output biochar	kg/hr
(f)	Flow rate of flue gas through the chimney	m^3/hr
(g)	P_{int} (pressure inside pyrolysis unit)	
	Pyrolysis conditions	
(h)	t_{p0} (time at start of pyrolysis)	°C
(i)	t_{pend} (time at end of pyrolysis)	°C
	Record (b) to (g) at t_{p0}	
	Record (b) to (g) at t_{pend}	
	Final conditions	
(j)	t_{end} (time at end of cooling)	°C
(k)	Record (b) to (g) at t_{end}	

Table 6.3 Data to Be Collected on Process Outputs

	Biochar characteristics	Units
(a)	Mass of biochar produced	kg
(b)	Average particle size	mm
(c)	Biochar analysis (laboratory)	%total C, O, H, N
(d)	Ash (mineral) content	% K, P, Ca, Mg, Na, Fe, Cl, S, etc
	Analysis of flue gas and gas from oxidiser/engine	
(e)	Total quantity of gas produced	kg
(f)	Total quantity of each gas	kg CO, CO_2, H_2, CH_4, N_2, NO_x,
(g)	Quantity of gas produced for emissions standards purposes	ppm NO_x, kg CO, CO_2, CH_4. From the engine VOCs, SO_x, and acid gases

6.5. Quality Control

Biochar should be sampled at different points throughout the process and tested as extensively as budgetary constraints allow in order to establish the process conditions that produce a high quality product. This section outlines the range of biochar testing, in addition to the laboratory analyses mentioned in Table 6.3.

6.5.1 Eco-toxicity Testing

To determine the suitability of a biochar material for improving soil health and agronomic performance, a minimum set of eco-toxicological assessments need to be undertaken. These tests will not guarantee the biochar has a positive influence on crop performance; however, they will assess any potential harm a poorly-produced biochar may impart in soil. Table 6.54 below gives analyses for the eco-toxicological assessment of biochar. Simple versions of these tests are described in IBI's A Guide to Conducting Biochar Trials (Major, J., 2009).

Table 6.4 Ecological Toxicity Testing of Biochar

Required analysis	Recommended method	Minimum criteria to be termed biochar (or notes)
Earthworm avoidance	Toxicity testing conducted using the Organisation for Economic Co-operation and Development (OECD) earth-worm avoidance method (OECD, 1984) as described in Van Zwieten et al., 2004. *Biochar is applied into OECD standard soil at a rate of 1% w/w, with 10 replicates.*	Biometrical analysis against controls should show no biometrically significant earthworm avoidance to the biochar treatment.
Germination inhibition assay	Germination inhibition is tested against three test species using OECD standard soil (OECD 2004). Method descrip-tion in Van Zwieten et al., 2009.	Biometrical analysis against controls should show no biometrically significant decrease in plant germination.

(Australian New Zealand Biochar Researchers Network, 2009)

6.5.2 Germination Testing

Simple germination testing is a basic test which can be carried out on site to ensure seeds are able to germinate in the biochar amended soil.

6.5.3. Adsorption and Cation Exchange Capacity Testing

Adsorption Capacity and Cation Exchange Capacity (CEC) are difficult to measure, but are important in understanding biochar's role in the soil. Adsorption capacity is the extent that biochar has activated carbon properties. CEC is the extent to which biochar has ion exchange properties. Many biochars exhibit significant and measurable amounts of CEC and adsorption capacity. Tests for these two qualities are described in, *"All Biochars are Not Created Equal, and How to Tell Them Apart",* (McLaughlin et al 2009).

6.5.4 Agronomic Testing

Once biochar is produced that is not harmful to plants, more extensive testing can be carried out to refine the operation of the pyrolysis production plant. If the eco-toxicity and germination tests are positive, it is recommended that agronomic testing be undertaken by a certified soil testing laboratory. An example of a comprehensive agronomic test for biochar is shown in Figure 6.1.

Laboratory No		Limit of	
Sample ID	Unit	reporting	
EC	dS/m	0.01	**2.9**
pH (CaCl2)	pH units	0.04	**6.0**
Colwell Phosphorus	mg/kg	2	**2100**
Bray Phosphorus	mg/kg	0.06	**1400**
Total Nitrogen	%	0.02	**1.1**
Total Carbon	%	0.2	**21**
KCl Extractable Ammonium-N	mg/kg	0.3	**34**
KCl Extractable Nitrate-N	mg/kg	0.2	**<0.2**
Organic Carbon	%	0.05	**17**
Total Elements			
Aluminium	%	0.00024	**1.4**
Arsenic	mg/kg	3	**<3**
Boron	mg/kg	1.9	**12**
Calcium	%	0.00016	**4.6**
Cadmium	mg/kg	0.9	**1.2**
Cobalt	mg/kg	1.2	**6.3**
Chromium	mg/kg	1	**27**
Copper	mg/kg	0.9	**24**
Iron	%	0.00016	**1.7**
Potassium	%	0.0038	**0.69**
Magnesium	%	0.0001	**0.38**
Manganese	mg/kg	1	**1400**
Molybdenum	mg/kg	1.2	**<1.2**
Sodium	%	0.0007	**0.30**
Nickel	mg/kg	1.3	**8.9**
Phosphorus	%	0.0003	**1.1**
Lead	mg/kg	1.7	**10**
Sulfur	%	0.0022	**0.15**
Selenium	mg/kg	6.6	**<6.6**
Zinc	mg/kg	1.1	**97**

Laboratory No		Limit of	
Sample ID	Unit	reporting	
Exchangeable Cations	cmol(+)/kg	0.034	
Aluminium	cmol(+)/kg	0.013	**1.6**
Calcium	cmol(+)/kg	0.085	**29**
Potassium	cmol(+)/kg	0.003	**8.3**
Magnesium	cmol(+)/kg	0.001	**9.9**
Manganese	cmol(+)/kg	0.037	**2.5**
Sodium			**11**
Exchangeable Cations with pre digestion			
Aluminium	cmol(+)/kg	0.034	**5.3**
Calcium	cmol(+)/kg	0.013	**80**
Potassium	cmol(+)/kg	0.085	**9.3**
Magnesium	cmol(+)/kg	0.003	**17**
Manganese	cmol(+)/kg	0.001	**4.5**
Sodium	cmol(+)/kg	0.037	**12**

Figure 6.1 An Example of a Comprehensive Agronomic Test for Biochar

6.5.5 *Field Trials*

Field trials are the final step in testing the efficacy of the biochar. See IBI's "A Guide to Conducting Biochar Trials" (Major, J., 2009). This guide is available as a free downloadable pdf file on the IBI web site at www.biochar-international.org/publications/IBI.

6.6 Data Analysis

Appendix B provides some of the equations required to calculate relevant pyrolysis plant characteristics.

APPENDICES

APPENDIX A: EXAMPLES OF ENVIRONMENTAL PROTECTION LEGISLATION

Please note: This Appendix gives a few examples of environmental protection authorities at National and State or Provincial levels and the legislation they administer. Please contact your local authority for information relevant to your location.

Australia
Department of the Environment, Water, Heritage and the Arts
www.environment.gov.au
Environment Protection and Biodiversity Conservation Act
www.environment.gov.au/epbc/index.html

India
Ministry of Environment and Forests
www.moef.nic.in/index.php
The Air (Prevention and Control of Pollution) Act
www.envfor.nic.in/legis/air/air1.html

New Zealand
Ministry for the Environment
www.mfe.govt.nz

UK/Europe
Environment Agency (Emissions and Pollution)
www.environment-agency.gov.uk/
DEFRA (Waste Incineration)
http://www.defra.gov.uk/environment/index.htm
European Union Environment IPPC
http://ec.europa.eu/environment/air/pollutants/stationary/ippc/index.htm

United States - National
United States Environmental Protection Agency
www.epa.gov
Clean Air Act
www.epa.gov/lawsregs/laws/caa.html

United States –State of California
California Environmental Protection Agency
www.calepa.ca.gov
Laws and Regulations
www.arb.ca.gov/html/lawsregs.htm

APPENDIX B: GASIFIER TESTING

The following test procedures for gasifiers may be adapted for use with small pyrolysis plants. They contain information on operation, maintenance and safety considerations which is highly applicable to small pyrolysis plants.

Guideline for Safe and Eco-Friendly Biomass Gasification
Intelligent Energy Europe
www.gasification-guide.eu/

Test Procedures for Gasifier Systems
Indian Institute of Technology, Mumbai
www.me.iitb.ac.in/~garp/sit2000_dual_fuel.pdf
www.me.iitb.ac.in/~garp/sit2000_sipge.pdf
www.me.iitb.ac.in/~garp/sit2000_thermal.pdf

APPENDIX C: EQUATIONS FOR BASIC DATA ANALYSIS

1. Gas Analysis

Total quantity of gas produced:

$m_{gas\ total}$ (kg) = Flow rate (m^3/s) x gas density (kg/m^3) x time (s)

Energy value of gas produced:

$Q_{gas\ out}$ (kJ) = $m_{gas\ total}$ (kg) x $CV_{gas\ out}$ (kJ/kg)

Where CV is the calorific value.

Quantity of each component gas, eg carbon dioxide:

m_{CO2} (kg) = Flow rate (m^3/s) x gas density (kg/m^3) x time (s)

NOx or other emissions as per gas chromatograph measurements to be compared with emissions standards.

2. Char Yield

Biochar yield (%): $$\%y_{char} = \frac{100 m_{char}}{m_{biomass}}$$

Biochar volatile matter content (%): $$\%VM = \frac{100\ m_{char} - m_{cc}}{m_{char}}$$

Biochar ash content (%): $$\%A = \frac{100 m_{ash}}{m_{char}}$$

Biochar fixed-carbon content (%): $$\% fc = 100 - \%VM - \%CA$$

Biochar fixed-carbon yield (%): $$\%y_{fc} = \%y_{char}\left[\frac{\% fc}{100\ 1 - m_{ash} / m_{biomass}}\right]$$

Where

$m_{biomass}$ = dry biomass mass [kg]

m_{char} = dry char mass after pyrolysis [kg]

m_{cc} = dry mass of carbonised carbon determined in proximate analysis according to ASTM D 1762-84 [kg]

m_{ash} = dry ash mass determined in proximate analysis according to ASTM D 1762-84 [kg]

3. Mass Balance

Mass Balance

$m_{feedstock\ in} + m_{air\ in} = m_{biochar\ out} + m_{gas\ out\ (CO\ +\ CO2\ +H2\ +\ CH4\ +\ N2\ +\ CxHyOz\ +CaHb)}$

APPENDIX D. PROCESS INSTRUMENTATION DIAGRAM

See the diagram at right for an example of a Process Instrumentation Diagram (PID). This particular PID was produced by Stephen Joseph for Cornell University.

REFERENCES

Australian New Zealand Biochar Researchers Network (2009) Guidelines for a Safe Biochar Industry, http://www.anzbiochar.org

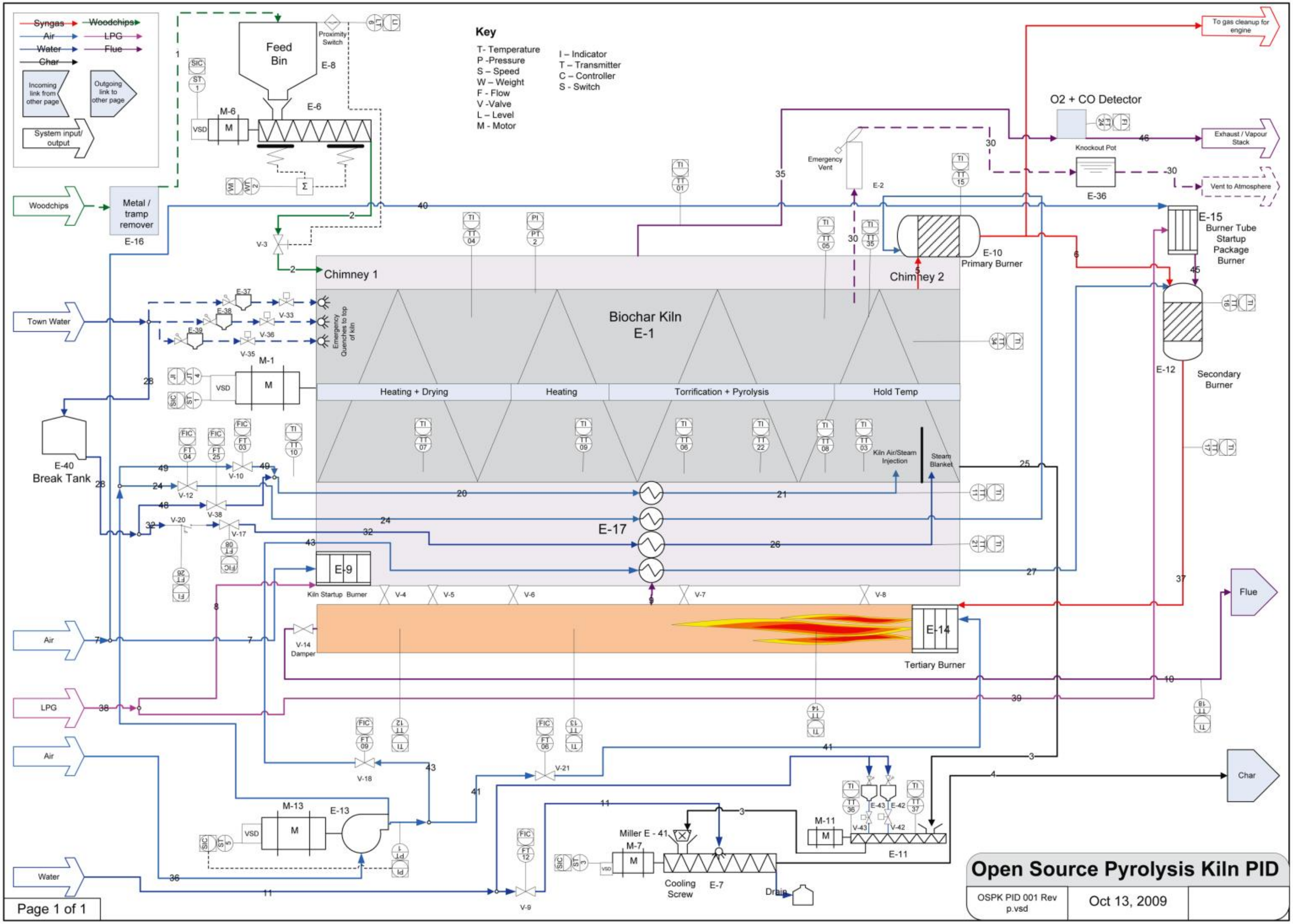
Joseph, S. (2009) Open Source Pyrolysis Kiln, for Cornell University.

Lehmann, J. and Joseph S. (2009) Biochar for Environmental Management: Science and Technology, London, UK, 416 pp.

McLaughlin, H., Anderson, P. S., Shields F. E., Reed T. B. (2009) All Biochars are Not Created Equal and How to Tell them Apart, North American Biochar Conference, Boulder, CO, http://www.biochar-international.org/node/1029

Major, J. (2009) A Guide to Conducting Biochar Trials, International Biochar Initiative, http://www.biochar-international.org/sites/default/files/ IBI%20Biochar%20Trial%20Guide%20final.pdf

Roberts K, Gloy B, Joseph S, Scott N and Lehmann J (2010) Life cycle assessment of biochar systems: Estimating the energetic, economic and climate change potential, Environmental Science and Technology 44, 827–833.



Open Source Pyrolysis Kiln PID
OSPK PID 001 Rev p.vsd
Oct 13, 2009
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Key
T- Temperature
P -Pressure
S – Speed
W – Weight
F - Flow
V -Valve
L – Level
M - Motor
I – Indicator
T – Transmitter
C – Controller
S - Switch
Syngas
Woodchips
Air
LPG
Water
Flue
Char
Incoming link from other page
Outgoing link to other page
System input/ output
Woodchips
Metal / tramp remover
E-16
Feed Bin
E-8
Proximity Switch
E-6
M-6
Town Water
E-40 Break Tank
Air
LPG
Water
Biochar Kiln E-1
Chimney 1
Chimney 2
Heating + Drying
Heating
Torrification + Pyrolysis
Hold Temp
Emergency Quenches to top of kiln
Kiln Air/Steam Injection
Steam Blanket
E-17
E-9
Kiln Startup Burner
V-14 Damper
E-14
Tertiary Burner
E-10 Primary Burner
E-2
Emergency Vent
O2 + CO Detector
Knockout Pot
E-36
To gas cleanup for engine
Exhaust / Vapour Stack
Vent to Atmosphere
E-15 Burner Tube Startup Package Burner
E-12
Secondary Burner
Flue
Char
M-13
E-13
Miller E - 41
M-7
Cooling Screw
E-7
Drain
M-11
E-11