# PROCEDURE

# ON BIOMASS POWER PLANT ACCEPTANCE TEST AND PERFORMANCE ASSESSMENT FOR FEED-IN TARIFF (FiT) PROJECTS IN MALAYSIA


**SUSTAINABLE ENERGY DEVELOPMENT AUTHORITY (SEDA)**

**MALAYSIA**



**2013**

# FOREWORD

The enforcement of the Renewable Energy Act 2011 (Act 725) on 1st December 2011 has enabled the Feed-in-Tariff (FiT) mechanism to be implemented in Malaysia paving for a sustainable for renewable energy (RE) growth trajectory for the RE Industry in Malaysia including biomass and biogas. Both RE resources have shown promising development and it could be seen from the number of projects which has benefited from the FiT mechanism. Biomass coming from plantation sector especially from the palm oil industry waste such as empty fruit bunches (EFB) and palm oil mill effluent (POME) has a huge potential to be tapped for power generation. SEDA Malaysia, being the agency responsible for facilitation of RE growth is playing its role to ensure installations especially those under the Feed-in Tariff (FiT) mechanism meet and complying to the international standards in terms of quality, reliability and safety which will indirectly impact the performance of the biomass power plants.

**The Procedure on Biomass Power Plant Acceptance Test and Performance Assessment** for Feed-In Tariff is prepared to provide assistance to the Feed-in Approval Holders (FiAHs) under the biomass category. The scope of this Procedure is only relevant to biomass resources which refer to lignocelluloses materials such as palm empty fruit bunches (EFB), mesocarb fibre, palm kernel shell, woods, logs, branches, tree stumps, saw dust, wood chips, bark and wood pellets but does not include municipal solid waste (MSW) and any paper or products treated with paint or glue. This Procedure is useful when preparing the plant performance assessment and for continuous performance assurance reporting by the biomass project developers in preparing test report for FiT commencement date (FiTCD). The test report is important as it will be used to determine the expected performance of the biomass power plants.

I would like record my deep appreciation to Malaysia Palm Oil Board (MPOB), Energy Commission, Tenaga Nasional Bhd (TNB), developers and technology providers who has deliberated exhaustively and contributed in giving inputs in the process of preparing the Procedure.

Lastly, I would also like to thank Energy Institute Malaysia for assisting SEDA Malaysia develop the Procedure on Biomass Power Plant Acceptance Test and Performance Assessment which will be an important document for use by the RE industry players.

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# LIST OF ABBREVIATION

| Symbol | Description |
|---|---|
| AF | As-fired |
| AC | Alternating Current |
| ASTM | American Society for Testing and Materials |
| ASME | American Society of Mechanical Engineer |
| B | Heat Credits to the System |
| $B_{Ae}$ | Heat credit supplied by entering air |
| $B_{ze}$ | Heat credit supplied by atomizing steam |
| $B_{fe}$ | Heat credit supplied by sensible heat in fuel |
| $B_{xe}$ | Heat credit supplied by auxiliary drives |
| $B_{mAe}$ | Heat credit supplied from the moisture entering with the inlet air |
| $C$ | Carbon |
| $CO_2$ | Carbon Dioxide |
| CO | Carbon Monoxide |
| $C_b$ | Carbon burned per lb of “as-fired” fuel |
| $C_{pG'}$ | Mean specific heat of the dry flue gas |
| $C_{pA'}$ | Mean specific heat of dry air |
| $C_{Ps}$ | Mean specific heat of steam |
| $C_{pf}$ | Mean specific heat of fuel |
| $C_{Ps}$ | Mean specific heat of steam |
| CW | Cooling Water |
| CAS | Chemical Abstracts Service |
| DC | Direct Current |
| $h_z$ | Enthalpy of atomizing steam |
| $h_{Rv}$ | Enthalpy of saturated vapor |
| $h_{wFW}$ | Enthalpy of feed-water entering unit |
| $h_{wSH}$ | Enthalpy of super-heater spray water |
| $h_{wS}$ | Enthalpy of spray water |
| $h_{wB}$ | Enthalpy of blow-down |
| $h_{wI}$ | Enthalpy of injection water |
| $h_{wL}$ | Enthalpy of leak-off |
| $h_{sSH,O}$ | Enthalpy of steam at super-heater outlet |
| $h_{sR,I}$ | Enthalpy of steam at re-heater inlet |
| $h_{sR,O}$ | Enthalpy of steam at re-heater outlet |
| $H$ | Hydrogen |
| $H_{f'}$ | Laboratory determination by fuel analysis on dry basis |
| $H_f$ | High heat value of the fuel on the “as-fired” basis |

| Symbol | Description |
|---|---|
| $H_{d'p'}$ | High heat value of total dry refuse (laboratory analysis) |
| ISO | International Organisation for Standardization |
| $E_{H_f}$ | Chemical Heat Input from the fuel |
| $E_{out}$ | Total Heat Absorbed by Working Fluid |
| L | Total Losses |
| $L_{UC}$ | Heat loss due to unburned carbon in refuse |
| $L_{G'}$ | Heat loss due to heat in dry flue gas |
| $L_{mf}$ | Heat loss due to moisture in the "as-fired" fuel |
| $L_H$ | Heat loss due to moisture from burning of hydrogen |
| $L_{mA}$ | Heat loss due to moisture in the air |
| $L_Z$ | Heat loss due to heat in atomizing steam |
| $L_{CO}$ | Heat loss due to formation of carbon monoxide |
| $L_{UH}$ | Heat loss due to unburned hydrogen |
| $L_{UHC}$ | Heat loss due to unburned hydrocarbons |
| $L_\beta$ | Heat loss due to surface radiation and convection |
| $L_{[P]}$ | Heat loss due to radiation to ash-pit, sensible heat in slag |
| $L_d$ | Heat loss due to sensible heat in flue dust |
| $L_r$ | Heat loss due to heat in pulverizer rejects |
| $L_w$ | Heat loss due to heat pickup by cooling water entering envelope |
| $m_f$ | Percentage moisture in fuel as determined by analysis of moisture sample |
| $m_G$ | Moisture in the flue gas per lb of "as-fired" fuel |
| $m_p$ | Moisture evaporated in ash-pit per lb of "as-fired" fuel |
| N | Nitrogen |
| NREL | National Renewable Energy Laboratory |
| OEM | Original Equipment Manufacturer |
| O | Oxygen |
| $P_{mG}$ | Partial Pressure Of The Moisture In The Flue Gas |
| $P_A$ | Atmospheric pressure |
| S | Sulphur |
| SAMM | Skim Akreditasi Makmal Malaysia |
| TAPPI | Technical Association of the Pulp and Paper Industry |
| $t_G$ | Temperature of flue gas |
| $t_{RA}$ | Reference Air Temperature |
| $t_A$ | Inlet Air Temperature |
| $t_f$ | Temperature of Fuel |
| $W_{seSH}$ | Steam flow entering super-heater |
| $W_{seRH}$ | Reheat steam flow |

| Symbol | Description |
|---|---|
| $W_{weSH}$ | Super-heater spray water flow |
| $W_{weRH}$ | Reheat spray water flow |
| $W_{fe}$ | Rate of fuel firing (as-fired) |
| $W_z$ | Atomizing steam per lb of "as-fired" fuel |
| $W_{d'p'}$ | Dry refuse per lb of "as-fired" fuel |
| $W_{G'}$ | Dry gas per lb "as-fired" fuel burned |
| $W_{fe}$ | Measured fuel rate |
| Wt | Whole tonne |
| $\eta$ | Efficiency |
| $VM$ | Volatile Matter |

# PART 1 INTRODUCTION

The Feed in Tariff (FiT) is Malaysia's financial mechanism under the Renewable Policy and Action Plan to catalyse generation of Renewable Energy (RE), up to 30 MW in size. The mechanism allows electricity produced from RE resources to be sold to power utilities at a fixed premium price for a specific duration to enable financial viability of RE plant development.

FiT rates had been introduced through RE Act in 2011 to promote RE technology in Malaysia. One of the RE technology which qualifies for FiT is biomass - an abundantly available waste resources from the palm oil industry.

Presently, direct-firing combustion is the primary approach for generating electricity from biomass where the fuel is burned in a boiler to produce high-pressure steam. The steam is then used to drive a steam turbine. The turbine shaft output is connected to an electric generator, to produce electricity. Biomass power boilers are typically in the 20-50 MW range, with typical plant efficiency between 7 – 27% [1]. The conventional direct-firing biomass power plant is illustrated in Fig. 1.

The main sections of a conventional direct-firing biomass power plant are the steam generating unit (boiler) and the turbine-generator. The overall performance of the power plants depends on the performance of each of this section, indicated by numbers of key performance indicators.

This guideline shall provide the principle methodology for assessment of a conventional direct-firing biomass power plant to be qualified for FiT commencement.

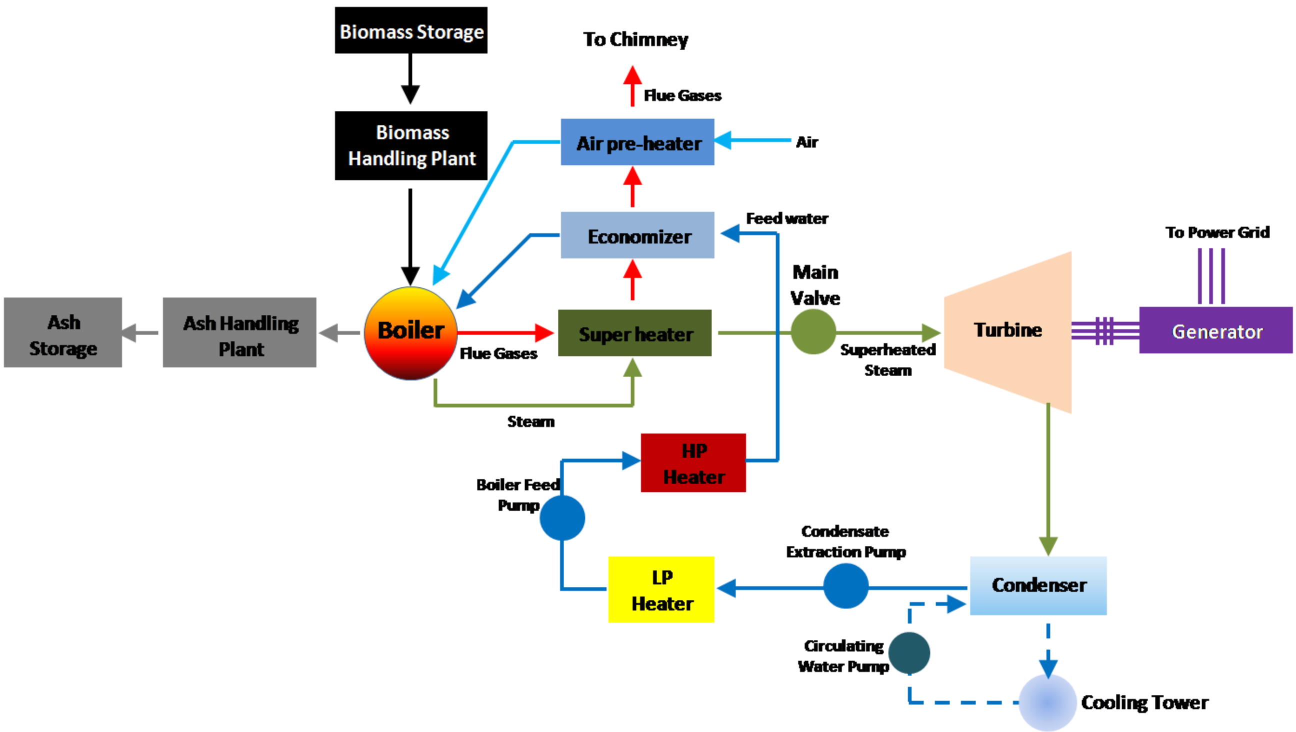


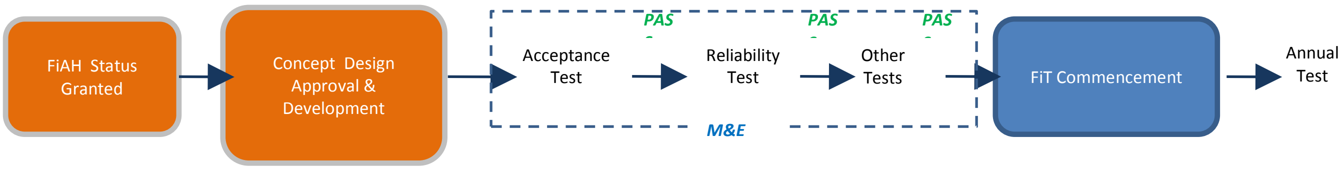

**Figure 1: Conventional Direct-Firing Biomass Power Plant**

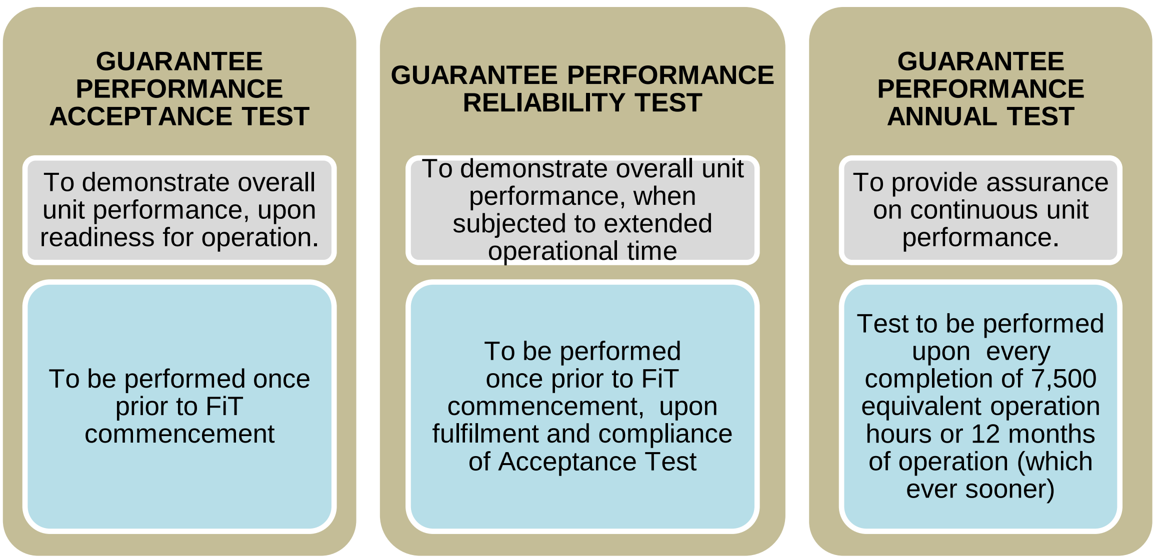
# PART 2 PLANT PERFORMANCE ASSESSMENT

*According to Guidelines and Determinations of the Sustainable Energy Development Authority Malaysia (SEDA Malaysia) (rev Feb 2013), Acceptance Tests and Reliability Test must be carried out in respect of all renewable energy installations. The Subparagraph 15(1)(a)(i) of the Technical and Operational Requirements Rules requires the submission by the Feed-in Approval Holder (FiAH) to the distribution licensee and the Authority of a certificate from a qualified person stating that the renewable energy installation and interconnection facilities have been designed, constructed, installed and tested in accordance with prudent utility practices. In addition, according to Subparagraph 8(a) of Third Schedule to the Technical and Operational Requirements Rules requires the submission by the FiAH to the distribution licensee and the Authority of a certificate from a qualified person stating that the renewable energy installation has successfully completed a Reliability Run.*

## 2.1. Performance Assessments

All new plants that have been granted FiAH status must be subjected to Acceptance Test and Reliability Test, prior to FiT commencement. The overall performance assessment is as follows:




Legacy plant previously under the Renewable Energy Power Purchase Agreements (REPPAs) is not required to undertake the Acceptance Test and Reliability Test prior to FiT Commencement. However, if the plant is claiming for any upgrades in its performance efficiency, a set of Acceptance Test and Reliability Test must be conducted to verify the claim. Otherwise, only Guarantee Performance Annual Test shall be performed to demonstrate the guaranteed efficiency or to apply for new efficiency bonus.

## 2.2. Key Performance Indicators

The key performance indicators listed in Table 1 shall be assessed during the performance assessment.

**Table 1: Performance Assessment Key Performance Indicators**

| No | Indicator | Qualification Criteria | Frequency of assessment | | |
|---|---|---|---|---|---|
| | | | Acceptance Test | Reliability Test | Annual Test |
| **Steam Generating Unit / Boiler** | | | | | |
| 1 | Energy Input | Must be reported | ✓ | | ✓ |
| 2 | Energy Output | Must be reported | ✓ | | ✓ |
| 3 | Efficiency | Minimum of 7% | ✓ | ✓ | ✓ |
| 4 | Flue gas monitoring | Online monitoring or consistent sampling to must be reported | ✓ | | ✓ |
| 5 | Plant particulate emissions | Compliance to Environmental Quality (Clean Air) Regulations, 1978 | ✓ | | ✓ |
| **Turbine-Generator** | | | | | |
| 1 | Heat Rate (corrected value) | In accordance to Rated Capability by OEM. Permissible deviation ± 5% | ✓ | ✓ | ✓ |
| 2 | Power Output (corrected value) | In accordance to Rated Capability by OEM. Permissible deviation ±5% | ✓ | ✓ | ✓ |
| 3 | Steam Rate (corrected value) | In accordance to Rated Capability by OEM. Permissible deviation ± 5% | ✓ | | ✓ |

# PART 3 PERFORMANCE ASSESSMENT GUIDELINE

## 3.1. Scope Of Assessment

### 3.1.1. Steam Generating Unit/ Boiler

Performance test to be carry out with reference to ASME Performance Test Code (PTC) 4.1 for the Steam Generating Unit/ Boiler and its supplementary test codes. The parameters to be assessed are:

a. Energy Input
b. Energy Output
c. Boiler Efficiency (Guarantee Parameters)
d. Flue gas and plant emission

### 3.1.2. Turbine-Generator

Performance test to be carried out with reference to ASME PTC 6 for Steam Turbines and its supplementary test codes. The Guarantee Parameters to be evaluated are:

a. Corrected Power (kW) (Guarantee Parameters)
b. Corrected Heat Rate (kJ/kWh) (Guarantee Parameters)
c. Steam Rate

## 3.2. Test Requirements

### 3.2.1. The rated capability

The rated capability of the unit must be specified prior to testing. The followings are recommended rated capability parameters, which shall be provided by the OEM:

a. Boiler efficiency
b. Turbine-generator heat rate – heat consumption per unit output per hour (kJ/kWhr)
c. Turbine-generator power output– useful energy per unit of time delivered by turbine-generator unit after reduction of parasitic load.

### 3.2.2. Minimum test runs and test durations

a. For Acceptance Test and Annual Test, the minimum test runs are for:
    - 50% TMCR (Turbine Maximum Continuous Rating)
    - 75% TMCR
    - 100% TMCR

    Each test run shall be conducted twice (two sets for each run).
    Each set of test run shall be conducted for minimum of 4 hours
b. For Reliability Test
    - Test run shall be performed once at 100% TMCR
    - Test shall be conducted for a minimum of 300 hours duration (approximately for 14 days, 24 hrs operation, 90% uptime)

### 3.2.3. Frequency of data recording/ measurements

a. All readings shall be taken as often as necessary to minimize error.
b. It is recommended that automatic data recording system to be used and data recorded at no more than 60-seconds intervals.
c. In the absence of automatic data loggers, the following frequency of readings shall be observed:

| | | |
|---|---|---|
| Flow measurements | : | 5 minutes |
| Pressure measurements | : | 10 minutes |
| Temperature measurements | : | 10 minutes |
| Storage vessels water level measurements | : | 10 minutes |
| Electrical power measurements | : | 5 minutes |
| Flue gas sampling | : | 15 minutes |
| Fuel sampling | : | 15 minutes |
| Ash sample analysis | : | 15 minutes |

## 3.3. Test Preparation

All FiAH shall first ensure the provision and ports for measurements are incorporated in the plant design and development stage to enable data collection during performance verification and annual certification. Prior to test commencement, a review of the required documents inclusive of the Process and Instrumentation Diagrams (P & IDs) for the plant and system is required. The followings pre-test checklist shall also be performed:

a. Complete list of all equipment to be subjected to the test and its respective performance guarantee values at installation. The historical data on present operating conditions of equipment and operating hours logged must be established.
b. Establish specific test procedures, with reference to this guideline. Procedures shall explicitly describe any exceptions.
c. Prepare a complete test datasheet containing parameter to be measured, methods of measurement and instruments to be used shall be established with reference to this guideline
d. Establish performance analysis procedure, with reference to this guideline
e. Check for calibration record of all instruments to be used for measurement. All equipment shall be calibrated prior to testing. . The valid calibration certificate, not more than six months old, conforming to internationally recognized calibration standards, for all the instruments installed in the field and used as portable along with the traceability should be available for verification prior to test.
f. Check that typical test data logged automatically in all data-logging system
g. Establish specific time duration for each test and minimum number of tests.
h. Check all operating parameters under which the performance needs to be evaluated, for each equipment in the system.
i. Ensure all heat transfer surfaces to be clean and the entire unit shall be checked for leakage
j. Prior to the test, it shall be ensured that the intended fuel is being used as the as-fired fuel

k. Prepare list of personnel assigned for data measurement/recording throughout the test
l. It is also essential to obtain the performance, losses and correction curves data, generally supplied by the respective Original Equipment Manufacturer (OEM)

**3.3.1. Preliminary Test Run**

a. Preliminary Test Run shall be conducted by unit operator prior to each test run.
b. During preliminary test run, the unit must reach its stabilization at its rated capacity output.
c. Upon reaching stabilization, three sets of readings must be taken for all data to ensure all system are operating at basic design conditions and all the measurement instruments are functional.

**3.3.2. Stabilization period**

Unit shall operate at the test load conditions for a minimum of 2 hours before beginning of each measurement to ensure stable conditions

**3.3.3. Test Operating Conditions**

a. Steady State Conditions
    - Boiler must reach steady state condition before it is subjected to test load and measurements.
    - To ensure equilibrium is reached, the unit shall have been in continuous operation of firing test fuel for minimum of 2-hours before acquiring the measurement.
    - As a reference, the rate of fuel, rate of feed water, excess air and all controllable temperature and pressure shall all be the same at the beginning and end of run.
    - The load fluctuations shall be kept at minimum. As reference, the permissible fluctuations provided in Table 3 shall be observed.
b. Practicable Design Conditions
    - The unit must be operating as close as practicable to design i.e. in normal commercial operation with terminal conditions remain steady and as close as possible to the scheduled values. These operating conditions must be defined prior to testing.
    - General operating conditions to be specified as practicable to design is listed in Table 2
c. All auxiliary steam extraction from the steam generator for other utilities shall be isolated
d. Both intermittent and continuous blow-down shall be isolated for the test duration
e. The bottom ash hopper shall be emptied before each test
f. Soot-blowers shall be operated prior to each test to ensure boiler cleanliness. Use of soot-blowers during testing is not allowed
g. Plant Isolation is essential to ensure test requirements are met. The followings shall be observed during test duration:
    - No unmeasured flow recirculates through or bypasses the flow-meters.
    - No unmeasured water or steam enters or leaves the system
    - All blow-down and soot-blowing operations are suspended

**Table 2: Test General Operating Conditions**

| Operating Conditions | Unit |
|---|---|
| CW Inlet Temperature | °C |
| Make-Up | % |
| Power Factor | % |
| Grid Frequency | Hz |
| Average Air Temperature | °C |
| As-fired fuel type | To be specified |

**Table 3: Permissible Data Fluctuations**

| Operating Conditions | Permissible Deviation for the average of the test conditions from design or rated conditions |
|---|---|
| Steam Pressure (bar) | |
| @ 50% TMCR | ± 0.4 |
| @ 75% TMCR | ± 0.3 |
| @ 100% TMCR | ± 0.2 |
| Steam Temperature, °C | ± 2°C (if superheat is between 15°C-30°C)<br>± 4°C (if superheat >30°C) |
| Hot Reheat Temperature, °C | ± 4.0 |
| Corrected Power Output kW | ± 0.25% |
| Power Factor, % | ± 1% |

### 3.3.4. Operation and control

a. Plant must be ensured to operate closest to the design cycle operation with permissible bias as listed in Table 3, for the basis of performance guarantee.
b. Prior to testing, all relevant plant automatic control systems are to be set, function effectively to achieve the required values and stability

### 3.3.5. Pre-Test System Checks

a. Plant system checks are to be made with the unit operating on the design cycle, at nominally full load and terminals conditions to be held as close as possible to specified values. Plant shutdown for pre-test check may takes up to five days duration (shorter or longer, subjected to plant condition). The followings are pre-test checks:

- Check for turbine cycle operating conditions at nominal full load. This includes values and stability of steam inlet pressure, temperature, and their respective patterns through the cycle.
- Inspection of all valves for leakage and passing
- Condenser air leakage test
- Air heater leakage test
- Preliminary checks of boiler's combustion circuit and steam circuit for test set-up
- Firing conditions optimization
- Excess air, nozzle positions and air distribution
- Soot-blower operation

b. All work done during plant system checks must be included in the test report

### 3.3.6. Test Manning Plan

a. Distribution Licensee, SEDA Malaysia or its appointed representative shall be presented to witness the conduct of performance assessment. Notification shall be given to the respective authorised personnel at minimum of 14 days prior to performance assessment commencement.

b. The followings personnel shall be presented during test:
   - Overall test controller
   - Boiler test engineer
   - Boiler operation engineer
   - Turbine test engineer
   - Turbine operations engineer
   - Test electrical engineer
   - Test instrumentations technician
   - Fuel and ash sampling teams
   - Observers for manual readings
   - Other personnel as needed

c. List of presented personnel must be included in the test report.

# PART 4 TEST INSTRUMENTATIONS AND DATA ACQUISITION

## 4.1. Measuring Instrumentations Bias Limits

Instruments to be used during test are recommended to have following accuracy tolerances.

**a. Temperature measurements**

- Thermocouples Standard Type-K

| Range | 32-530°F (0 – 277 °C) | 530-2,300°F (277- 1,260°C) |
|---|---|---|
| Bias limits | ±4°F | ±0.8% |

- Thermocouples Premium Type-K

| Range | 32-530°F (0 – 277 °C) | 530-2,300°F (277- 1,260°C) |
|---|---|---|
| Bias limits | : ±2°F | ±0.4% |

- Resistance Temperature Device (RTD)

| Range | 32°F | 200°F | 400°F | 570°F | 750°F | 930°F | 1,100°F | 1,300°F |
|---|---|---|---|---|---|---|---|---|
| | 0 °C | 100°C | 200°C | 300°C | 400°C | 500°C | 600°C | 700°C |
| Bias limits | ±0.3% | ±0.8% | ±1.3% | ±1.8% | ±2.3% | ±2.8% | ±3.3% | ±3.8% |

- Temperature Gauge ±*2%* of span
- Mercury-in-Glass Thermometer ±*0.5 gradation*

**b. Pressure measurements**

| Type | Standard Gauge | Manometer | Standard Transducers | High Accuracy Transducers | Aneroid Barometer |
|---|---|---|---|---|---|
| Bias limits | ±1% of span | ±0.5 gradation | ±0.25% of span | ±1% of span | ±0.05 in Hg |

**c. Flow measurements**

| Type | Flow Nozzle – pipe taps | Venturi – throat taps | Orifice |
|---|---|---|---|
| Bias limits | ±0.5% for steam<br>±0.4% for water | ±0.5% for steam<br>±0.4% for water | ±0.5% for steam<br>±0.4% for water |

**d. Storage vessels water level measurements**

| Type | Weigh tanks | Volumetric tanks |
|---|---|---|
| Bias limits | ±0.1of load range | ±0.25% of load range |

**e. Electrical power measurements**

| Type | Voltage or Current - Transformer | Voltage or Current – Hand-held Digital Ammeter | Power-meter |
|---|---|---|---|
| Bias limits | ±0.3% | ±0.25% | ±0.25% |

## 4.2. Recommended Test Instrumentation and Methodology

The followings are recommended test instrumentation and methodology for data acquisition:

### 4.2.1. Flow measurements

a. ISO 5167 can be as the guideline for flow measurement techniques, design, construction, location and installation of flow meters.
b. Test flow-meters shall be preserved its as-calibrated condition. This can be done by installation during unit shutdown immediately before test and removal after unit shutdown immediately after test
c. Test data measurement shall be conducted in accordance to PTC19.5 (R2004) - Supplementary Code on Instruments & Apparatus for Flow Measurements
d. Recommended instrumentations:
   - Condensate flow – calibrated precision flanged flow-meter
   - Heater drains flow and other leak-off flows – calibrated orifice
   - Fuel flow - highly accurate, reliable and calibrated metering system to be used to measure the quantity of fuel supplied to the plant during testing. For solid fuel quantity measurement, it shall be made in accordance to the guidelines Supplementary Code on Instruments & Apparatus for Measurements of Quantity of Materials
   - Air and Exhaust Flue Gas flow (for velocities > 3 m/s and for temperature up to $700^0$C) - Calibrated pitot tube/manometer.
   - Air and Exhaust Flue Gas flow (for velocities ≤ 3m/s) – calibrated anemometer Sampling Grid for obtaining flow measurement along stack or duct can be established using guidelines in the following section

### 4.2.2. Pressure measurements

a. Test data measurement shall be conducted in accordance to PTC 19.2 - (R1998) - Supplementary Code on Instruments & Apparatus for Pressure Measurement
b. Recommended instrumentations:
   - Differential pressure across each flow-meter - Calibrated differential pressure transducers
   - Steam and water pressure – high accuracy calibrated pressure transducers
   - Exhaust pressure – calibrated absolute pressure transducers
   - Boiler air and gas pressure – calibrated U-tubes or test manometers
   - Atmospheric pressure – calibrated precision barometer
   - For measurement of low pressures ≤0.2 MPa (absolute), manometers can be used.

### 4.2.3. Temperature measurements

a. Test data measurement shall be conducted in accordance to ASME PTC 19.3 (R1998) - Supplementary Code on Instruments & Apparatus for Temperature Measurement
b. Temperature of air supplied for combustion - The TAPPI TIP 0416-18 “Performance Test Procedure for Boilers Using Biomass as Fuel” can be used as reference document.

c. Recommended instrumentations:
   - Condensate, feed and steam temperatures - Calibrated platinum resistance temperature detectors (RTDs).
   - Air heater inlet and outlet temperature – Grid of K-type thermocouples. Grid shall be installed along the gas sampling grid.

### 4.2.4. Storage vessels water level measurements

a. Design, construction and operation of measuring equipment shall be made in accordance to the guidelines Supplementary Code on Instruments & Apparatus for Measurements of Quantity of Materials
b. Recommended instrumentations:
   - Steam or condensate entering or leaving the cycle - Weigh tanks
   - Water volume - Volumetric tanks
   - Control room panel (where applicable)

### 4.2.5. Electrical power measurements

a. Calibrated power analyser to be connected to the installed transformer to measure total output at the high voltage terminals of the main transformer
b. In case of existence of any external tap between the generator and the point of measurement, supplementary metering of equivalent accuracy may be provided to determine the total generator output.
c. The ASME PTC 19.6 “Electrical Measurements in Power Circuit” or equivalent standard test code shall be use for detailed instructions for measurement of electrical quantities
d. Recommended instrumentations:
   - AC Generators – single-phase watt-hour meter to be used in each phase to determine power output
   - Power factor, current and voltage - Ammeter and voltmeter
   - DC Generators – DC-ammeters and DC-voltmeters

### 4.2.6. Ash sample analysis

a. Fly ash samples to be collected from ash abatement system. Samples shall be collected continuously, weighted, packaged, sealed and properly labelled at each test.
b. Siftings ash / front bottom ash shall be obtained by combining 2kg samples from the discharge of the scraper conveyors at 15-minutes intervals. Samples shall be collected continuously, weighted, packaged, sealed and properly labelled at each test.
c. The followings procedures are recommended for ash sample analysis:
   - ASTM D5373 - 08 Standard Test Methods for Instrumental Determination of Carbon, Hydrogen, and Nitrogen in Laboratory Samples of Coal (Replacing ASTM D3178-89(2002) Standard Test Methods for Carbon and Hydrogen in the Analysis Sample of Coal and Coke (Withdrawn 2007))
   - ASTM D6316 - 09b Standard Test Method for Determination of Total, Combustible and Carbonate Carbon in Solid Residues from Coal and Coke (Replacing ASTM D1756-02(2007) Standard Test Method for Determination as Carbon Dioxide of Carbonate Carbon in Coal (Withdrawn 2013))

- Content of combustible in refuse stream (flue gas, siftings and front bottom ash) shall be calculated in accordance with TAPPI TIP 0416-18 “Performance Test Procedure for Boilers Using Biomass as Fuel” reference document.

#### 4.2.7. Measurement of Time

The measurement of time of test durations and other observations can be determined by observations of synchronized stop watches by the individual observers. Watches and clocks can be synchronized at the start of the test with the plant data and instruments.

## 4.3. Air Flow, Exhaust Flue Gas Flow And Temperature Sampling Grid

The following methodology provides guideline for establishing sampling grid at the stack/ duct.

**a. Measurement Site**

- Select a site in a straight section of stack or duct located at least eight stack or duct diameters downstream and two stack or duct diameters upstream of any flow disturbance such as a bend, expansion, contraction, visible flame, junction, or stack exit.
- In the case of rectangular stacks or ducts, an equivalent diameter ($D_e$) shall be used in determining the downstream and upstream distances.

$$D_e = \frac{2LW}{L + W}$$

Where
L = stack length
W = stack width

- In circular stacks or ducts, at least two sampling ports with a 90° separation are required. For particulate traverses, one diameter should be in the plane of an upstream flow disturbance.
- For rectangular flow areas, ports are located on the most accessible face of the duct. The number of ports will be determined by the total number of traverse points.

**b. Number of Traverse Points**

- the required minimum number of traverse points for a circular or rectangular cross section is determined from Table 4
- When the eight- and two-diameter criteria cannot be satisfied, the minimum number of traverse points is determined from Fig. 2
- Determine the number of diameters upstream and downstream from the sampling site to the flow disturbances. Then using Fig. 2, determine the minimum number of traverse points corresponding to (a) the number of duct diameters upstream, (b) the number of duct diameters downstream.
- Select the higher of the minimum numbers of traverse points from (a) and (b). In the case of circular cross sections, if the required number of points does not equal a multiple of four then the required number of points must be increased to the next greater multiple of four

**Table 4: Minimum Number of Traverse Points for Sampling Sites that meet the Eight- and Two-diameter Criteria**

| Stack or Duct Diameter (m) | Required Minimum Number of Traverse Points | |
|---|---|---|
| | Circular Duct | Rectangular Duct |
| **> 0.61** | 12 | 12 |
| **0.30 to 0.61** | 8 | 9 |

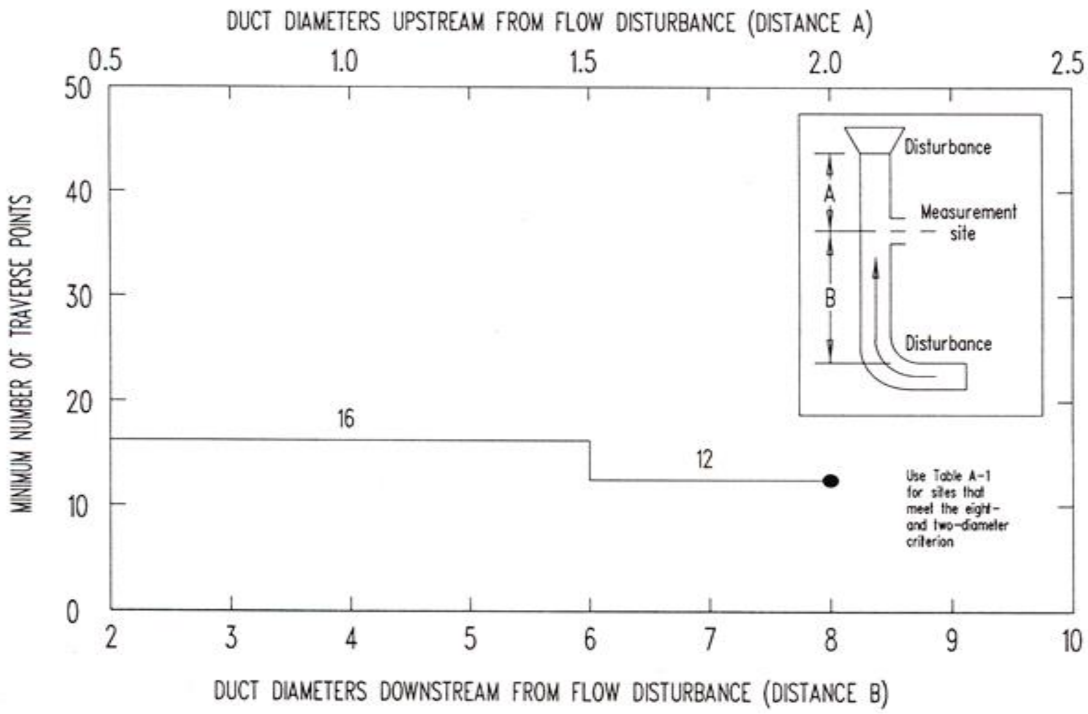



**Figure 2: Minimum Number of Traverse Points**

**c. Location of Traverse Points**

- For stacks or ducts with a circular cross section, locate the traverse points according to Table 5. These points are located at the centroid of equal areas of the cross section
- The minimum distance between the stack wall and a traverse point shall be 2.5 cm (1.0 in) for stacks with diameters greater than 0.61 m (24 in) and 1.3 cm (0.5 in) for stacks with diameters less than 0.61 m (24 in)
- For rectangular cross sections, the area is divided into as many equal rectangular sections as there are sampling points
- Locate the traverse points at the centroid of these rectangular sections.
- The cross-sectional layout of a rectangular duct shall be chosen such that the ratio of the length to the width is between 1.0 and 2.0

**Table 5: Location of Traverse Points in Circular Stacks - Percent of Stack Diameter from Inside Wall to Traverse Point**

| Traverse Point Number on a Diameter | Number of Traverse Points on a Diameter | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **2** | **4** | **6** | **8** | **10** | **12** | **14** | **16** | **18** | **20** | **22** | **24** |
| **1** | 14.6 | 6.7 | 4.4 | 3.3 | 2.5 | 2.1 | 1.8 | 1.6 | 1.4 | 1.3 | 1.1 | 1.1 |
| **2** | 85.4 | 25.0 | 14.7 | 10.5 | 8.2 | 6.7 | 5.7 | 4.9 | 4.4 | 3.9 | 3.5 | 3.2 |
| **3** | | 75.0 | 29.5 | 19.4 | 14.6 | 11.8 | 9.9 | 8.5 | 7.5 | 6.7 | 6.0 | 5.5 |
| **4** | | 93.3 | 70.5 | 32.3 | 22.6 | 17.7 | 14.6 | 12.5 | 10.9 | 9.7 | 8.7 | 7.9 |
| **5** | | | 85.3 | 67.7 | 34.2 | 25.0 | 20.1 | 16.9 | 14.6 | 12.9 | 11.6 | 10.5 |
| **6** | | | 95.6 | 80.6 | 65.8 | 35.5 | 26.9 | 22.0 | 18.8 | 16.5 | 14.6 | 13.2 |
| **7** | | | | 89.5 | 77.4 | 64.5 | 36.6 | 28.3 | 23.6 | 20.4 | 18.0 | 16.1 |
| **8** | | | | 96.7 | 85.4 | 75.0 | 63.4 | 37.5 | 29.6 | 25.0 | 21.8 | 19.4 |
| **9** | | | | | 91.8 | 75.0 | 63.4 | 37.5 | 29.6 | 25.0 | 21.8 | 19.4 |
| **10** | | | | | 97.5 | 88.2 | 79.9 | 71.7 | 61.8 | 38.8 | 31.5 | 27.2 |
| **11** | | | | | | 93.3 | 85.4 | 78.0 | 70.4 | 61.2 | 39.3 | 32.3 |
| **12** | | | | | | 97.9 | 90.1 | 83.1 | 76.4 | 69.4 | 60.7 | 39.8 |
| **13** | | | | | | | 94.3 | 87.5 | 81.2 | 75.0 | 68.5 | 60.2 |
| **14** | | | | | | | 98.2 | 91.5 | 85.4 | 79.6 | 73.9 | 67.7 |
| **15** | | | | | | | | 95.1 | 89.1 | 83.5 | 78.2 | 72.8 |
| **16** | | | | | | | | 98.4 | 92.5 | 87.1 | 82.0 | 77.0 |
| **17** | | | | | | | | | 95.6 | 90.3 | 85.4 | 80.6 |
| **18** | | | | | | | | | 98.6 | 93.3 | 88.4 | 83.9 |
| **19** | | | | | | | | | | 96.1 | 91.3 | 86.8 |
| **20** | | | | | | | | | | 98.7 | 94.0 | 89.5 |
| **21** | | | | | | | | | | | 96.5 | 92.1 |
| **22** | | | | | | | | | | | 98.9 | 94.5 |
| **23** | | | | | | | | | | | | 96.8 |
| **24** | | | | | | | | | | | | 98.9 |

- An example of the location of traverse points for a circular and rectangular stack is illustrated in Fig. 3

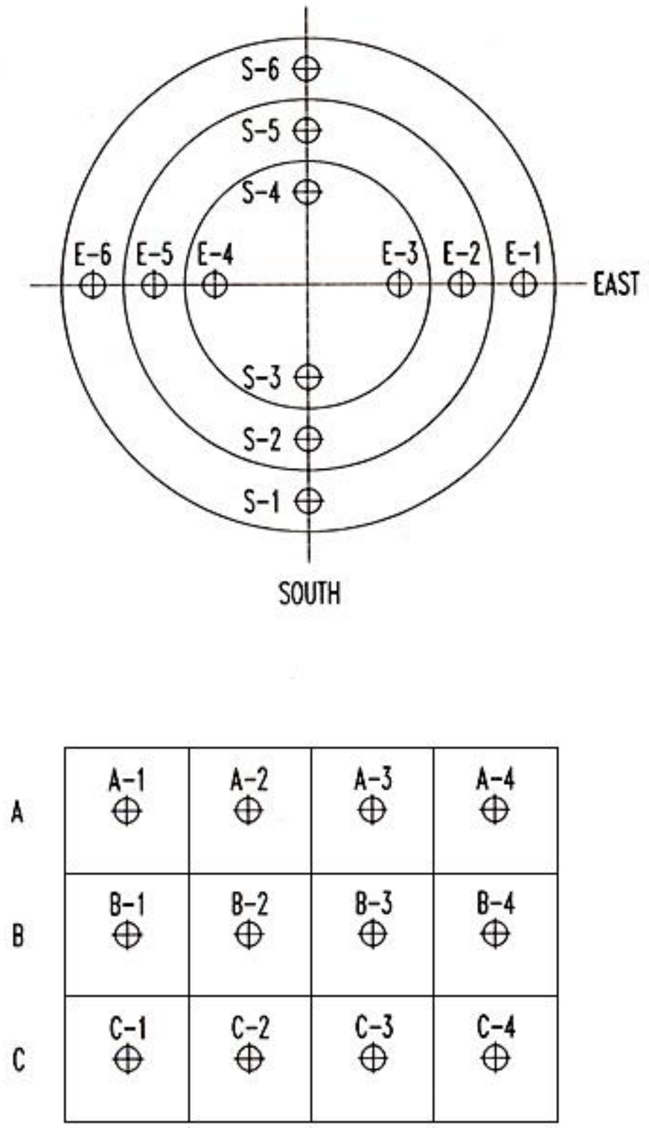



**Figure 3: Example of the Location of Traverse Points**

## 4.4. Flue Gas Analysis

### 4.4.1. General guideline for flue gas analysis:

a. Flue gas samples entering and leaving air heaters to be continuously collected point test sampling probes within the respective gas ducts.
b. Flue gas sampling must be taken at the same point used for flue gas temperature measurement, using similar guideline for sampling points
c. Calibrated Orsat flue gas analyser shall be used to analyse the samples for oxygen, carbon dioxide and carbon monoxide.
d. Flue gas compositions: Sampling and analysis of $CO_2$, $O_2$ and CO in accordance with ASME PTC 19.10 Supplementary Code on Instruments & Apparatus - Flue and Exhaust Gas Analyses and reference methodology specified in this document

### 4.4.2. Analytes

Flue gas analysis shall be observed for the analytes in Table 6

### 4.4.3. Apparatus

**a. Probe**

Stainless steel or borosilicate glass tubing equipped with an in-stack or out-stack filter to remove particulate matter (a plug of glass wool is satisfactory for this purpose).
Any other material inert to $O_2$, $CO_2$, CO, and $N_2$ and resistant to temperature at sampling conditions may be used for the probe; examples of such material are aluminum, copper, quartz glass and Teflon.

**b. Pump**

A one-way squeeze bulb, or equivalent, to transport the gas sample to the analyser.

**c. Gas analyser**

An Orsat type combustion flue gas analyser (Fig 4).

**Table 6: Flue gas analysis analytes**

| No | Analyte | CAS No |
|---|---|---|
| 1 | Oxygen, $O_2$ | 7782-44-7 |
| 2 | Nitrogen, $N_2$ | 7727-37-9 |
| 3 | Carbon dioxide, $CO_2$ | 124-38-9 |
| 4 | Carbon Monoxide, CO | 630-08-0 |

**Figure 4: Orsat Gas Analyser**

### 4.4.4. Safety and Health Precautions

**a. Safety.**

- This method may involve hazardous materials, operations, and equipment.
- This guideline may not address all of the safety problems associated with its use. It is the responsibility of the user of this test method to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to performing this test method.

**b. Corrosive Reagents.**

- A typical Orsat analyser requires four reagents: a gas-confining solution, $CO_2$ absorbent, $O_2$ absorbent, and CO absorbent. These reagents may contain potassium hydroxide, sodium hydroxide, cuprous chloride, cuprous sulfate, alkaline pyrogallic acid, and/or chromous chloride. Follow manufacturer's operating instructions and observe all warning labels for reagent use.
- For Orsat analyser maintenance and operation procedures, follow the instructions recommended by the manufacturer, unless otherwise specified herein.

### 4.4.5. Procedures and Analysis

a. Set up the gas sampling equipment, making sure all connections ahead of the analyser are tight. It is recommended that the Orsat analyser be leak-checked
b. Place the probe in the stack, with the tip of the probe positioned at the sampling point Purge the sampling line long enough to allow at least 5 exchanges.
c. Draw a sample into the analyser and immediately analyse it for percent $CO_2$, $O_2$ and CO. Determine the percentage of the gas that is $N_2$ by subtracting the sum of the percentage of $CO_2$, $O_2$ and CO from 100%.
d. Repeat the sampling, analysis, and calculation procedures, until the dry molecular weights of any three grab samples differ from their mean by no more than 0.3 g/g-mole (0.3 lb/lb-mole).
e. Average these three molecular weights, and report the results to the nearest 0.1 g/g-mole (lb/lb-mole).
f. After the analysis is completed, leaks check (mandatory) the Orsat analyser once again. For the results of the analysis to be valid, the Orsat analyser must pass this leak test before and after the analysis.
g. For results validation, calculate the fuel factor, $F_o$ using the following equation:

$$F_o = \frac{20.9 - \%O_2}{\%CO_2} \qquad \textbf{Eqn. F1}$$

Where:

$\%O_2 = \%O_2\ (adj) = \%O_2 - 0.5\ \%CO$
$\%CO_2 = \%CO_2\ (adj) = \%CO_2 + \%CO$
%CO = Percent CO by volume (dry basis).
20.9 = Percent $O_2$ by volume in ambient air.

Compare the calculated $F_O$ factor with the expected $F_o$ values. The acceptable ranges for the expected $F_o$ is 1.003 -1.130.

## 4.5. Fuel Sampling and Analysis

### 4.5.1. General guideline for sampling of biomass:

a. Frequency
   Sample shall be taken at regular intervals during each performance test run
b. Point
   Sample shall be collected as close to the boiler as possible such as at the conveyor
c. Sampling apparatus
   Dimension of sampling apparatus and the size of the sample are suitable for the maximum fuel size
d. Sample preparation
   - When sample has been taken, two laboratory samples are to be prepared – one for moisture analysis, and another one for analysis of ash content, chemical and physical properties
   - When sample has been taken for moisture analysis, it must be weighted as soon as possible. For storage, it must be kept in a sealed, air-tight container and to be stored at a temperature lower than where the samples are taken
e. No of individual samples
   No of individual samples depends on the non-homogeneity of the fuel which varies according to fuel type, particle size and the segregation rate.
f. The minimum size of an individual sample: Depends on the particle size of the fuel. Minimum size of individual samples when at least 95% of the fuel is smaller than 100mm (4 inches) shall be 10 litres. In addition, the followings shall be noted:
   - When sampling from a stopped conveyor, the width of the belt at the sampling point should be at least 2.5 times the maximum fuel size
   - When sampling from truck or pile, the minimum opening size of the sampling device (scoop or probe) should be 2.5 times the maximum fuel size
g. Test report
   Sampling test report shall describe the followings:
   - Sampling method
   - Design of sampling equipment
   - Sampling procedure
   - Number of individual samples
h. Sample labelling
   Sampling container shall describe the followings:
   - Name and designation of sampler
   - Type of fuel
   - Test number, test date and time
   - Sample collection number, date, time
   - Total solids content

### 4.5.2. Guidelines for Sampling from Conveyor Belt (fuel flow - stationary or in motion)

a. The recommended number of individual samples for determining ash and gross heating value content when sampling from fuel flow is given in Table 7.
b. The recommended number of individual samples for determining moisture content when sampling from fuel flow is given in Table 8:
c. For obtaining correct sample, the sample consisting of a whole section of a stopped belt conveyor is to be taken. Individual samples shall be taken across the full width of the belt and comprise all material within the sample section.
d. Sample shall be taken at a regular time intervals. Avoid taking samples at the beginning and the end of the fuel flow
e. Precision reference value for sampling are provided in Table 9

**Table 7: Number of Individual Samples for Determining Ash and Gross Heating Value**

| Fuel | Fuel delivery sizes (tonnes) | | |
|---|---|---|---|
| | <60 | 60 - 150 | 150-1000* |
| Wood chips | 6 | 3 per 20 tonnes | 18 |
| Hog Fuel | 6 | 3 per 20 tonnes | 18 |
| EFB, Milled peat | 4 | 2 per 20 tonnes | 11 |
| Pelletized Peat | 10 | 4 per 20 tonnes | 22 |

**Table 8: Number of Individual Samples for Determining Moisture Content**

| Fuel | Fuel delivery sizes (tonnes) | | |
|---|---|---|---|
| | <60 | 60 - 150 | 150-1000* |
| Wood chips | 6 | 2 per 20 tonnes | 15 |
| Hog Fuel | 6 | 2 per 20 tonnes | 15 |
| EFB, Milled peat | 3 | 1 per 20 tonnes | 8 |
| Pelletized Peat | 6 | 2 per 20 tonnes | 15 |

*Note * for delivery over 1000 tonnes, it shall be divided into a 1000 tonnes or less small sections and a separate collective samples to be generated for each sections*

**Table 9: Precision reference value**

| Parameter | Reference Value | Remarks |
|---|---|---|
| Ash content | ± 0.2 percentage | If the ash content is 2.0%, the result will be between 1.8 and 2.2%. All ash content figures are based on the dry weight of the fuel sample |
| Moisture content | ± 2.0 percentage | If the moisture content is 50%, the result will be between 48 and 52% |

### 4.5.3. Reference Procedure for Sample Preparations

Principally, the sample shall be dried, milled and sieved before submitted to further compositional analysis. This procedure describes a reproducible way to convert a variety of biomass samples into a uniform material suitable for compositional analysis. It is a guideline for drying, size reduction, obtaining samples with a uniform particle size and representative sampling of biomass samples prior to analysis for many other constituents. The procedures is similar to ASTM E1757-01(2007), TAPPI Test Method T264 cm-97 and NREL/TP-510-42620. This procedure is applicable for most types of biomass and biomass- derived solids for compositional analysis. However, it is not applicable for the followings:

a. Materials that pass through a 20-mesh sieve.
b. Materials that cannot be dried by the described methods to a total solids content of greater than 90% of the sample's oven dried weight.

#### 4.5.3.1. Safety and Health Considerations

This Procedure does not address all of the safety concerns associated with its use. It is the responsibility of the user of this guideline to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use. However, the followings safety and health considerations shall be observed during sampling:

a. Milling and sieving actions both produce large amounts of dust. This dust can be a nuisance, hazard, or irritant. Use appropriate respiratory protection and eye protection as needed.
b. If excessive amounts of dust are allowed to become airborne, a potential explosion hazard is possible. Provide appropriate dust control measures as needed.
c. Follow all applicable laboratory chemical handling procedures.

#### 4.5.3.2. Methods, Apparatus, Reagents And Materials

a. **Method:**
   To obtain a dried biomass sample for further analysis, the solids content of the sample is to be tested throughout this procedure. Solid content can be tested using any of the following standards:
   - NREL/TP-510-42621 (2008) Laboratory Analytical Procedure (LAP) for Determination of Total Solids in Biomass and Total Dissolved Solids in Liquid Process Samples
   - TAPPI Method T412 om-02. 2002. "Moisture in Pulp, Paper and Paperboard." Test methods of the Technical Association of the Pulp and Paper Industry 2002-2003.
   - ASTM E1756 - 08 Standard Test Method for Determination of Total Solids in Biomass

b. **Apparatus:**

The followings are the required apparatus for sample preparations:

- Large table or drying rack for air drying biomass (method A only).
- Convection oven capable of maintaining 45 ±5ºC (method B only).
- Freeze-Drier - System with vacuum chamber and pump capable of maintaining a pressure of <1 torr and a cold finger in the chamber capable of maintaining a temperature of -50°C (method C only).
- Assorted trays
- Containers as appropriate for the selected drying method.
- Balance, sensitive to 0.1 g.
- Standard laboratory knife mill with 2 mm screen. A Wiley Mill, size No. 4 with a 2-mm screen, is suitable for samples >20 g, and the intermediate model Wiley Mill, with 1-mm screen, is suitable for samples <20 g that will not be sieved. Equivalent knife mills are acceptable.
- Sieve Shaker that provides motion in both horizontal and vertical axes- for optional sieving step
- Sieve Set, No. 20 (850 μm), No. 80 (180 μm) stackable sieves with lid and bottom pan. Sieves and bottom pan should be 8.9 cm (31/2 in.) in height. Sieves should conform to ASTM Specification E 11.
- Riffle Sampler with Pans — A manual sample divider that splits the milled biomass into two or more equivalent sub-samples. Riffle divisions should be between 6.4 mm and 12.7 mm (1/4 to 1/2 in.) with at least twenty-four riffle openings. The feed chute and riffles should have a slope of at least 60°. Collection pans, one to pour the sample into the riffler, and two or more to collect the sub–samples.

c. **Reagents**

This is applicable for lyophilization method only

- Acetone (electronic grade)
- Dry ice (ground).

**4.5.3.3. Sample Drying Procedure**

Dried biomass sample shall be prepared using one of these methods

**4.5.3.3.1. Method A - Air-drying.**

a. This method is suitable for the preparation of large quantities (>20 g) of field-collected samples
b. Biomass samples must be prepared as pieces with overall dimensions less than 5cm x 5cm x 0.6 cm.
c. The biomass material is then to be spread out on a suitable surface and allowed to air-dry prior to any milling. Do not pile the material deeper than 15 cm.
d. Turn the material at least once per day to ensure even drying and inhibit microbial growth in samples.
e. Check the solids content of the biomass sample using one of the methods described above
f. The material is considered dried when the moisture content is less than 10% by weight and the change in weight is less than 1% in 24 hours.

#### 4.5.3.3.2. Method B - Convection Oven Drying.

a. This drying method is suitable for small samples of biomass (<20 g) and when air-drying is impossible. This method is recommended for
   - very wet biomass samples that are at risk for microbial growth during air-drying,
   - wet pre-treated biomass,
   - samples that would not be stable during prolonged exposure to ambient conditions,
   - drying materials when ambient humidity does not allow the sample to air-dry to a moisture content

b. Select a container suitable for oven drying the biomass sample and dry this container at 45± 3°C for a minimum of 3 h.
c. Place the container in desiccators and allow the container to cool to room temperature.
d. Weigh the container to the nearest 0.1 g and record this weight as $W_t$.
e. Place the biomass material into the dried container to a maximum depth of 1 cm.
f. Weigh the container and biomass to the nearest 0.1 g and record this weight as $W_i$.
g. Place the container and biomass in a drying oven maintaining the temperature at 45 ± 3°C. Allow the material to dry for 24 to 48 h.
h. Remove the container and biomass from the drying oven, place in desiccators and allow the sample to cool to room temperature.
i. Weigh the container and biomass to the nearest 0.1 g and record this weight as $W_f$.
j. Return the sample to the drying oven, maintaining the temperature at 45 ± 3°. Keep the sample in the drying oven at 45 ± 3°C for minimum of 4 hr.
k. Remove the container and biomass from the drying oven, place in a desiccators and allow the sample to cool to room temperature
l. Weigh each sample to the nearest 0.1 mg and record this weight.
m. Return the samples to the drying oven at 45°C for 1 h.
n. Remove the container and biomass from the drying oven, place in desiccators and allow the sample to cool to room temperature.
o. Weigh each sample to the nearest 0.1 mg and record this weight.
p. Repeat steps (m) through (o) until the change in the mass of the biomass is less than 1% in one hour.
q. To calculate the percent of total solids obtained by drying at 45ºC, use the following equation:

$$\%T_{45} = \frac{W_f - W_t}{W_i - W_t} \times 100 \qquad \textbf{\textit{Eqn.S1}}$$

Where:
$\% T_{45}$ = percent total solids of a sample oven dried at 45ºC,
$W_t$ = tare weight of freeze-drier container,
$W_i$ = initial weight of container and sample
$W_f$ = final weight of container and sample.

4.5.3.3.3. **Method C – Lyophilization** (freeze-drying).

a. This drying method is suitable for small samples of biomass (<20 g).
b. This method is recommended for
   - very wet biomass that is at risk for microbial growth during air-drying
   - wet pre-treated biomass
   - samples that would not be stable during prolonged exposure to ambient conditions
   - drying materials when ambient humidity does not allow the sample to air-dry to a moisture content below 10%
   - materials that are heat sensitive and would degrade if subjected to oven drying
c. Weigh a suitable freeze-drier container to the nearest 0.1 g and record this weight as $W_t$.
d. Place the biomass material in the container. For solid samples, do not fill the container more than half full. For liquid or slurry materials, limit the sample to the amount of material that gives a uniform coating of around 0.5 cm on the walls of the container when the sample is frozen.
e. Weigh the container and biomass to the nearest 0.1 g and record this weight as $W_i$.
f. Combine the dry ice and acetone in a shallow container suitable for shell freezing.
g. Place the freeze dry flask containing the biomass sample in the dry ice acetone mixture. Slowly turn the container (10 rev/min) to freeze the material into a uniform layer on the walls of the container.
h. Immediately place the container on the freeze-drier and allow the material to dry until all visible traces of ice and frost are gone from the sample. This process typically takes 12 hours for small (<20 g) samples, and can extend to more than 96 hours for large samples (>250 g).
i. Remove the container and biomass from the freeze drier.
j. Allow the sample to warm to room temperature.
k. Weigh the container and biomass to the nearest 0.1 g and record this weight as $W_f$.
l. To calculate the percent of total solids obtained, use the following equation:

$$\%T_{fd} = \frac{W_f - W_t}{W_i - W_t} \times 100 \qquad \textbf{Eqn. S2}$$

Where:
% $T_{fd}$ = percent total solids of a freeze-dried sample,
$W_t$ = tare weight of freeze-drier container,
$W_i$ = initial weight of container and sample
$W_f$ = final weight of container and sample.

#### 4.5.3.4. Sample Milling Procedure

The followings are guideline for sample milling:

a. Feed the air-dried biomass into the knife-mill, and mill until the entire sample passes through the 2 mm screen in the bottom of the mill, or a 1mm screen on small mills. Laboratory mills can generate enough heat to damage biomass samples.
b. Monitor the mill closely and allow the mill to cool to room temperature between batches if necessary.
c. If the prepared sample is not analysed immediately, the sample should be stored in an airtight container or sealable polyethylene bag and kept at -20°C until needed.

#### 4.5.3.5. Sample Sieving Procedure

Sieving shall be performed if

a. The ash content is high. ASTM E1755 - 01(2007) Standard Test Method for Ash in Biomass can be used as reference test procedure
b. Homogeneous particle size is a critical.

However, if the entire biomass sample needs to be analysed, sieving can frequently cause fractionation and should not be performed. The followings are guideline for sample sieving:

a. Stack the sieves in the following order, starting at the bottom: solid catch pan, 80-mesh sieve, 20-mesh sieve.
b. Place the milled biomass in the 20-mesh sieve. The sample should be no more than 7 cm deep in the 20-mesh sieve. The milled sample may be processed in batches if necessary.
c. Place the cover on the sieve stack and secure the stack in the sieve shaker.
d. Shake the sieves for 15 ± 1 min.
e. The fraction retained on the 20-mesh sieve (+20 mesh fraction) should be reprocessed (knife-mill until the entire sample passes through the 2 mm screen in the bottom of the mill, or a 1mm screen on small mills) until no biomass remains on the 20-mesh sieve.
f. The fraction retained on the 80-mesh sieve (-20/+80 mesh fraction) should be retained for compositional analysis.
g. The material in the solid catch pan is the fines (-80mesh) fraction. Retain this material for ash analysis.
h. Combine all of the -20/+80 mesh batches. Weigh the combined -20/+80 mesh fraction to the nearest 0.1 g. Record the weight of the -20/+80 mesh fraction as Wt20/80.
i. Combine all of -80 mesh batches. Weigh the combined fines to the nearest 0.1 g. Record the weight of fines fraction as Wt80.
j. If multiple sieved samples were combined they must homogenized. Pour the - 20/+80 mesh fraction into the riffle sampler. The sample must be distributed evenly onto all the riffle openings. A pan, as wide as the riffle opening, should be used. Pour the sample evenly off the entire side of the pan and not from the end or the corner. Do not transfer the biomass sample from a narrow-mouth container such as a jar.
k. Recombine the riffled sub-samples.
l. Repeat steps (j) through (k) a total of four times.

m. Determine the total solids content (TS) of both the –20/+80 mesh fraction and the fines fraction using one of the methods described above. Record the total solids of the -20/+80 mesh fraction as TS20/80. Record the total solids content of the fines as TS-80.
n. Determine the ash content of each fraction and record the ash content of the -20/+80 mesh fraction as Ash20/80. Record the ash content of the fines as Ash-80. The ASTM E1755 - 01(2007) Standard Test Method for Ash in Biomass can be used as reference test procedure
o. Calculate the percent of each fraction in the original, biomass sample. The fraction weight percent is used to reconstruct the composition of the original biomass sample.
   - To calculate the fraction percent of –20/+80 mesh fraction, use the following equation:

$$Fraction_{20/80}\% = \frac{Wt_{20/80}}{Wt_{20/80} + Wt_{80}} \times 100 \qquad \textbf{Eqn. S3}$$

Where:
$W_{t\ 20/80}$ = weight of –20/+80 mesh fraction (g)
$W_{t80}$ = weight of fines fraction (g)

   - To calculate the fraction percent of -80 mesh fraction, use the following equation:

$$Fraction_{80}\% = \frac{Wt_{80}}{Wt_{20/80} + Wt_{80}} \times 100 \qquad \textbf{Eqn. S3}$$

Where:
$W_{t\ 20/80}$ = weight of –20/+80 mesh fraction (g)
$W_{t80}$ = weight of fines fraction (g)

p. If the total sample needs to be subdivided into smaller samples, use the riffler to make this
q. If the prepared sample is not analyzed immediately after sieving and riffling, the sample should be stored in an airtight container or sealable polyethylene bag and kept at -20°C until needed.

### 4.5.4. Precision And Bias

a. *Repeatability* – Duplicate determinations on splits of the gross sample, by the same operator, using the same sieves, should duplicate the percent mass fractions within 2% absolute.
b. *Reproducibility* – Duplicate determinations on splits of the gross sample, by different operators, using the same sieves, should duplicate the percent mass fractions within 2% absolute.

### 4.5.5. Reference procedure for Sample Analysis

The followings are recommended standard test method to be used for fuel sample analysis:

a. ASME E870 Standard Test Methods for Analysis of Woods Fuels shall be used as standard reference for compositions analysis.
b. ASTM E871 Standard Test Methods for Volatile Matter in the Analysis Sample of Refuse-derived Fuel
c. ASTM D1102 Standard Test Methods for Ash in Wood
d. ASTM E711 Standard Bomb Calorimeter Test Method for Gross Calorific Value of Refuse-derived Fuel
e. ASTM E777 Standard Test Methods for Carbon and Hydrogen in the Analysis Sample of Refuse-derived Fuel
f. ASTM E778 Standard Test Methods for Nitrogen in the Analysis Sample of Refuse-derived Fuel
g. ASTM E775 Standard Test Methods for Total Sulphur in the Analysis Sample of Refuse-derived Fuel

## 4.6. Calibration of Test Instrumentations

a. All instruments used for measurement must be calibrated before the test.
b. Valid equipment and measuring instruments calibrations report must be included in the full test report. Validity of calibrated equipment and measuring instruments shall be as stated in the calibration test certificate.
c. All properties evaluation must be performed by SAMM Accredited Laboratory, in compliance to ISO/IEC 17025 or its equivalent

# PART 5 TEST DATA AND RESULTS ANALYSIS

## 5.1. Steam Generating Unit / Boiler Performance

In a steam generating unit, Energy Input, $E_{in}$ is defined as the chemical heat in the fuel (high heat value, HHV of the fuel as determined from laboratory analysis) plus heat credits added to the working fluid/air/gas and other fluid circuits which cross the envelope boundary. For biomass, the HHV is determined based on ASTM E711 Standard Bomb Calorimeter Test Method for Gross Calorific Value of Refuse-derived Fuel. Heat credits, *B* are the heat added to the envelope of steam generating unit other than the chemical heat in the fuel. The Energy Output $E_{out}$ is defined as the heat absorbed by the working fluid or fluids. The relationship between Energy Input, $E_{in}$, Energy Output $E_{out}$, Heat credits, *B* and Losses, *L* is presented in Fig. 5. For the purpose of performance assessment, the envelope boundary which encompasses all the equipment in the specific steam generating unit must be established.

The heat balance for steam generating system is

$$\sum \text{Energy Input to the system} = \sum \text{Energy Output from the system}$$

$$\sum \text{Chemical Heat Input from the Fuel, } E_{H_f} + \sum \text{Heat Credits to the System, B} = \sum \text{Total Heat Absorbed by Working Fluid, } E_{out} + \sum \text{Total Losses , L} \qquad \textbf{\textit{Eqn.}\ 1}$$

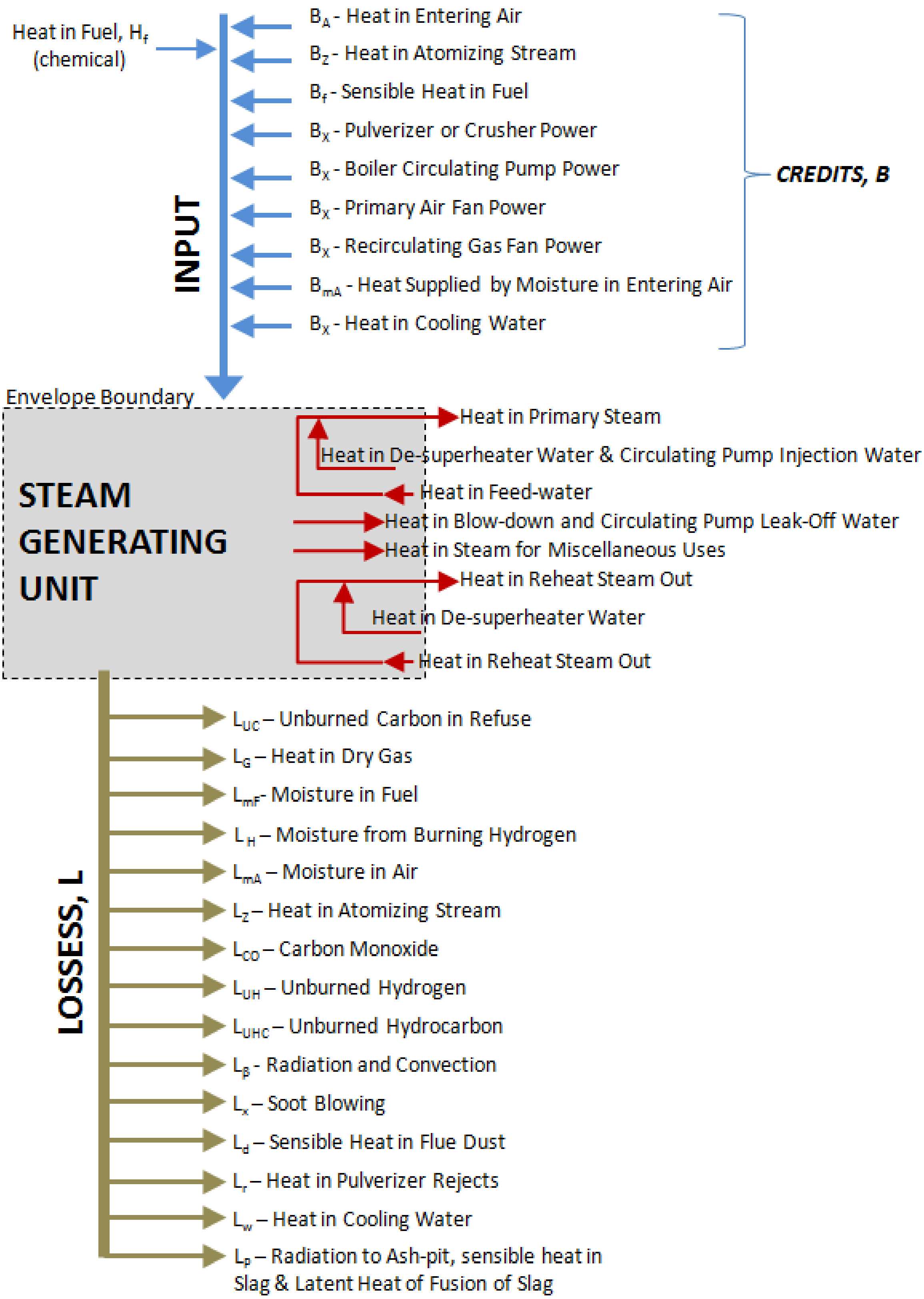



**Figure 5: Energy Balance for a Steam Generating Unit (Boiler)**

### 5.1.1. Chemical Energy Input and Heat Credits

$$\text{Total Chemical Heat Input}, E_{H_f} = \text{Fuel heat value} \times \text{Rate of fuel firing}$$

Heat in fuel is the heating value of fuel to be obtained by laboratory analysis and adjusted to an "as-fired" basis from laboratory determination of moisture in fuel. Heat in fuel is determined as follows:

$$\text{Heat in fuel}, H_f\left(\frac{Btu}{lb\ A.F\ Fuel}\right) = H_{f'} \times \frac{100 - m_f}{100} \qquad \textbf{Eqn. 2}$$

Where

$H_{f'}$ = Laboratory determination by fuel analysis on dry basis

$m_f$ = Percentage moisture in fuel as determined by analysis of moisture sample

Heat Credits is the total heat credits per pound of "as-fired" fuel added to the steam generator in the form of sensible heat. Heat credits are determined as follows:

$$\text{Heat Credit, B}\left(\frac{\text{Btu credit}}{\text{lb A.F Fuel}}\right) = \frac{B_{Ae} + B_{ze} + B_{fe} + B_{xe} + B_{mAe}}{W_{fe}} \qquad \textbf{Eqn. 3}$$

Where

$B_{Ae}$ = Heat credit supplied by entering air

$B_{ze}$ = Heat credit supplied by atomizing steam

$B_{fe}$ = Heat credit supplied by sensible heat in fuel

$B_{xe}$ = Heat credit supplied by auxiliary drives

$B_{mAe}$ = Heat credit supplied from the moisture entering with the inlet air

$W_{fe}$ = Measured fuel rate

### 5.1.2. Energy Output and Losses

The total energy absorbed by the working fluid is determined as follows:

$$\text{Total heat absorbed by working fluid}, E_{out} = \text{Energy in steam entering superheater} + \text{Energy in superheater spray water flow} + \text{Energy in reheat steam flow} + \text{Energy in reheat spray water flow} + \text{Energy in blowdown flow} + \text{Energy in injection flow} + \text{Energy in leak off flow} \qquad \textbf{Eqn. 4}$$

Total Heat Losses, L are determined as follows:

$$\text{Total Heat Losses, L}\left(\frac{\text{Btu loss}}{\text{lb A.F Fuel}}\right) = L_{UC} + L_G + L_{mf} + L_H + L_{mA} + L_Z + L_{CO} + L_{UH} + L_{UHC} + L_{\beta} + L_{[P]} + L_d + L_r + L_w \qquad \textbf{Eqn. 5}$$

Where

| | | |
|---|---|---|
| $L_{UC}$ | = | Heat loss due to unburned carbon in refuse |
| $L_{G'}$ | = | Heat loss due to heat in dry flue gas |
| $L_{mf}$ | = | Heat loss due to moisture in the “as-fired” fuel |
| $L_{H}$ | = | Heat loss due to moisture from burning of hydrogen |
| $L_{mA}$ | = | Heat loss due to moisture in the air |
| $L_{Z}$ | = | Heat loss due to heat in atomizing steam |
| $L_{CO}$ | = | Heat loss due to formation of carbon monoxide |
| $L_{UH}$ | = | Heat loss due to unburned hydrogen |
| $L_{UHC}$ | = | Heat loss due to unburned hydrocarbons |
| $L_{\beta}$ | = | Heat loss due to surface radiation and convection |
| $L_{[P]}$ | = | Heat loss due to radiation to ash-pit, sensible heat in slag |
| $L_{d}$ | = | Heat loss due to sensible heat in flue dust |
| $L_{r}$ | = | Heat loss due to heat in pulveriser rejects |
| $L_{w}$ | = | Heat loss due to heat pickup by cooling water entering envelope |

### 5.1.3. Efficiency

Boiler efficiency and operating capacity are the commonly accepted indicators for boiler performance. Typical biomass plant operates with efficiency in the range 7~27% on HHV basis. Performance efficiency of a steam generating unit shall be based on its gross efficiency. However, abbreviated efficiency is acceptable for routine testing / acceptance test of a small steam generating unit. Abbreviated efficiency only considers major losses which are:

| | | |
|---|---|---|
| $L_{UC}$ | = | Heat loss due to unburned carbon in refuse |
| $L_{G'}$ | = | Heat loss due to heat in dry flue gas |
| $L_{mf}$ | = | Heat loss due to moisture in the “as-fired” fuel |
| $L_{H}$ | = | Heat loss due to moisture from burning of hydrogen |
| $L_{\beta}$ | = | Heat loss due to surface radiation and convection |

Two methods can be used for efficiency calculation – the Input/ Output Method and the Heat Loss Method. The Heat Loss Method is more accurate and preferable because it considers all the Losses and Heat Credits. For a steam generating unit, ASME PTC 4 Performance Test Code for Fired Steam Generators and TIP 0416-18 Performance Test Procedure for Boilers Using Biomass as Fuel shall be used as reference. Efficiency is calculated based on accurate data on accountable losses and heat credits. Based on Heat Loss Method,

$$\text{Efficiency}, \eta = 100 - \left(\frac{\text{Total Heat Losses, L}}{\text{Heat in fuel, H}_\text{f} + \text{Heat credits, B}} \times 100\right) \qquad \textit{Eqn. 6}$$

### 5.1.4. Input data required for steam generating unit/ boiler performance assessments

| A | Fuel Data (Proximate Analysis) | Symbol | Unit | Remarks |
|---|---|---|---|---|
| 1 | Moisture content | $m$ | % wt | ASME 870 |
| 2 | Moisture per lb of "as-fired" fuel | $m_f$ | $\frac{\text{lb}}{\text{lb A. F Fuel}}$ | Eqn. A1 |
| 3 | Volatile Matter | $VM$ | %wt | ASTM 871 |
| 4 | Fixed Carbon | | %wt | ASTM E777 |
| 5 | Ash | $a$ | %wt | ASTMD1102 |
| 6 | High heat value of the fuel on the "as-fired" basis | $H_f$ | $\frac{\text{Btu}}{\text{lb A. F Fuel}}$ | Eqn. A2 |
| 7 | High heat value of the fuel on a dry basis | $H_{f'}$ | $\frac{\text{Btu}}{\text{lb Fuel(dry basis)}}$ | ASTM E711 |

| B | Fuel Data (Ultimate Analysis) - ASME E870 | Symbol | Unit | Remarks |
|---|---|---|---|---|
| 1 | Carbon | $C$ | $\frac{\text{lb of carbon}}{\text{lb A. F Fuel}}$ | ASTM E777 |
| 2 | Hydrogen | $H$ | $\frac{\text{lb of hydrogen}}{\text{lb A. F Fuel}}$ | ASTM E777 |
| 3 | Oxygen | $O$ | $\frac{\text{lb of oxygen}}{\text{lb A. F Fuel}}$ | Diff. |
| 4 | Nitrogen | $N$ | $\frac{\text{lb of nitrogen}}{\text{lb A. F Fuel}}$ | ASTM E778 |
| 5 | Sulphur | $S$ | $\frac{\text{lb of sulfur}}{\text{lb A. F Fuel}}$ | ASTM E775 |

| C | Flue Gas Analysis | Symbol | Unit | Remarks |
|---|---|---|---|---|
| 1 | Carbon Dioxide | $CO_2$ | % | Measured |
| 2 | Oxygen | $O_2$ | % | Measured |
| 3 | Carbon Monoxide | $CO$ | % | Measured |
| 4 | Nitrogen (by difference) | $N_2$ | % | Diff. |
| 5 | Carbon burned per lb of "as-fired" fuel | $C_b$ | $\frac{\text{lb of carbon burned}}{\text{lb A. F Fuel}}$ | Eqn. A3 |

| D | Unit Quantities | Symbol | Unit | Remarks |
|---|---|---|---|---|
| 1 | Dry gas per lb "as-fired" fuel burned | $W_{G'}$ | $\frac{\text{lb of dry gas}}{\text{lb A.F Fuel}}$ | Eqn. A4 |
| 2 | Dry refuse per lb of "as-fired" fuel | $W_{d'p'}$ | $\frac{\text{lb of dry refuse}}{\text{lb A.F Fuel}}$ | Eqn. A10 |
| 3 | High heat value of total dry refuse (laboratory analysis) | $H_{d'p'}$ | $\frac{\text{Btu}}{\text{lb dry refuse}}$ | Take 14,500 |
| 4 | Excess Air | $A_x$ | % | Eqn. A5 |
| 5 | Mean specific heat of the dry flue gas | $C_{pG'}$ | $\frac{\text{Btu}}{\text{lb F}}$ | Take 0.24 |
| 6 | Temperature of flue gas (Boiler/ Economizer/Air Heater) | $t_G$ | F | Measured |
| 7 | Reference Air Temperature (Temperature of Air for Combustion) | $t_{RA}$ | F | Measured |
| 8 | Enthalpy of vapor at Partial Pressure Of The Moisture In The Flue Gas ($P_{mG}$) and Exit Gas Temperature ($t_G$) | $h_{B/E/AH}$ | $\frac{\text{Btu}}{\text{lb}}$ | Refer Steam Tables |
| 9 | Partial Pressure Of The Moisture In The Flue Gas | $P_{mG}$ | $\frac{\text{lb}}{\text{sq in. abs}}$ | Eqn. A6 |
| 10 | Atmospheric pressure | $P_A$ | psia | Measured |
| 11 | Moisture in the flue gas per lb of "as-fired" fuel | $m_G$ | $\frac{\text{lb moisture}}{\text{lb A.F Fuel}}$ | Eqn. A7 |
| 12 | Moisture per lb of dry air at boiler inlet (indicated by specific humidity, at the respective dry and wet bulb temperature, at the observed barometric pressure) | $W_{mA'}$ | $\frac{\text{lb moisture}}{\text{lb dry air}}$ | Appendix 1 Psychrometric Table |
| 13 | Dry air per lb of "as-fired" fuel | $W_{A'}$ | $\frac{\text{lb of dry air}}{\text{lb A.F Fuel}}$ | Eqn. A8 |
| 14 | Atomizing steam per lb of "as-fired" fuel | $W_z$ | $\frac{\text{lb of atomizing steam}}{\text{lb A.F Fuel}}$ | Measured |
| 15 | Moisture evaporated in ash-pit per lb of "as-fired" fuel | $m_p$ | $\frac{\text{lb of moisture evapor}}{\text{lb A.F Fuel}}$ | |
| 16 | Enthalpy of saturated liquid (At Reference Air Temperature($t_{RA}$)) | $h_{Rw}$ | $\frac{\text{Btu}}{\text{lb}}$ | Steam Table |
| 17 | Rate of fuel firing (as-fired) | $W_{fe}$ | $\frac{\text{lb of A.F fuel}}{\text{hr}}$ | Measured |
| 18 | Mean specific heat of dry air (At inlet temperature, constant pressure) | $C_{pA'}$ | $\frac{\text{Btu}}{\text{lb F}}$ | Appendix 2 |
| 19 | Inlet Air Temperature (with heat credit) (If there is heat supplied from external source (steam or water coil air heater) prior to entering main air heater, $t_A$ shall be measured after this heater) | $t_A$ | F | Measured |
| 20 | Atomizing steam flow | $W_{ze}$ | $\frac{\text{lb}}{\text{hr}}$ | Measured |
| 21 | Enthalpy of atomizing steam (Taken at pressure and temperature at metering point | $h_z$ | $\frac{\text{Btu}}{\text{lb}}$ | Steam Table |
| 22 | Enthalpy of saturated vapor (At Reference Air Temperature) | $h_{Rv}$ | $\frac{\text{Btu}}{\text{lb}}$ | Steam Table |
| 23 | Mean specific heat of fuel | $C_{pf}$ | $\frac{\text{Btu}}{\text{lb F}}$ | Lab |
| 24 | Temperature of Fuel | $t_f$ | F | Measured |
| 25 | Steam flow rate to all the steam driven auxiliaries | $W_{sxe}$ | $\frac{\text{lb}}{\text{hr}}$ | Measured |

| D | Unit Quantities | Symbol | Unit | Remarks |
|---|---|---|---|---|
| 26 | Enthalpy of steam supplied to any auxiliary steam drive | $h_{sx}$ | $\frac{Btu}{lb}$ | Steam Table |
| 27 | Enthalpy at the exhaust pressure and the initial entropy of steam supplied to drive the auxiliaries | $h_{ix}$ | $\frac{Btu}{lb}$ | Steam Table |
| 28 | Overall drive efficiency<br>(Includes turbine and gear efficiency) | $\eta_x$ | | Provided by OEM |
| 29 | Dry air supplied per hour | $W_{A'e}$ | $\frac{lb}{hr}$ | Eqn. A9 |
| 30 | Mean specific heat of steam | $C_{Ps}$ | $\frac{Btu}{lbF}$ | Appendix 3 |
| 31 | Temperature of Air at inlet (without heat credit)<br>(If the steam or water coil air heater is being supplied by heat direct from the unit, $t_A$ shall be measured ahead of this heater) | $t_A$ | F | Measured |
| 32 | % Comb. In Refuse Sample | $C_R$ | % | Refer Method M1 |
| 33 | Residue flow leaving with the flue gas | $W_{Rfg}$ | $\frac{lb}{hr}$ | Measured |
| 34 | Carbon content of flue gas residue (laboratory analysis of sample) | $C_{Rfg}$ | % | Lab |
| 35 | Siftings flow | $W_{Rsf}$ | $\frac{lb}{hr}$ | Measured |
| 36 | Carbon content of sifting (laboratory analysis of sample) | $C_{Rsf}$ | % | Lab |
| 37 | Carbon content of front residue (laboratory analysis of sample) | $C_{Rfr}$ | % | Lab |
| 38 | Total Ash flow | $W_{Rta}$ | $\frac{lb}{hr}$ | Eqn. M1-1 |
| 39 | Ash in flue gas residue | $W_{Rfga}$ | $\frac{lb}{hr}$ | Eqn. M1-2 |
| 40 | Total bottom ash | $W_{Rba}$ | $\frac{lb}{hr}$ | Eqn. M1-3 |
| 41 | Ash in siftings | $W_{Rsa}$ | $\frac{lb}{hr}$ | Eqn. M1-4 |
| 42 | Ash in front bottom | $W_{Rfba}$ | $\frac{lb}{hr}$ | Eqn. M1-5 |
| 43 | Rate of each refuse stream | $X_i$ | % | Eqn. M1-6 |

| E | Energy Heat Input And Output Calculations | Symbol | Unit | Remarks |
|---|---|---|---|---|
| 1 | Steam flow entering super-heater | $W_{seSH}$ | $\frac{\text{lb steam}}{\text{hr}}$ | Measured |
| 2 | Reheat steam flow | $W_{seRH}$ | $\frac{\text{lb steam}}{\text{hr}}$ | Measured |
| 3 | Super-heater spray water flow | $W_{weSH}$ | $\frac{\text{lb water}}{\text{hr}}$ | Measured |
| 4 | Reheat spray water flow | $W_{weRH}$ | $\frac{\text{lb water}}{\text{hr}}$ | Measured |
| 5 | Blow-down flow | $W_{weB}$ | $\frac{\text{lb water}}{\text{hr}}$ | Measured |
| 6 | Injection flow (If circulating pump included in envelope boundary) | $W_{weI}$ | $\frac{\text{lb water}}{\text{hr}}$ | Measured |
| 7 | Leak-off flow (If circulating pump included in envelope boundary) | $W_{weL}$ | $\frac{\text{lb water}}{\text{hr}}$ | Measured |
| 8 | Enthalpy of feed-water entering unit | $h_{wFW}$ | $\frac{\text{Btu}}{\text{lb water}}$ | Steam Table |
| 9 | Enthalpy of super-heater spray water | $h_{wSH}$ | $\frac{\text{Btu}}{\text{lb water}}$ | Steam Table |
| 10 | Enthalpy of spray water | $h_{wS}$ | $\frac{\text{Btu}}{\text{lb water}}$ | Steam Table |
| 11 | Enthalpy of blow-down | $h_{wB}$ | $\frac{\text{Btu}}{\text{lb water}}$ | Steam Table |
| 12 | Enthalpy of injection water (If circulating pump included in envelope boundary) | $h_{wI}$ | $\frac{\text{Btu}}{\text{lb water}}$ | Steam Table |
| 13 | Enthalpy of leak-off (If circulating pump included in envelope boundary) | $h_{wL}$ | $\frac{\text{Btu}}{\text{lb water}}$ | Steam Table |
| 14 | Enthalpy of steam at super-heater outlet | $h_{sSH,O}$ | $\frac{\text{Btu}}{\text{lb steam}}$ | Steam Table |
| 15 | Enthalpy of steam at re-heater inlet | $h_{sR,I}$ | $\frac{\text{Btu}}{\text{lb steam}}$ | Steam Table |
| 16 | Enthalpy of steam at re-heater outlet | $h_{sR,O}$ | $\frac{\text{Btu}}{\text{lb steam}}$ | Steam Table |
| | **Total Chemical Heat Input** | $E_{Hf}$ | $\frac{\text{Btu}}{\text{hr}}$ | Eqn. M2-1 |
| | **Total Heat Absorbed By Working Fluid** | $E_{out}$ | $\frac{\text{Btu}}{\text{Hr}}$ | Eqn. M3-1 |
| | **Heat Loss Calculation** | | | |
| L1 | Heat loss due to heat in dry flue gas | $L_{G'}$ | $\frac{\text{Btu loss}}{\text{lb A.F fuel}}$ | Eqn. L1 |
| L2 | Heat loss due to moisture in the “as-fired” fuel | $L_{mf}$ | $\frac{\text{Btu loss}}{\text{lb A.F fuel}}$ | Eqn. L2 |
| L3 | Heat loss due to moisture from burning of hydrogen | $L_H$ | $\frac{\text{Btu loss}}{\text{lb A.F fuel}}$ | Eqn. L3 |
| L4 | Heat loss due to surface radiation and convection | $L_\beta$ | $\frac{\text{Btu loss}}{\text{lb A.F fuel}}$ | Eqn. L4. |
| L5 | Heat loss due to unburned carbon in refuse | $L_{UC}$ | $\frac{\text{Btu loss}}{\text{lb A.F fuel}}$ | Eqn. L5 |
| | **Heat Credits Calculations** | | | |
| B1 | Heat credit supplied by entering air | $B_{Ae}$ | $\frac{\text{Btu credit}}{\text{hr}}$ | Eqn. B1 |
| B2 | Heat credit supplied by atomizing steam | $B_{ze}$ | $\frac{\text{Btu credit}}{\text{hr}}$ | Eqn. B2 |
| B3 | Heat credit supplied by sensible heat in the fuel | $B_{fe}$ | $\frac{\text{Btu credit}}{\text{hr}}$ | Eqn. B3 |
| B4 | Heat credit supplied by auxiliary drives within the envelope | $B_{xe}$ | $\frac{\text{Btu credit}}{\text{hr}}$ | Eqn. B4 |
| B5 | Heat credit supplied from the moisture entering with the inlet air | $B_{mAe}$ | $\frac{\text{Btu credit}}{\text{hr}}$ | Eqn. B5 |

### 5.1.5. Boiler Performance Calculation

#### 5.1.5.1. Basic Parameters Calculation

- Percentage of moisture in fuel as determined by analysis of moisture sample,

$$m_f = \frac{\text{lb of water}}{\text{lb of A. F fuel}} \qquad \textbf{Eqn. A1}$$

- High heat value of the fuel on the "as-fired" basis,

$$H_f = H_{f'} - 0.212H - 0.0008(O + N) \qquad \textbf{Eqn. A2}$$

Ref: Biomass Energy Data Book 2011

- Carbon burned per lb of "as-fired" fuel, $C_b$

$$C_b = \frac{C}{100} - \frac{W_{d'p'} \times H_{d'p'}}{14500} \qquad \textbf{Eqn. A3}$$

- Dry gas per lb "as-fired" fuel burned, $W_{G'}$

$$W_{G'} = \frac{44.01CO_2 + 32.00O_2 + 28.02N_2 + 28.01CO}{12.01\,(CO_2 + CO)} \times \left(C_b + \frac{12.01}{8}S\right) \qquad \textbf{Eqn. A4}$$

- Excess Air, $A_x$

$$A_x = 100 \times \frac{O_2 - \frac{CO}{2}}{0.268\,N_2 - (O_2 - \frac{CO}{2})} \qquad \textbf{Eqn. A5}$$

- Partial Pressure of the Moisture In The Flue Gas, $P_{mG}$

$$P_{mG} = \frac{P_A}{1 + \frac{100 \times 1.5C_b}{m_G(CO_2 + CO)}} \qquad \textbf{Eqn. A6}$$

- Moisture in the flue gas per lb of "as-fired" fuel, $m_G$

$$m_G = 8.936H + W_{mA'} + W_{A'} + m_f + W_z + m_p \qquad \textbf{Eqn. A7}$$

- Dry air per lb of "as-fired" fuel, $W_{A'}$

$$W_{A'} = \frac{[\frac{28.02N_2}{12.01(CO_2 + CO)}(C_b + \frac{12.01S}{32.07})] - N}{0.7685} \qquad \textbf{Eqn. A8}$$

- Dry air supplied per hour, $W_{A'e}$

$$W_{A'e} = W_{A'} \times W_{fe} \qquad \textbf{Eqn. A9}$$

- Dry refuse per lb of "as-fired" fuel, $W_{d'p'}$

$$W_{d'p'} = \frac{\%Ash\ in\ \text{as-fire}\ fuel}{100 - \%\ comb.in\ refuse\ sample} \qquad \textbf{Eqn. A10}$$

#### 5.1.5.2. Special Methodologies Calculations

**M-1: Method to determine percentage of combustible in Refuse Sample**

Data required:

i. Rate of fuel firing (as-fired), $W_{fe}$ (lb/hr)
ii. Ash Content (%)
iii. Measured value for:
   a. Residue flow leaving with the flue gas, $W_{R,fg}$
   b. Carbon content of flue gas residue (%) (laboratory analysis of sample)
   c. Siftings flow (lb/hr), $W_{R,sf}$
   d. Carbon content of siftings (%) (laboratory analysis of sample)
   e. Carbon content of front residue (%) (laboratory analysis of sample)

Calculation:

- Total ash flow

$$Total\ ash\ flow = \text{Rate of fuel firing} \times \text{Ash Content} \qquad \textbf{Eqn. M1} - \textbf{1}$$

- Ash in flue gas residue

$$Ash\ in\ flue\ gas\ residue = \text{Residue flow leaving with the flue gas} \times \left(1 - \frac{\text{carbon content of flue gas residue}}{100}\right) \qquad \textbf{Eqn. M1} - \textbf{2}$$

- Total bottom ash

$$Total\ bottom\ ash = Total\ ash\ flow - Ash\ in\ flue\ gas\ residue \qquad \textbf{Eqn. M1} - \textbf{3}$$

- Ash in siftings

$$Ash\ in\ siftings\ = \text{Siftings flow} \times \left(1 - \frac{\text{Carbon content of siftings}}{100}\right) \qquad \boldsymbol{Eqn. M1-4}$$

- Ash in front bottom

$$\text{Ash in front bottom} = \text{Total bottom ash} - \text{ash in siftings} \qquad \boldsymbol{Eqn. M1-5}$$

Using the calculated flow of each refuse, the percentage of combustible in refuse sample is determined based on the average carbon content of the refuse sample, which is calculated by weighted average of each streams

$$\text{Percentage of combustible in refuse sample} = \sum X_i C_i$$

Where

$C_i$ = Carbon Content of each refuse stream ($C_{Rfg}$ , $C_{Rsf}$ , $C_{Rfr}$)
$X_i$ = Rate of refuse stream per total refuse streams

- Rate of refuse stream per total refuse stream

$$\text{Rate of refuse stream per total refuse stream} = \frac{\text{measured refuse stream flow rate}}{\text{Total refuse stream flow rate}} \qquad \boldsymbol{Eqn. M1-6}$$

For flue gas stream,

$$\text{Rate of flue gas stream} = \frac{\text{Residue flow leaving with the flue gas}}{\text{Residue flow leaving with the flue gas} + \text{Siftings flow} + \left(\frac{\text{Ash in front bottom}}{1 - \frac{\text{Carbon content of front residue}}{100}}\right)}$$

For siftings stream,

$$\text{Rate of siftings stream} = \frac{\text{Siftings flow}}{\text{Residue flow leaving with the flue gas} + \text{Siftings flow} + \left(\frac{\text{Ash in front bottom}}{1 - \frac{\text{Carbon content of front residue}}{100}}\right)}$$

For front bottom ash stream,

$$\text{Rate of front bottom ash stream} = \frac{\left(\frac{\text{Ash in front bottom}}{1 - \frac{\text{Carbon content of front residue}}{100}}\right)}{\text{Residue flow leaving with the flue gas} + \text{Siftings flow} + \left(\frac{\text{Ash in front bottom}}{1 - \frac{\text{Carbon content of front residue}}{100}}\right)}$$

**M-2: Method to determine Total Chemical Heat Input to the Unit**

$$\text{Total Chemical Heat Input}, \mathrm{E_{H_f}} = \mathrm{H_f} \times \mathrm{W_{fe}} \qquad \textbf{Eqn. M2} - \textbf{1}$$

**M-3: Method to determine Total Heat Absorbed by Working Fluid**

$$Total\ heat\ absorbed\ by\ working\ fluid, E_{out} = W_{seSH}\left(h_{sSH,O} - h_{wFW}\right) + W_{weSH}\left(h_{sSH,O} - h_{wSH}\right) + W_{seRH}\left(h_{sR,O} - h_{sR,I}\right) + W_{weRH}\left(h_{sR,O} - h_{wS}\right) + W_{weB}\left(h_{wB} - h_{wFW}\right) + W_{weL}\left(h_{wL} - h_{wI}\right) + \left(W_{weI} - W_{weL}\right)\left(h_{wFW} - h_{wI}\right) \qquad \textbf{Eqn. M3} - \textbf{1}$$

### 5.1.5.3. Efficiency Major Heat Loss Calculations

- Heat loss due to heat in dry flue gas, $L_{G'}$

$$L_{G'} = W_{G'} \times C_{pG'}(t_G - t_{RA}) \qquad \textbf{Eqn. L1}$$

- Heat loss due to moisture in the "as-fired" fuel, $L_{mf}$

$$L_{mf} = m_f \times \left(h_{\mathrm{B/E/AH}} - h_{Rw}\right) \qquad \textbf{Eqn. L2}$$

- Heat loss due to moisture from burning of hydrogen, $L_H$

$$L_H = 8.936 \times H\left(h_{\mathrm{B/E/AH}} - h_{Rw}\right) \qquad \textbf{Eqn. L3}$$

- Heat loss due to surface radiation and convection, $L_\beta$

$$L_\beta = Percentage\ of\ radiation\ loss \times H_f \qquad \textbf{Eqn. L4}$$

*Refer to ABMA Standard Radiation Loss Chart with Corrected Air Velocities in Appendix 4 and Appendix 5.*
*Heat loss shall be accounted as contract value fixed by the ABMA curve as 0.18% at TMCR, 0.23% at 75%TMCR and 0.33% at 50%TMCR*

- Heat loss due to unburned carbon in refuse, $L_{UC}$

$$L_{UC} = \%\ \mathrm{Comb.\ In\ Refuse\ Sample} \times \left(\frac{\mathrm{Ash}}{1 - \%\ \mathrm{Comb.\ In\ Refuse\ Sample}}\right) \times \mathrm{High\ heat\ value\ of\ total\ dry\ refuse} \qquad \textbf{Eqn. L5}$$

Total Losses, L is calculated as follows:

$$\boldsymbol{L} = L_{G'} + L_{mf} + L_H + L_\beta + L_{UC} \qquad \left(\frac{Btu}{lb\ A.F\ fuel}\right)$$

#### 5.1.5.4. Efficiency Heat Credits Calculations

- Heat credit supplied by entering air, $B_{Ae}$

$$B_{Ae} = (W_{A\prime} - W_{A'5}) \times W_{fe} \times C_{p\,A'}(t_A - t_{RA}) + W_{A'5} \times W_{fe} \times C_{p\,A'}(t_{A\prime 5} - t_{RA}) \quad \boldsymbol{Eqn.B1}$$

- Heat credit supplied by atomizing steam, $B_{ze}$

$$B_{ze} = W_{ze} \times (h_z - h_{Rv}) \quad \boldsymbol{Eqn.B2}$$

- Heat credit supplied by sensible heat in the fuel, $B_{fe}$

$$B_{fe} = W_{fe} \times C_{pf}\left(t_f - t_{RA}\right) \quad \boldsymbol{Eqn.B3}$$

- Heat credit supplied by auxiliary drives within the envelope, $B_{xe}$

$$B_{xe} = W_{sxe} \times (h_{sx} - h_{ix})\eta_x \quad \boldsymbol{Eqn.B4}$$

- Heat credit supplied from the moisture entering with the inlet air, $B_{mAe}$

$$B_{mAe} = W_{mA\prime} \times W_{A\prime e} \times C_{ps}(t_A - t_{RA}) \quad \boldsymbol{Eqn.B5}$$

*Total Heat Credit, B is calculated as follows*

$$\boldsymbol{B} = \frac{B_{Ae} + B_{ze} + B_{fe} + B_{xe} + B_{mAe}}{W_{fe}} \qquad \left(\frac{Btu}{lb\ A.F\ fuel}\right)$$

***Based on the above calculations, boiler performance efficiency can be determined as follows:***

$$\boldsymbol{Efficiency, \eta = 100 - \left(\frac{Total\ Heat\ Losses, L}{Heat\ in\ fuel, H_f + Heat\ credits, B} \times 100\right)}$$

## 5.2. Turbine-Generator Performance

### 5.2.1. Heat Rate

Heat Rate (kJ/kWh) is heat consumption per unit output per hour (kJ/kWhr). This indicates the amount of energy required to produce the given amount of electric power.

### 5.2.2. Power Output

Power (kW) is the useful energy per unit of time, delivered by the turbine-generator unit. Evaluated based on the power output at the high voltage terminals of the main transformer.

### 5.2.3. Input data required for turbine-generator performance assessment

| No | Parameters | Unit | Rated Capability / Conditions | Test Data / Measured |
|---|---|---|---|---|
| 1 | Turbine Capability | *kW* | *Rated Value* | Measured |
| 2 | Throttle steam pressure | *psia* | *Rated Value* | Measured |
| 3 | Throttle steam temperature | *°F* | *Rated Value* | Measured |
| 4 | Throttle steam enthalpy | *Btu/lbm* | *Rated Value* | Measured |
| 5 | Exhaust pressure | *in Hg abs* | *Rated Value* | Measured |
| 6 | Cycle make-up | *%* | *Rated Value* | Measured |
| 7 | Power Factor | *%* | *Rated Value* | Measured |
| 8 | Hydrogen Pressure | *psig* | *Rated Value* | Measured |
| 9 | Reference heat rate (max valve opening, operating at the rated conditions) | *Btu/kWh* | *Rated Value* | Measured |
| 10 | Generator Output Power | *kW* | *Rated Value* | Measured |
| 11 | Generator - Power Factor | %% | *Rated Value* | Measured |
| 12 | Generator - Hydrogen Pressure | psig | *Rated Value* | Measured |

| No | Parameters | Unit | Calculated Data/ Reference |
|---|---|---|---|
| 1 | Test period | *hr* | Measured |
| 2 | Feed-water temperature | ℉ | Measured |
| 3 | Feed-water Enthalpy | $\frac{Btu}{lbm}$ | Measured |
| 4 | Feed-water flow to steam generator | *lbm/hr* | Measured |
| 5 | Condenser hot-well storage level changes over the test period | *lbm/hr* | Measured |
| 6 | Steam generator storage level changes over the test period | *lbm/hr* | Measured |
| 7 | Steam to air ejector | *lbm/hr* | Measured |
| 8 | Hotwell pump gland leakage | *lbm/hr* | Measured |
| 9 | System Leakage | $\frac{lbm}{hr}$ | *Eqn. T1* |
| 10 | Throttle Steam Flow | $\frac{lbm}{hr}$ | *Eqn. T2* |
| 11 | Losses for % power factor (test data) | *kW* | *(Based on Manufacturer's Turbine Performance Data, based on* Generator Output and %PF *)* |
| 12 | Losses for % power factor (rated capability) | *kW* | *(Based on Manufacturer's Turbine Performance Data, based on* Generator Output and %PF*)* |
| 13 | Losses due to deviation from rated/specified power factor value | *kW* | *Eqn. T3* |
| 14 | Losses due to deviation from rated or specified hydrogen pressure | *kW* | *(Based on Manufacturer's Turbine Performance Data)* |
| 15 | Corrected Generator Output Power to specified PF and $H_2$ pressure | *kW* | *Eqn. T4* |
| 16 | Heat Rate | *Btu/kWhr* | *Eqn. T5* |
| 17 | Corrected Heat Rate | *Btu/kWhr* | *Eqn. T6* |
| 18 | Flow Correction Factor | | *Eqn T7* |
| 19 | Corrected Steam Flow rate | $\frac{lbm}{hr}$ | *Eqn. T8* |
| 20 | Steam Rate | $\frac{lbm}{kWhr}$ | *Eqn. T9* |
| 21 | Corrected Steam Rate | $\frac{lbm}{kWhr}$ | *Eqn. T10* |
| 22 | Corrected Generator Output | *kW* | *Eqn. T11* |

#### 5.2.4. Turbine-Generator Performance Calculations

- $\text{System leakage} = \text{Condenser hot} - \text{well storage level changes over the test period} - \text{Steam generator storage level changes over the test period}$ $\quad$ ***Eqn.T1***

- $\text{Throttle steam flow rate} = \text{Feedwater flow to steam generator} - \text{system leakage} - \text{Steam generator storage level changes over the test period} - \text{steam to air ejector}$ $\quad$ ***Eqn.T2***

- $\text{Losses due to deviation from rated or specified power factor value} = \text{Losses for \% power factor (test data)} - \text{Losses for \% power factor (rated capability)}$ $\quad$ ***Eqn.T3***

  Refer to Generator Electrical Losses Chart (to be provided by OEM) as in Appendix 6

- $\text{Corrected Generator Output Power to specified PF and } H_2 \text{ pressure} = \text{Measured Generator Output Power} + \text{Losses due to deviation from rated or specified power factor value} - \text{Losses due to deviation from rated or specified hydrogen pressure}$ $\quad$ ***Eqn.T4***

  Refer to Generator Electrical Losses Chart (to be provided by OEM) as in Appendix 6

- Heat Rate

$$\text{Heat Rate} = \frac{(\text{throttle steam flow rate x throttle steam enthalpy})}{\text{Corrected Generator Output Power}} - \frac{(\text{feedwater flow rate to steam generator x feedwater enthalpy})}{\text{Corrected Generator Output Power}} \quad \textit{Eqn.T5}$$

- Corrected Heat Rate

$$\text{Corrected Heat Rate} = \frac{\text{Test Heat Rate}}{\text{Correction Divisor}} \quad \textit{Eqn.T6}$$

- Flow Correction Factor

$$\text{Flow correction factor} = \sqrt{\frac{\text{throttle steam pressure}_{\text{rated}}}{\text{throttle steam pressure}_{\text{test}}} \times \frac{\text{specific volume}_{\text{test}}}{\text{specific volume}_{\text{rated}}}} \quad \textit{Eqn T7}$$

- Corrected Steam Flow Rate

$$\text{Corrected steam flow rate} = \text{throttle steam flow rate} \times \text{flow correction factor} \quad \textit{Eqn.T8}$$

- Steam Rate

$$\text{Steam Rate} = \frac{\text{throttle steam flow rate}}{\text{Corrected generator output power}} \qquad \textbf{\textit{Eqn.T9}}$$

- Corrected Steam Rate

$$\text{Corrected Steam Rate} = \frac{\text{Steam Rate}}{\text{Correction Divisor}} \qquad \textbf{\textit{Eqn.T10}}$$

- Corrected Generator Output

$$\text{Corrected Generator Output} = \frac{\text{Corrected steam flow rate}}{\text{Corrected Steam Rate}} \qquad \textbf{\textit{Eqn.T11}}$$

# PART 6 PERFORMANCE RESULTS ASSESSMENTS

Based on the results obtained during performance evaluation, results assessment as listed in Table 10 shall be made

**Table 10: Results Assessments**

| No | Key Performance Indicators | Deviation Assessment | | | |
|---|---|---|---|---|---|
| | | Test Results | Rated value from OEM / statutory requirements | % Deviation | Accepted/ Rejected |
| **A** | **STEAM GENERATING UNIT / BOILER** | | | | |
| 1 | Energy Input | | | | |
| 2 | Energy Output | | | | |
| 3 | Efficiency | | | | |
| 4 | Flue gas monitoring | | | | |
| 5 | Plant particulate emissions | | | | |
| **B** | **TURBINE-GENERATOR** | | | | |
| 1 | Heat Rate (corrected value) | | | | |
| 2 | Power Output (corrected value) | | | | |
| 3 | Steam Rate (corrected value) | | | | |

It is also desirable but not mandatory for a performance curve showing plant output data throughout the test to be plotted for all test runs.

# PART 7 CONCLUSIONS

A comprehensive guideline has been established for performance assessment of biomass power plant for Acceptance Test and Reliability Test prior to FiT commencement.

This guideline was established based on international standards, however considerations have been given for real engineering practices and applicability for harnessing RE in Malaysian context.

The guideline is anticipated to facilitate RE site owners to meet the requirement set by the RE Act 2011 – Renewable Energy (Technical and Operational Requirements) Rules 2011

# PART 8 LIST OF REFERENCES

[1] Dave Andrews (2009) "Owning and Operating Costs of Waste and Biomass Power Plant" Claverton Energy Conference, 2009

[2] BEE Code for Co-Generation. Indian Renewable Energy Development Agency (2006)

[3] State of California AIR RESOURCES BOARD "METHOD 3 Gas Analysis for Carbon Dioxide, Oxygen, Excess Air, and Dry Molecular Weight" (1999)

[4] ASME Performance Test Code PTC 4.1 for Sthe Steam Generating Unit/ Boiler

[5] ASME Performance Test Code PTC 6 for Steam Turbines

[6] ASME PTC 6A Appendix A to Test Code for Steam Turbines

[7] ASME PTC6-REPORT Guidance for evaluation of Measurement Uncertainty in Test Code for Steam Turbines

[8] ASME PTC6S-REPORT Procedures for Routine Performance Test of Steam Turbines

[9] PTC19.5 (R2004) - Supplementary Code on Instruments & Apparatus for Flow Measurements

[10] PTC 19.6 Electrical Measurements In Power Circuits Instruments And Apparatus

[11] PTC19.2 - (R1998) - Supplementary Code on Instruments & Apparatus for Pressure Measurements

[12] ASME PTC 19.3 (R1998) - Supplementary Code on Instruments & Apparatus for Temperature Measurement

[13] TAPPI TIP 0416-18 "Performance Test Procedure for Boilers Using Biomass as Fuel"

[14] ASME PTC 19.10 Supplementary Code on Instruments & Apparatus - Flue and Exhaust Gas Analyses

[15] TAPPI TIP 0416-17 "Sampling Procedures for Biomass Fuel for Boiler Performance Testing"

[16] ASME E870 Standard Test Methods for Analysis of Woods Fuels shall be used as standard reference for compositions analysis.

[17] ASTM E871 Standard Test Methods for Volatile Matter in the Analysis Sample of Refuse-derived Fuel

[18] ASTM D1102 Standard Test Methods for Ash in Wood

[19] ASTM E711 Standard Bomb Calorimeter Test Method for Gross Calorific Value of Refuse-derived Fuel

[20] ASTM E777 Standard Test Methods for Carbon and Hydrogen in the Analysis Sample of Refuse-derived Fuel

[21] ASTM E778 Standard Test Methods for Nitrogen in the Analysis Sample of Refuse-derived Fuel

[22] ASTM E775 Standard Test Methods for Total Sulphur in the Analysis Sample of Refuse-derived Fuel

[23] ASTM D5373 - 08 Standard Test Methods for Instrumental Determination of Carbon, Hydrogen, and Nitrogen in Laboratory Samples of Coal (Replacing ASTM D3178-89(2002) Standard Test Methods for Carbon and Hydrogen in the Analysis Sample of Coal and Coke (Withdrawn 2007))

[24] ASTM D6316 - 09b Standard Test Method for Determination of Total, Combustible and Carbonate Carbon in Solid Residues from Coal and Coke (Replacing ASTM D1756-02(2007) Standard Test Method for Determination as Carbon Dioxide of Carbonate Carbon in Coal (Withdrawn 2013))

[25] Biomass Energy Data Book 2011

[26] BS EN-12952-152003 Water Tube Boilers and Auxiliary Installations : Part 15 Acceptance Test

[27] EPA Method 3, Gas Analysis for Determination of Dry Molecular Weight, CFR40, Part 60

[28] ASTM E1757 - 01(2007) Standard Practice for Preparation of Biomass for Compositional Analysis

[29] TAPPI Test Method T264 cm-97, "Preparation of wood for chemical analysis" In TAPPI Test Methosd 2002-2003. Atlanta, GA: Technical Association of the Pulp and Paper Industry

[30] NREL/TP-510-42620 Analytical Procedure (LAP) for Preparation of Samples for Compositional Analysis Laboratory, 2008

[31] NREL/TP-510-42621 (2008) Laboratory Analytical Procedure (LAP) for Determination of Total Solids in Biomass and Total Dissolved Solids in Liquid Process Samples

[32] TAPPI Method T412 om-02. 2002. "Moisture in Pulp, Paper and Paperboard." Test methods of the Technical Association of the Pulp and Paper Industry 2002-2003.

[33] ASTM E1756 - 08 Standard Test Method for Determination of Total Solids in Biomass

[34] Reference Method EPS 1/RM/8 – "Standard Reference Methods for Source Testing: Measurement of Emissions of Particulates from Stationary Sources" Environment Canada Catalogue No. En 49-24/1-8E, ISBN 0-662-21355-6 (1994)

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| Appendix 6 | Generator Electrical Losses |
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# APPENDIX 1
# PSYCHROMETRIC TABLE



**Table 2 Thermodynamic Properties of Moist Air at Standard Atmospheric Pressure, 101.325 kPa**

| Temp., °C | Humidity Ratio, kg(w)/kg(da) | Specific Volume, $m^3$/kg (dry air) | | | Specific Enthalpy, kJ/kg (dry air) | | | Specific Entropy, kJ/(kg·K) (dry air) | | | Condensed Water Specific Enthalpy, kJ/kg | Condensed Water Specific Entropy, kJ/(kg·K) | Condensed Water Vapor Pressure, kPa | Temp., °C |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $t$ | $W_s$ | $v_{da}$ | $v_{as}$ | $v_s$ | $h_{da}$ | $h_{as}$ | $h_s$ | $s_{da}$ | $s_{as}$ | $s_s$ | $h_w$ | $s_w$ | $p_s$ | $t$ |
| −60 | 0.0000067 | 0.6027 | 0.0000 | 0.6027 | −60.351 | 0.017 | −60.334 | −0.2495 | 0.0001 | −0.2494 | −446.29 | −1.6854 | 0.00108 | −60 |
| −59 | 0.0000076 | 0.6056 | 0.0000 | 0.6056 | −59.344 | 0.018 | −59.326 | −0.2448 | 0.0001 | −0.2447 | −444.63 | −1.6776 | 0.00124 | −59 |
| −58 | 0.0000087 | 0.6084 | 0.0000 | 0.6084 | −58.338 | 0.021 | −58.317 | −0.2401 | 0.0001 | −0.2400 | −442.95 | −1.6698 | 0.00141 | −58 |
| −57 | 0.0000100 | 0.6113 | 0.0000 | 0.6113 | −57.332 | 0.024 | −57.308 | −0.2354 | 0.0001 | −0.2353 | −441.27 | −1.6620 | 0.00161 | −57 |
| −56 | 0.0000114 | 0.6141 | 0.0000 | 0.6141 | −56.326 | 0.028 | −56.298 | −0.2308 | 0.0001 | −0.2306 | −439.58 | −1.6542 | 0.00184 | −56 |
| −55 | 0.0000129 | 0.6170 | 0.0000 | 0.6170 | −55.319 | 0.031 | −55.288 | −0.2261 | 0.0002 | −0.2260 | −437.89 | −1.6464 | 0.00209 | −55 |
| −54 | 0.0000147 | 0.6198 | 0.0000 | 0.6198 | −54.313 | 0.036 | −54.278 | −0.2215 | 0.0002 | −0.2214 | −436.19 | −1.6386 | 0.00238 | −54 |
| −53 | 0.0000167 | 0.6226 | 0.0000 | 0.6227 | −53.307 | 0.041 | −53.267 | −0.2170 | 0.0002 | −0.2168 | −434.48 | −1.6308 | 0.00271 | −53 |
| −52 | 0.0000190 | 0.6255 | 0.0000 | 0.6255 | −52.301 | 0.046 | −52.255 | −0.2124 | 0.0002 | −0.2122 | −432.76 | −1.6230 | 0.00307 | −52 |
| −51 | 0.0000215 | 0.6283 | 0.0000 | 0.6284 | −51.295 | 0.052 | −51.243 | −0.2079 | 0.0002 | −0.2076 | −431.03 | −1.6153 | 0.00348 | −51 |
| −50 | 0.0000243 | 0.6312 | 0.0000 | 0.6312 | −50.289 | 0.059 | −50.230 | −0.2033 | 0.0003 | −0.2031 | −429.30 | −1.6075 | 0.00394 | −50 |
| −49 | 0.0000275 | 0.6340 | 0.0000 | 0.6341 | −49.283 | 0.067 | −49.216 | −0.1988 | 0.0003 | −0.1985 | −427.56 | −1.5997 | 0.00445 | −49 |
| −48 | 0.0000311 | 0.6369 | 0.0000 | 0.6369 | −48.277 | 0.075 | −48.202 | −0.1944 | 0.0004 | −0.1940 | −425.82 | −1.5919 | 0.00503 | −48 |
| −47 | 0.0000350 | 0.6397 | 0.0000 | 0.6398 | −47.271 | 0.085 | −47.186 | −0.1899 | 0.0004 | −0.1895 | −424.06 | −1.5842 | 0.00568 | −47 |
| −46 | 0.0000395 | 0.6426 | 0.0000 | 0.6426 | −46.265 | 0.095 | −46.170 | −0.1855 | 0.0004 | −0.1850 | −422.30 | −1.5764 | 0.00640 | −46 |
| −45 | 0.0000445 | 0.6454 | 0.0000 | 0.6455 | −45.259 | 0.108 | −45.151 | −0.1811 | 0.0005 | −0.1805 | −420.54 | −1.5686 | 0.00721 | −45 |
| −44 | 0.0000500 | 0.6483 | 0.0001 | 0.6483 | −44.253 | 0.121 | −44.132 | −0.1767 | 0.0006 | −0.1761 | −418.76 | −1.5609 | 0.00811 | −44 |
| −43 | 0.0000562 | 0.6511 | 0.0001 | 0.6512 | −43.247 | 0.137 | −43.111 | −0.1723 | 0.0006 | −0.1716 | −416.98 | −1.5531 | 0.00911 | −43 |
| −42 | 0.0000631 | 0.6540 | 0.0001 | 0.6540 | −42.241 | 0.153 | −42.088 | −0.1679 | 0.0007 | −0.1672 | −415.19 | −1.5453 | 0.01022 | −42 |
| −41 | 0.0000708 | 0.6568 | 0.0001 | 0.6569 | −41.235 | 0.172 | −41.063 | −0.1636 | 0.0008 | −0.1628 | −413.39 | −1.5376 | 0.01147 | −41 |
| −40 | 0.0000793 | 0.6597 | 0.0001 | 0.6597 | −40.229 | 0.192 | −40.037 | −0.1592 | 0.0009 | −0.1584 | −411.59 | −1.5298 | 0.01285 | −40 |
| −39 | 0.0000887 | 0.6625 | 0.0001 | 0.6626 | −39.224 | 0.216 | −39.007 | −0.1549 | 0.0010 | −0.1540 | −409.77 | −1.5221 | 0.01438 | −39 |
| −38 | 0.0000992 | 0.6653 | 0.0001 | 0.6654 | −38.218 | 0.241 | −37.976 | −0.1507 | 0.0011 | −0.1496 | −407.96 | −1.5143 | 0.01608 | −38 |
| −37 | 0.0001108 | 0.6682 | 0.0001 | 0.6683 | −37.212 | 0.270 | −36.942 | −0.1464 | 0.0012 | −0.1452 | −406.13 | −1.5066 | 0.01796 | −37 |
| −36 | 0.0001237 | 0.6710 | 0.0001 | 0.6712 | −36.206 | 0.302 | −35.905 | −0.1421 | 0.0014 | −0.1408 | −404.29 | −1.4988 | 0.02005 | −36 |
| −35 | 0.0001379 | 0.6739 | 0.0001 | 0.6740 | −35.200 | 0.336 | −34.864 | −0.1379 | 0.0015 | −0.1364 | −402.45 | −1.4911 | 0.02235 | −35 |
| −34 | 0.0001536 | 0.6767 | 0.0002 | 0.6769 | −34.195 | 0.375 | −33.820 | −0.1337 | 0.0017 | −0.1320 | −400.60 | −1.4833 | 0.02490 | −34 |
| −33 | 0.0001710 | 0.6796 | 0.0002 | 0.6798 | −33.189 | 0.417 | −32.772 | −0.1295 | 0.0018 | −0.1276 | −398.75 | −1.4756 | 0.02772 | −33 |
| −32 | 0.0001902 | 0.6824 | 0.0002 | 0.6826 | −32.183 | 0.464 | −31.718 | −0.1253 | 0.0020 | −0.1233 | −396.89 | −1.4678 | 0.03082 | −32 |
| −31 | 0.0002113 | 0.6853 | 0.0002 | 0.6855 | −31.178 | 0.517 | −30.661 | −0.1212 | 0.0023 | −0.1189 | −395.01 | −1.4601 | 0.03425 | −31 |
| −30 | 0.0002346 | 0.6881 | 0.0003 | 0.6884 | −30.171 | 0.574 | −29.597 | −0.1170 | 0.0025 | −0.1145 | −393.14 | −1.4524 | 0.03802 | −30 |
| −29 | 0.0002602 | 0.6909 | 0.0003 | 0.6912 | −29.166 | 0.636 | −28.529 | −0.1129 | 0.0028 | −0.1101 | −391.25 | −1.4446 | 0.04217 | −29 |
| −28 | 0.0002883 | 0.6938 | 0.0003 | 0.6941 | −28.160 | 0.707 | −27.454 | −0.1088 | 0.0031 | −0.1057 | −389.36 | −1.4369 | 0.04673 | −28 |
| −27 | 0.0003193 | 0.6966 | 0.0004 | 0.6970 | −27.154 | 0.782 | −26.372 | −0.1047 | 0.0034 | −0.1013 | −387.46 | −1.4291 | 0.05175 | −27 |
| −26 | 0.0003533 | 0.6995 | 0.0004 | 0.6999 | −26.149 | 0.867 | −25.282 | −0.1006 | 0.0037 | −0.0969 | −385.55 | −1.4214 | 0.05725 | −26 |
| −25 | 0.0003905 | 0.7023 | 0.0004 | 0.7028 | −25.143 | 0.959 | −24.184 | −0.0965 | 0.0041 | −0.0924 | −383.63 | −1.4137 | 0.06329 | −25 |
| −24 | 0.0004314 | 0.7052 | 0.0005 | 0.7057 | −24.137 | 1.059 | −23.078 | −0.0925 | 0.0045 | −0.0880 | −381.71 | −1.4059 | 0.06991 | −24 |
| −23 | 0.0004762 | 0.7080 | 0.0005 | 0.7086 | −23.132 | 1.171 | −21.961 | −0.0885 | 0.0050 | −0.0835 | −379.78 | −1.3982 | 0.07716 | −23 |
| −22 | 0.0005251 | 0.7109 | 0.0006 | 0.7115 | −22.126 | 1.292 | −20.834 | −0.0845 | 0.0054 | −0.0790 | −377.84 | −1.3905 | 0.08510 | −22 |
| −21 | 0.0005787 | 0.7137 | 0.0007 | 0.7144 | −21.120 | 1.425 | −19.695 | −0.0805 | 0.0060 | −0.0745 | −375.90 | −1.3828 | 0.09378 | −21 |
| −20 | 0.0006373 | 0.7165 | 0.0007 | 0.7173 | −20.115 | 1.570 | −18.545 | −0.0765 | 0.0066 | −0.0699 | −373.95 | −1.3750 | 0.10326 | −20 |
| −19 | 0.0007013 | 0.7194 | 0.0008 | 0.7202 | −19.109 | 1.729 | −17.380 | −0.0725 | 0.0072 | −0.0653 | −371.99 | −1.3673 | 0.11362 | −19 |
| −18 | 0.0007711 | 0.7222 | 0.0009 | 0.7231 | −18.103 | 1.902 | −16.201 | −0.0686 | 0.0079 | −0.0607 | −370.02 | −1.3596 | 0.12492 | −18 |
| −17 | 0.0008473 | 0.7251 | 0.0010 | 0.7261 | −17.098 | 2.092 | −15.006 | −0.0646 | 0.0086 | −0.0560 | −368.04 | −1.3518 | 0.13725 | −17 |
| −16 | 0.0009303 | 0.7279 | 0.0011 | 0.7290 | −16.092 | 2.299 | −13.793 | −0.0607 | 0.0094 | −0.0513 | −366.06 | −1.3441 | 0.15068 | −16 |
| −15 | 0.0010207 | 0.7308 | 0.0012 | 0.7320 | −15.086 | 2.524 | −12.562 | −0.0568 | 0.0103 | −0.0465 | −364.07 | −1.3364 | 0.16530 | −15 |
| −14 | 0.0011191 | 0.7336 | 0.0013 | 0.7349 | −14.080 | 2.769 | −11.311 | −0.0529 | 0.0113 | −0.0416 | −362.07 | −1.3287 | 0.18122 | −14 |
| −13 | 0.0012262 | 0.7364 | 0.0014 | 0.7379 | −13.075 | 3.036 | −10.039 | −0.0490 | 0.0123 | −0.0367 | −360.07 | −1.3210 | 0.19852 | −13 |
| −12 | 0.0013425 | 0.7393 | 0.0016 | 0.7409 | −12.069 | 3.327 | −8.742 | −0.0452 | 0.0134 | −0.0318 | −358.06 | −1.3132 | 0.21732 | −12 |
| −11 | 0.0014690 | 0.7421 | 0.0017 | 0.7439 | −11.063 | 3.642 | −7.421 | −0.0413 | 0.0146 | −0.0267 | −356.04 | −1.3055 | 0.23775 | −11 |
| −10 | 0.0016062 | 0.7450 | 0.0019 | 0.7469 | −10.057 | 3.986 | −6.072 | −0.0375 | 0.0160 | −0.0215 | −354.01 | −1.2978 | 0.25991 | −10 |
| −9 | 0.0017551 | 0.7478 | 0.0021 | 0.7499 | −9.052 | 4.358 | −4.693 | −0.0337 | 0.0174 | −0.0163 | −351.97 | −1.2901 | 0.28395 | −9 |
| −8 | 0.0019166 | 0.7507 | 0.0023 | 0.7530 | −8.046 | 4.764 | −3.283 | −0.0299 | 0.0189 | −0.0110 | −349.93 | −1.2824 | 0.30999 | −8 |
| −7 | 0.0020916 | 0.7535 | 0.0025 | 0.7560 | −7.040 | 5.202 | −1.838 | −0.0261 | 0.0206 | −0.0055 | −347.88 | −1.2746 | 0.33821 | −7 |
| −6 | 0.0022811 | 0.7563 | 0.0028 | 0.7591 | −6.035 | 5.677 | −0.357 | −0.0223 | 0.0224 | −0.0000 | −345.82 | −1.2669 | 0.36874 | −6 |
| −5 | 0.0024862 | 0.7592 | 0.0030 | 0.7622 | −5.029 | 6.192 | 1.164 | −0.0186 | 0.0243 | −0.0057 | −343.76 | −1.2592 | 0.40178 | −5 |
| −4 | 0.0027081 | 0.7620 | 0.0033 | 0.7653 | −4.023 | 6.751 | 2.728 | −0.0148 | 0.0264 | −0.0115 | −341.69 | −1.2515 | 0.43748 | −4 |
| −3 | 0.0029480 | 0.7649 | 0.0036 | 0.7685 | −3.017 | 7.353 | 4.336 | −0.0111 | 0.0286 | −0.0175 | −339.61 | −1.2438 | 0.47606 | −3 |
| −2 | 0.0032074 | 0.7677 | 0.0039 | 0.7717 | −2.011 | 8.007 | 5.995 | −0.0074 | 0.0310 | −0.0236 | −337.52 | −1.2361 | 0.51773 | −2 |
| −1 | 0.0034874 | 0.7705 | 0.0043 | 0.7749 | −1.006 | 8.712 | 7.706 | −0.0037 | 0.0336 | −0.0299 | −335.42 | −1.2284 | 0.56268 | −1 |
| 0 | 0.0037895 | 0.7734 | 0.0047 | 0.7781 | 0.000 | 9.473 | 9.473 | 0.0000 | 0.0364 | 0.0364 | −333.32 | −1.2206 | 0.61117 | 0 |
| 0* | 0.003789 | 0.7734 | 0.0047 | 0.7781 | 0.000 | 9.473 | 9.473 | 0.0000 | 0.0364 | 0.0364 | 0.06 | −0.0001 | 0.6112 | 0 |
| 1 | 0.004076 | 0.7762 | 0.0051 | 0.7813 | 1.006 | 10.197 | 11.203 | 0.0037 | 0.0391 | 0.0427 | 4.28 | 0.0153 | 0.6571 | 1 |
| 2 | 0.004381 | 0.7791 | 0.0055 | 0.7845 | 2.012 | 10.970 | 12.982 | 0.0073 | 0.0419 | 0.0492 | 8.49 | 0.0306 | 0.7060 | 2 |
| 3 | 0.004707 | 0.7819 | 0.0059 | 0.7878 | 3.018 | 11.793 | 14.811 | 0.0110 | 0.0449 | 0.0559 | 12.70 | 0.0459 | 0.7581 | 3 |
| 4 | 0.005054 | 0.7848 | 0.0064 | 0.7911 | 4.024 | 12.672 | 16.696 | 0.0146 | 0.0480 | 0.0627 | 16.91 | 0.0611 | 0.8135 | 4 |
| 5 | 0.005424 | 0.7876 | 0.0068 | 0.7944 | 5.029 | 13.610 | 18.639 | 0.0182 | 0.0514 | 0.0697 | 21.12 | 0.0762 | 0.8725 | 5 |
| 6 | 0.005818 | 0.7904 | 0.0074 | 0.7978 | 6.036 | 14.608 | 20.644 | 0.0219 | 0.0550 | 0.0769 | 25.32 | 0.0913 | 0.9353 | 6 |
| 7 | 0.006237 | 0.7933 | 0.0079 | 0.8012 | 7.041 | 15.671 | 22.713 | 0.0255 | 0.0588 | 0.0843 | 29.52 | 0.1064 | 1.0020 | 7 |
| 8 | 0.006683 | 0.7961 | 0.0085 | 0.8046 | 8.047 | 16.805 | 24.852 | 0.0290 | 0.0628 | 0.0919 | 33.72 | 0.1213 | 1.0729 | 8 |
| 9 | 0.007157 | 0.7990 | 0.0092 | 0.8081 | 9.053 | 18.010 | 27.064 | 0.0326 | 0.0671 | 0.0997 | 37.92 | 0.1362 | 1.1481 | 9 |
| −10 | 0.0016062 | 0.7450 | 0.0019 | 0.7469 | −10.057 | 3.986 | −6.072 | −0.0375 | 0.0160 | −0.0215 | −354.01 | −1.2978 | 0.25991 | −10 |
| −9 | 0.0017551 | 0.7478 | 0.0021 | 0.7499 | −9.052 | 4.358 | −4.693 | −0.0337 | 0.0174 | −0.0163 | −351.97 | −1.2901 | 0.28395 | −9 |
| −8 | 0.0019166 | 0.7507 | 0.0023 | 0.7530 | −8.046 | 4.764 | −3.283 | −0.0299 | 0.0189 | −0.0110 | −349.93 | −1.2824 | 0.30999 | −8 |
| −7 | 0.0020916 | 0.7535 | 0.0025 | 0.7560 | −7.040 | 5.202 | −1.838 | −0.0261 | 0.0206 | −0.0055 | −347.88 | −1.2746 | 0.33821 | −7 |
| −6 | 0.0022811 | 0.7563 | 0.0028 | 0.7591 | −6.035 | 5.677 | −0.357 | −0.0223 | 0.0224 | −0.0000 | −345.82 | −1.2669 | 0.36874 | −6 |
| −5 | 0.0024862 | 0.7592 | 0.0030 | 0.7622 | −5.029 | 6.192 | 1.164 | −0.0186 | 0.0243 | −0.0057 | −343.76 | −1.2592 | 0.40178 | −5 |
| −4 | 0.0027081 | 0.7620 | 0.0033 | 0.7653 | −4.023 | 6.751 | 2.728 | −0.0148 | 0.0264 | −0.0115 | −341.69 | −1.2515 | 0.43748 | −4 |
| −3 | 0.0029480 | 0.7649 | 0.0036 | 0.7685 | −3.017 | 7.353 | 4.336 | −0.0111 | 0.0286 | −0.0175 | −339.61 | −1.2438 | 0.47606 | −3 |
| −2 | 0.0032074 | 0.7677 | 0.0039 | 0.7717 | −2.011 | 8.007 | 5.995 | −0.0074 | 0.0310 | −0.0236 | −337.52 | −1.2361 | 0.51773 | −2 |
| −1 | 0.0034874 | 0.7705 | 0.0043 | 0.7749 | −1.006 | 8.712 | 7.706 | −0.0037 | 0.0336 | −0.0299 | −335.42 | −1.2284 | 0.56268 | −1 |
| 0 | 0.0037895 | 0.7734 | 0.0047 | 0.7781 | 0.000 | 9.473 | 9.473 | 0.0000 | 0.0364 | 0.0364 | −333.32 | −1.2206 | 0.61117 | 0 |
| 0* | 0.003789 | 0.7734 | 0.0047 | 0.7781 | 0.000 | 9.473 | 9.473 | 0.0000 | 0.0364 | 0.0364 | 0.06 | −0.0001 | 0.6112 | 0 |
| 1 | 0.004076 | 0.7762 | 0.0051 | 0.7813 | 1.006 | 10.197 | 11.203 | 0.0037 | 0.0391 | 0.0427 | 4.28 | 0.0153 | 0.6571 | 1 |
| 2 | 0.004381 | 0.7791 | 0.0055 | 0.7845 | 2.012 | 10.970 | 12.982 | 0.0073 | 0.0419 | 0.0492 | 8.49 | 0.0306 | 0.7060 | 2 |
| 3 | 0.004707 | 0.7819 | 0.0059 | 0.7878 | 3.018 | 11.793 | 14.811 | 0.0110 | 0.0449 | 0.0559 | 12.70 | 0.0459 | 0.7581 | 3 |
| 4 | 0.005054 | 0.7848 | 0.0064 | 0.7911 | 4.024 | 12.672 | 16.696 | 0.0146 | 0.0480 | 0.0627 | 16.91 | 0.0611 | 0.8135 | 4 |
| 5 | 0.005424 | 0.7876 | 0.0068 | 0.7944 | 5.029 | 13.610 | 18.639 | 0.0182 | 0.0514 | 0.0697 | 21.12 | 0.0762 | 0.8725 | 5 |
| 6 | 0.005818 | 0.7904 | 0.0074 | 0.7978 | 6.036 | 14.608 | 20.644 | 0.0219 | 0.0550 | 0.0769 | 25.32 | 0.0913 | 0.9353 | 6 |
| 7 | 0.006237 | 0.7933 | 0.0079 | 0.8012 | 7.041 | 15.671 | 22.713 | 0.0255 | 0.0588 | 0.0843 | 29.52 | 0.1064 | 1.0020 | 7 |
| 8 | 0.006683 | 0.7961 | 0.0085 | 0.8046 | 8.047 | 16.805 | 24.852 | 0.0290 | 0.0628 | 0.0919 | 33.72 | 0.1213 | 1.0729 | 8 |
| 9 | 0.007157 | 0.7990 | 0.0092 | 0.8081 | 9.053 | 18.010 | 27.064 | 0.0326 | 0.0671 | 0.0997 | 37.92 | 0.1362 | 1.1481 | 9 |
| 10 | 0.007661 | 0.8018 | 0.0098 | 0.8116 | 10.059 | 19.293 | 29.352 | 0.0362 | 0.0717 | 0.1078 | 42.11 | 0.1511 | 1.2280 | 10 |
| 11 | 0.008197 | 0.8046 | 0.0106 | 0.8152 | 11.065 | 20.658 | 31.724 | 0.0397 | 0.0765 | 0.1162 | 46.31 | 0.1659 | 1.3128 | 11 |
| 12 | 0.008766 | 0.8075 | 0.0113 | 0.8188 | 12.071 | 22.108 | 34.179 | 0.0433 | 0.0816 | 0.1248 | 50.50 | 0.1806 | 1.4026 | 12 |
| 13 | 0.009370 | 0.8103 | 0.0122 | 0.8225 | 13.077 | 23.649 | 36.726 | 0.0468 | 0.0870 | 0.1337 | 54.69 | 0.1953 | 1.4979 | 13 |

*Extrapolated to represent metastable equilibrium with undercooled liquid.

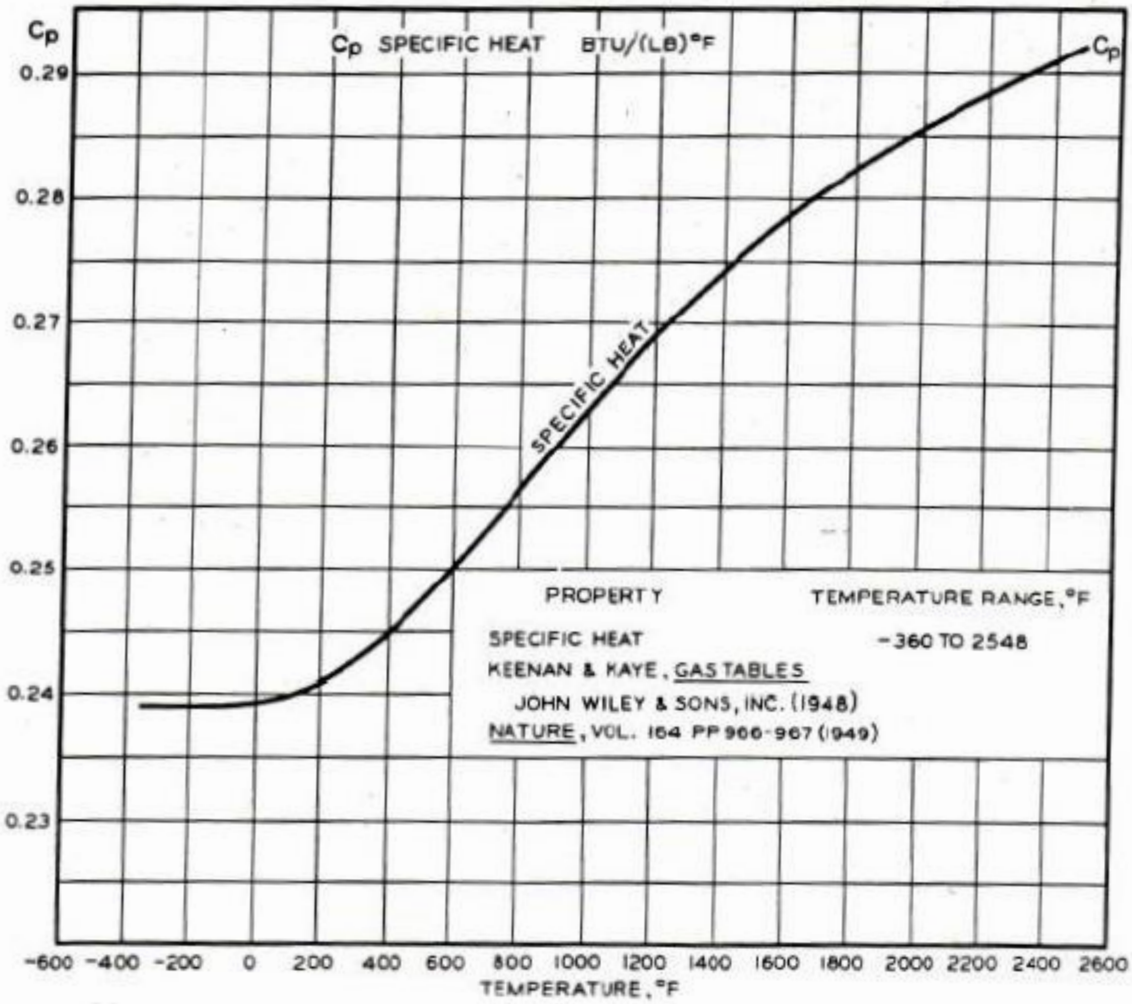
# APPENDIX 1
# PSYCHROMETRIC TABLE



**Table 2 Thermodynamic Properties of Moist Air at Standard Atmospheric Pressure, 101.325 kPa (*Continued*)**

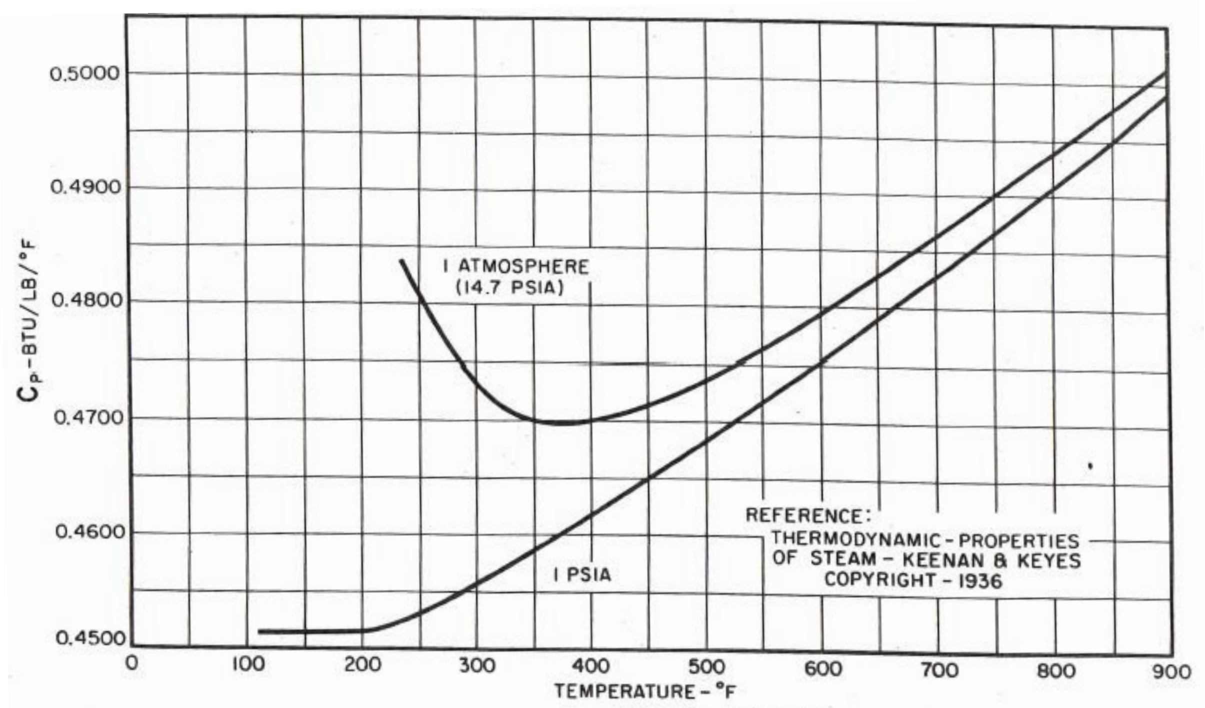
| Temp., °C | Humidity Ratio, kg(w)/kg(da) | Specific Volume, $m^3$/kg (dry air) | | | Specific Enthalpy, kJ/kg (dry air) | | | Specific Entropy, kJ/(kg·K) (dry air) | | | Condensed Water: Specific Enthalpy, kJ/kg | Condensed Water: Specific Entropy, kJ/(kg·K) | Condensed Water: Vapor Pressure, kPa | Temp., °C |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $t$ | $W_s$ | $v_{da}$ | $v_{as}$ | $v_s$ | $h_{da}$ | $h_{as}$ | $h_s$ | $s_{da}$ | $s_{as}$ | $s_s$ | $h_w$ | $s_w$ | $p_s$ | $t$ |
| 14 | 0.010012 | 0.8132 | 0.0131 | 0.8262 | 14.084 | 25.286 | 39.370 | 0.0503 | 0.0927 | 0.1430 | 58.88 | 0.2099 | 1.5987 | 14 |
| 15 | 0.010692 | 0.8160 | 0.0140 | 0.8300 | 15.090 | 27.023 | 42.113 | 0.0538 | 0.0987 | 0.1525 | 63.07 | 0.2244 | 1.7055 | 15 |
| 16 | 0.011413 | 0.8188 | 0.0150 | 0.8338 | 16.096 | 28.867 | 44.963 | 0.0573 | 0.1051 | 0.1624 | 67.26 | 0.2389 | 1.8185 | 16 |
| 17 | 0.012178 | 0.8217 | 0.0160 | 0.8377 | 17.102 | 30.824 | 47.926 | 0.0607 | 0.1119 | 0.1726 | 71.44 | 0.2534 | 1.9380 | 17 |
| 18 | 0.012989 | 0.8245 | 0.0172 | 0.8417 | 18.108 | 32.900 | 51.008 | 0.0642 | 0.1190 | 0.1832 | 75.63 | 0.2678 | 2.0643 | 18 |
| 19 | 0.013848 | 0.8274 | 0.0184 | 0.8457 | 19.114 | 35.101 | 54.216 | 0.0677 | 0.1266 | 0.1942 | 79.81 | 0.2821 | 2.1979 | 19 |
| 20 | 0.014758 | 0.8302 | 0.0196 | 0.8498 | 20.121 | 37.434 | 57.555 | 0.0711 | 0.1346 | 0.2057 | 84.00 | 0.2965 | 2.3389 | 20 |
| 21 | 0.015721 | 0.8330 | 0.0210 | 0.8540 | 21.127 | 39.908 | 61.035 | 0.0745 | 0.1430 | 0.2175 | 88.18 | 0.3107 | 2.4878 | 21 |
| 22 | 0.016741 | 0.8359 | 0.0224 | 0.8583 | 22.133 | 42.527 | 64.660 | 0.0779 | 0.1519 | 0.2298 | 92.36 | 0.3249 | 2.6448 | 22 |
| 23 | 0.017821 | 0.8387 | 0.0240 | 0.8627 | 23.140 | 45.301 | 68.440 | 0.0813 | 0.1613 | 0.2426 | 96.55 | 0.3390 | 2.8105 | 23 |
| 24 | 0.018963 | 0.8416 | 0.0256 | 0.8671 | 24.146 | 48.239 | 72.385 | 0.0847 | 0.1712 | 0.2559 | 100.73 | 0.3531 | 2.9852 | 24 |
| 25 | 0.020170 | 0.8444 | 0.0273 | 0.8717 | 25.153 | 51.347 | 76.500 | 0.0881 | 0.1817 | 0.2698 | 104.91 | 0.3672 | 3.1693 | 25 |
| 26 | 0.021448 | 0.8472 | 0.0291 | 0.8764 | 26.159 | 54.638 | 80.798 | 0.0915 | 0.1927 | 0.2842 | 109.09 | 0.3812 | 3.3633 | 26 |
| 27 | 0.022798 | 0.8501 | 0.0311 | 0.8811 | 27.165 | 58.120 | 85.285 | 0.0948 | 0.2044 | 0.2992 | 113.27 | 0.3951 | 3.5674 | 27 |
| 28 | 0.024226 | 0.8529 | 0.0331 | 0.8860 | 28.172 | 61.804 | 89.976 | 0.0982 | 0.2166 | 0.3148 | 117.45 | 0.4090 | 3.7823 | 28 |
| 29 | 0.025735 | 0.8558 | 0.0353 | 0.8910 | 29.179 | 65.699 | 94.878 | 0.1015 | 0.2296 | 0.3311 | 121.63 | 0.4229 | 4.0084 | 29 |
| 30 | 0.027329 | 0.8586 | 0.0376 | 0.8962 | 30.185 | 69.820 | 100.006 | 0.1048 | 0.2432 | 0.3481 | 125.81 | 0.4367 | 4.2462 | 30 |
| 31 | 0.029014 | 0.8614 | 0.0400 | 0.9015 | 31.192 | 74.177 | 105.369 | 0.1082 | 0.2576 | 0.3658 | 129.99 | 0.4505 | 4.4961 | 31 |
| 32 | 0.030793 | 0.8643 | 0.0426 | 0.9069 | 32.198 | 78.780 | 110.979 | 0.1115 | 0.2728 | 0.3842 | 134.17 | 0.4642 | 4.7586 | 32 |
| 33 | 0.032674 | 0.8671 | 0.0454 | 0.9125 | 33.205 | 83.652 | 116.857 | 0.1148 | 0.2887 | 0.4035 | 138.35 | 0.4779 | 5.0345 | 33 |
| 34 | 0.034660 | 0.8700 | 0.0483 | 0.9183 | 34.212 | 88.799 | 123.011 | 0.1180 | 0.3056 | 0.4236 | 142.53 | 0.4915 | 5.3242 | 34 |
| 35 | 0.036756 | 0.8728 | 0.0514 | 0.9242 | 35.219 | 94.236 | 129.455 | 0.1213 | 0.3233 | 0.4446 | 146.71 | 0.5051 | 5.6280 | 35 |
| 36 | 0.038971 | 0.8756 | 0.0546 | 0.9303 | 36.226 | 99.983 | 136.209 | 0.1246 | 0.3420 | 0.4666 | 150.89 | 0.5186 | 5.9468 | 36 |
| 37 | 0.041309 | 0.8785 | 0.0581 | 0.9366 | 37.233 | 106.058 | 143.290 | 0.1278 | 0.3617 | 0.4895 | 155.07 | 0.5321 | 6.2812 | 37 |
| 38 | 0.043778 | 0.8813 | 0.0618 | 0.9431 | 38.239 | 112.474 | 150.713 | 0.1311 | 0.3824 | 0.5135 | 159.25 | 0.5456 | 6.6315 | 38 |
| 39 | 0.046386 | 0.8842 | 0.0657 | 0.9498 | 39.246 | 119.258 | 158.504 | 0.1343 | 0.4043 | 0.5386 | 163.43 | 0.5590 | 6.9988 | 39 |
| 40 | 0.049141 | 0.8870 | 0.0698 | 0.9568 | 40.253 | 126.430 | 166.683 | 0.1375 | 0.4273 | 0.5649 | 167.61 | 0.5724 | 7.3838 | 40 |
| 41 | 0.052049 | 0.8898 | 0.0741 | 0.9640 | 41.261 | 134.005 | 175.265 | 0.1407 | 0.4516 | 0.5923 | 171.79 | 0.5857 | 7.7866 | 41 |
| 42 | 0.055119 | 0.8927 | 0.0788 | 0.9714 | 42.268 | 142.007 | 184.275 | 0.1439 | 0.4771 | 0.6211 | 175.97 | 0.5990 | 8.2081 | 42 |
| 43 | 0.058365 | 0.8955 | 0.0837 | 0.9792 | 43.275 | 150.475 | 193.749 | 0.1471 | 0.5041 | 0.6512 | 180.15 | 0.6122 | 8.6495 | 43 |
| 44 | 0.061791 | 0.8983 | 0.0888 | 0.9872 | 44.282 | 159.417 | 203.699 | 0.1503 | 0.5325 | 0.6828 | 184.33 | 0.6254 | 9.1110 | 44 |
| 45 | 0.065411 | 0.9012 | 0.0943 | 0.9955 | 45.289 | 168.874 | 214.164 | 0.1535 | 0.5624 | 0.7159 | 188.51 | 0.6386 | 9.5935 | 45 |
| 46 | 0.069239 | 0.9040 | 0.1002 | 1.0042 | 46.296 | 178.882 | 225.179 | 0.1566 | 0.5940 | 0.7507 | 192.69 | 0.6517 | 10.0982 | 46 |
| 47 | 0.073282 | 0.9069 | 0.1063 | 1.0132 | 47.304 | 189.455 | 236.759 | 0.1598 | 0.6273 | 0.7871 | 196.88 | 0.6648 | 10.6250 | 47 |
| 48 | 0.077556 | 0.9097 | 0.1129 | 1.0226 | 48.311 | 200.644 | 248.955 | 0.1629 | 0.6624 | 0.8253 | 201.06 | 0.6778 | 11.1754 | 48 |
| 49 | 0.082077 | 0.9125 | 0.1198 | 1.0323 | 49.319 | 212.485 | 261.803 | 0.1661 | 0.6994 | 0.8655 | 205.24 | 0.6908 | 11.7502 | 49 |
| 50 | 0.086858 | 0.9154 | 0.1272 | 1.0425 | 50.326 | 225.019 | 275.345 | 0.1692 | 0.7385 | 0.9077 | 209.42 | 0.7038 | 12.3503 | 50 |
| 51 | 0.091918 | 0.9182 | 0.1350 | 1.0532 | 51.334 | 238.290 | 289.624 | 0.1723 | 0.7798 | 0.9521 | 213.60 | 0.7167 | 12.9764 | 51 |
| 52 | 0.097272 | 0.9211 | 0.1433 | 1.0643 | 52.341 | 252.340 | 304.682 | 0.1754 | 0.8234 | 0.9988 | 217.78 | 0.7296 | 13.6293 | 52 |
| 53 | 0.102948 | 0.9239 | 0.1521 | 1.0760 | 53.349 | 267.247 | 320.596 | 0.1785 | 0.8695 | 1.0480 | 221.97 | 0.7424 | 14.3108 | 53 |
| 54 | 0.108954 | 0.9267 | 0.1614 | 1.0882 | 54.357 | 283.031 | 337.388 | 0.1816 | 0.9182 | 1.0998 | 226.15 | 0.7552 | 15.0205 | 54 |
| 55 | 0.115321 | 0.9296 | 0.1713 | 1.1009 | 55.365 | 299.772 | 355.137 | 0.1847 | 0.9698 | 1.1544 | 230.33 | 0.7680 | 15.7601 | 55 |
| 56 | 0.122077 | 0.9324 | 0.1819 | 1.1143 | 56.373 | 317.549 | 373.922 | 0.1877 | 1.0243 | 1.2120 | 234.52 | 0.7807 | 16.5311 | 56 |
| 57 | 0.129243 | 0.9353 | 0.1932 | 1.1284 | 57.381 | 336.417 | 393.798 | 0.1908 | 1.0820 | 1.2728 | 238.70 | 0.7934 | 17.3337 | 57 |
| 58 | 0.136851 | 0.9381 | 0.2051 | 1.1432 | 58.389 | 356.461 | 414.850 | 0.1938 | 1.1432 | 1.3370 | 242.88 | 0.8061 | 18.1691 | 58 |
| 59 | 0.144942 | 0.9409 | 0.2179 | 1.1588 | 59.397 | 377.788 | 437.185 | 0.1969 | 1.2081 | 1.4050 | 247.07 | 0.8187 | 19.0393 | 59 |
| 60 | 0.15354 | 0.9438 | 0.2315 | 1.1752 | 60.405 | 400.458 | 460.863 | 0.1999 | 1.2769 | 1.4768 | 251.25 | 0.8313 | 19.9439 | 60 |
| 61 | 0.16269 | 0.9466 | 0.2460 | 1.1926 | 61.413 | 424.624 | 486.036 | 0.2029 | 1.3500 | 1.5530 | 255.44 | 0.8438 | 20.8858 | 61 |
| 62 | 0.17244 | 0.9494 | 0.2614 | 1.2109 | 62.421 | 450.377 | 512.798 | 0.2059 | 1.4278 | 1.6337 | 259.62 | 0.8563 | 21.8651 | 62 |
| 63 | 0.18284 | 0.9523 | 0.2780 | 1.2303 | 63.429 | 477.837 | 541.266 | 0.2089 | 1.5104 | 1.7194 | 263.81 | 0.8688 | 22.8826 | 63 |
| 64 | 0.19393 | 0.9551 | 0.2957 | 1.2508 | 64.438 | 507.177 | 571.615 | 0.2119 | 1.5985 | 1.8105 | 268.00 | 0.8812 | 23.9405 | 64 |
| 65 | 0.20579 | 0.9580 | 0.3147 | 1.2726 | 65.446 | 538.548 | 603.995 | 0.2149 | 1.6925 | 1.9074 | 272.18 | 0.8936 | 25.0397 | 65 |
| 66 | 0.21848 | 0.9608 | 0.3350 | 1.2958 | 66.455 | 572.116 | 638.571 | 0.2179 | 1.7927 | 2.0106 | 276.37 | 0.9060 | 26.1810 | 66 |
| 67 | 0.23207 | 0.9636 | 0.3568 | 1.3204 | 67.463 | 608.103 | 675.566 | 0.2209 | 1.8999 | 2.1208 | 280.56 | 0.9183 | 27.3664 | 67 |
| 68 | 0.24664 | 0.9665 | 0.3803 | 1.3467 | 68.472 | 646.724 | 715.196 | 0.2238 | 2.0147 | 2.2385 | 284.75 | 0.9306 | 28.5967 | 68 |
| 69 | 0.26231 | 0.9693 | 0.4055 | 1.3749 | 69.481 | 688.261 | 757.742 | 0.2268 | 2.1378 | 2.3646 | 288.94 | 0.9429 | 29.8741 | 69 |
| 70 | 0.27916 | 0.9721 | 0.4328 | 1.4049 | 70.489 | 732.959 | 803.448 | 0.2297 | 2.2699 | 2.4996 | 293.13 | 0.9551 | 31.1986 | 70 |
| 71 | 0.29734 | 0.9750 | 0.4622 | 1.4372 | 71.498 | 781.208 | 852.706 | 0.2327 | 2.4122 | 2.6448 | 297.32 | 0.9673 | 32.5734 | 71 |
| 72 | 0.31698 | 0.9778 | 0.4941 | 1.4719 | 72.507 | 833.335 | 905.842 | 0.2356 | 2.5655 | 2.8010 | 301.51 | 0.9794 | 33.9983 | 72 |
| 73 | 0.33824 | 0.9807 | 0.5287 | 1.5093 | 73.516 | 889.807 | 963.323 | 0.2385 | 2.7311 | 2.9696 | 305.70 | 0.9916 | 35.4759 | 73 |
| 74 | 0.36130 | 0.9835 | 0.5662 | 1.5497 | 74.525 | 951.077 | 1025.603 | 0.2414 | 2.9104 | 3.1518 | 309.89 | 1.0037 | 37.0063 | 74 |
| 75 | 0.38641 | 0.9863 | 0.6072 | 1.5935 | 75.535 | 1017.841 | 1093.375 | 0.2443 | 3.1052 | 3.3496 | 314.08 | 1.0157 | 38.5940 | 75 |
| 76 | 0.41377 | 0.9892 | 0.6519 | 1.6411 | 76.543 | 1090.628 | 1167.172 | 0.2472 | 3.3171 | 3.5644 | 318.28 | 1.0278 | 40.2369 | 76 |
| 77 | 0.44372 | 0.9920 | 0.7010 | 1.6930 | 77.553 | 1170.328 | 1247.881 | 0.2501 | 3.5486 | 3.7987 | 322.47 | 1.0398 | 41.9388 | 77 |
| 78 | 0.47663 | 0.9948 | 0.7550 | 1.7498 | 78.562 | 1257.921 | 1336.483 | 0.2530 | 3.8023 | 4.0553 | 326.67 | 1.0517 | 43.7020 | 78 |
| 79 | 0.51284 | 0.9977 | 0.8145 | 1.8121 | 79.572 | 1354.347 | 1433.918 | 0.2559 | 4.0810 | 4.3368 | 330.86 | 1.0636 | 45.5248 | 79 |
| 80 | 0.55295 | 1.0005 | 0.8805 | 1.8810 | 80.581 | 1461.200 | 1541.781 | 0.2587 | 4.3890 | 4.6477 | 335.06 | 1.0755 | 47.4135 | 80 |
| 81 | 0.59751 | 1.0034 | 0.9539 | 1.9572 | 81.591 | 1579.961 | 1661.552 | 0.2616 | 4.7305 | 4.9921 | 339.25 | 1.0874 | 49.3670 | 81 |
| 82 | 0.64724 | 1.0062 | 1.0360 | 2.0422 | 82.600 | 1712.547 | 1795.148 | 0.2644 | 5.1108 | 5.3753 | 343.45 | 1.0993 | 51.3860 | 82 |
| 83 | 0.70311 | 1.0090 | 1.1283 | 2.1373 | 83.610 | 1861.548 | 1945.158 | 0.2673 | 5.5372 | 5.8045 | 347.65 | 1.1111 | 53.4746 | 83 |
| 84 | 0.76624 | 1.0119 | 1.2328 | 2.2446 | 84.620 | 2029.983 | 2114.603 | 0.2701 | 6.0181 | 6.2882 | 351.85 | 1.1228 | 55.6337 | 84 |
| 85 | 0.83812 | 1.0147 | 1.3518 | 2.3666 | 85.630 | 2221.806 | 2307.436 | 0.2729 | 6.5644 | 6.8373 | 356.05 | 1.1346 | 57.8658 | 85 |
| 86 | 0.92062 | 1.0175 | 1.4887 | 2.5062 | 86.640 | 2442.036 | 2528.677 | 0.2757 | 7.1901 | 7.4658 | 360.25 | 1.1463 | 60.1727 | 86 |
| 87 | 1.01611 | 1.0204 | 1.6473 | 2.6676 | 87.650 | 2697.016 | 2784.666 | 0.2785 | 7.9128 | 8.1914 | 364.45 | 1.1580 | 62.5544 | 87 |
| 88 | 1.12800 | 1.0232 | 1.8333 | 2.8565 | 88.661 | 2995.890 | 3084.551 | 0.2813 | 8.7580 | 9.0393 | 368.65 | 1.1696 | 65.0166 | 88 |
| 89 | 1.26064 | 1.0261 | 2.0540 | 3.0800 | 89.671 | 3350.254 | 3439.925 | 0.2841 | 9.7577 | 10.0419 | 372.86 | 1.1812 | 67.5581 | 89 |
| 90 | 1.42031 | 1.0289 | 2.3199 | 3.3488 | 90.681 | 3776.918 | 3867.599 | 0.2869 | 10.9586 | 11.2455 | 377.06 | 1.1928 | 70.1817 | 90 |

# APPENDIX 2
# SPECIFIC HEAT OF AIR



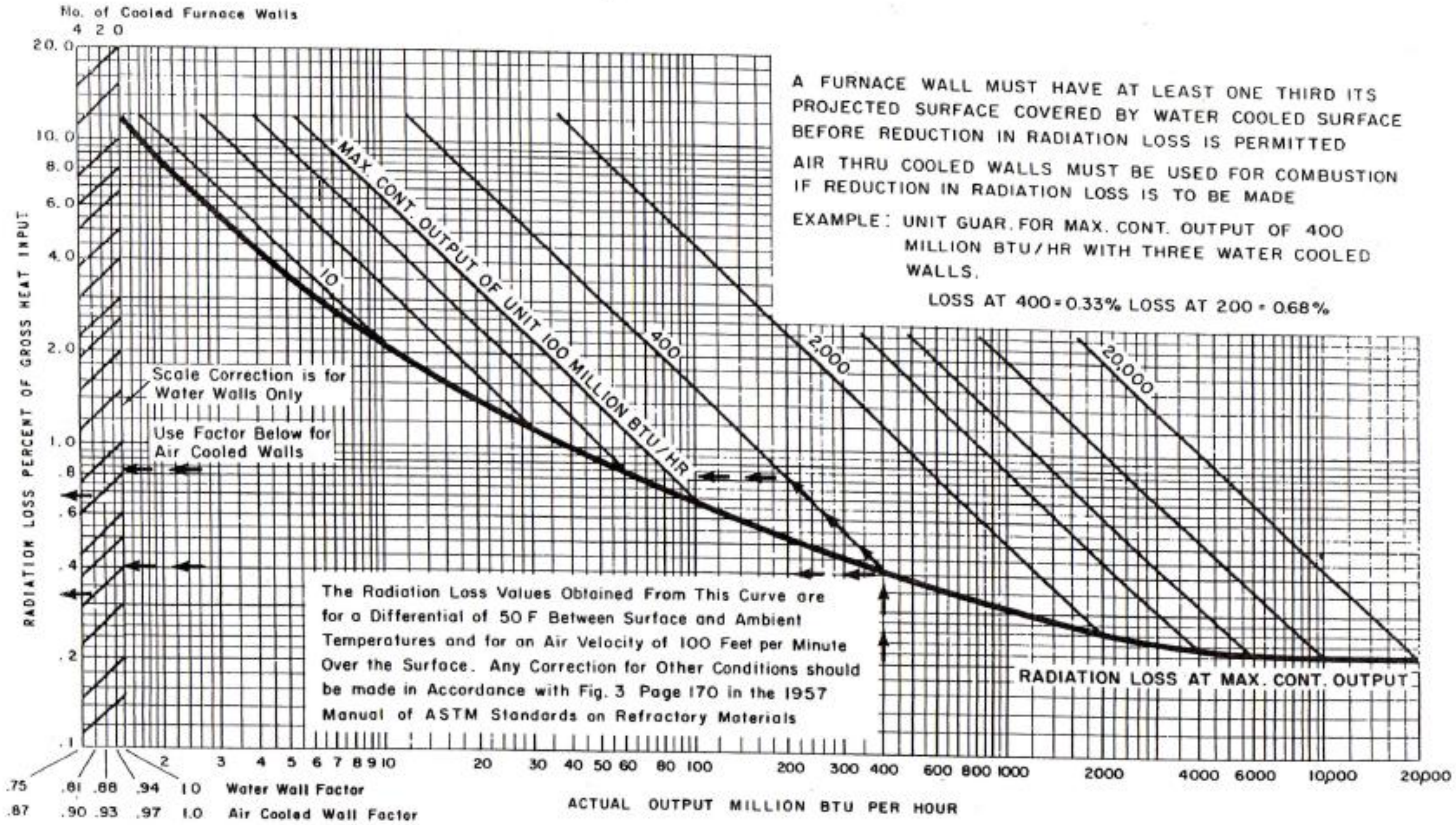

INSTANTANEOUS SPECIFIC HEAT OF AIR

# APPENDIX 3
# SPECIFIC HEAT OF STEAM



INSTANTANEOUS SPECIFIC HEAT OF STEAM

## APPENDIX 4
## ABMA STANDARD RADIATION LOSS CHART




ABMA STANDARD RADIATION LOSS CHART

(Published through the courtesy of the American Boiler Manufacturers Association.)

**APPENDIX 5**
**FOR ABMA CHART**

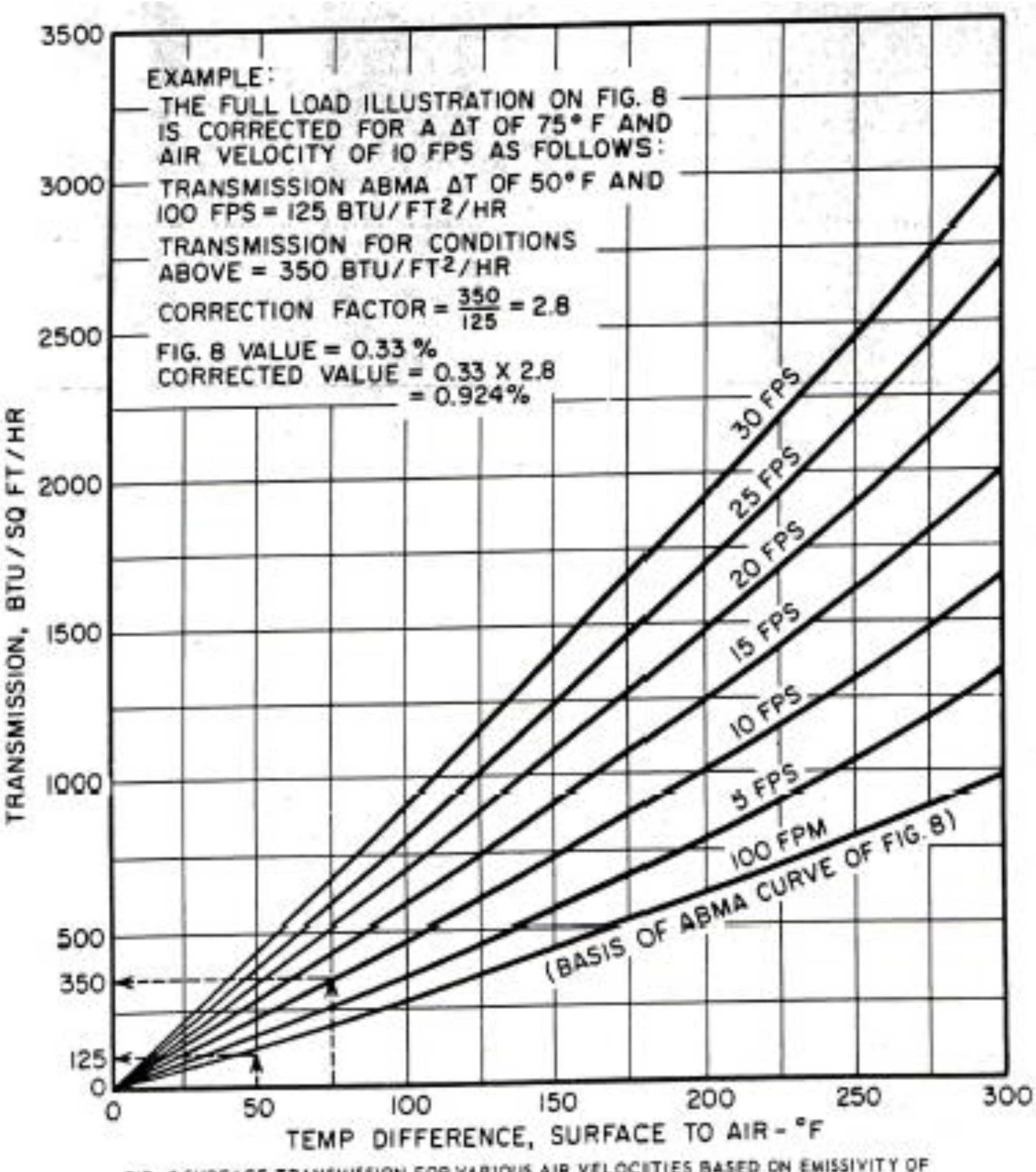
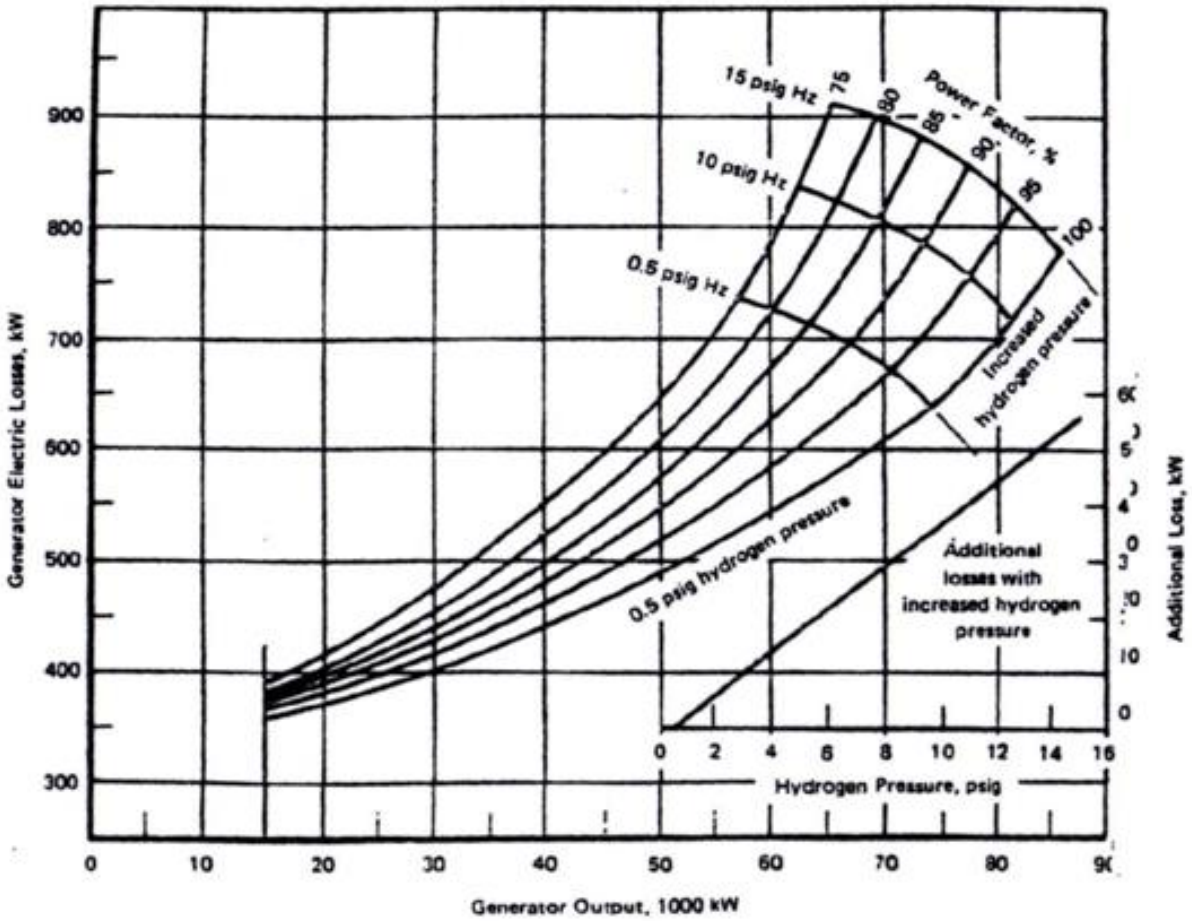



FIG. 9 SURFACE TRANSMISSION FOR VARIOUS AIR VELOCITIES BASED ON EMISSIVITY OF 0.95 AND AIR TEMPERATURE OF 70 F

(Basic data above were obtained from ASTM Standard on Refractory Materials)

**APPENDIX 6**
**GENERATOR ELECTRICAL LOSSES**




GENERATOR ELECTRICAL LOSSES

**APPENDIX 7**
**SPECIFIC HEAT OF FLUE GAS**

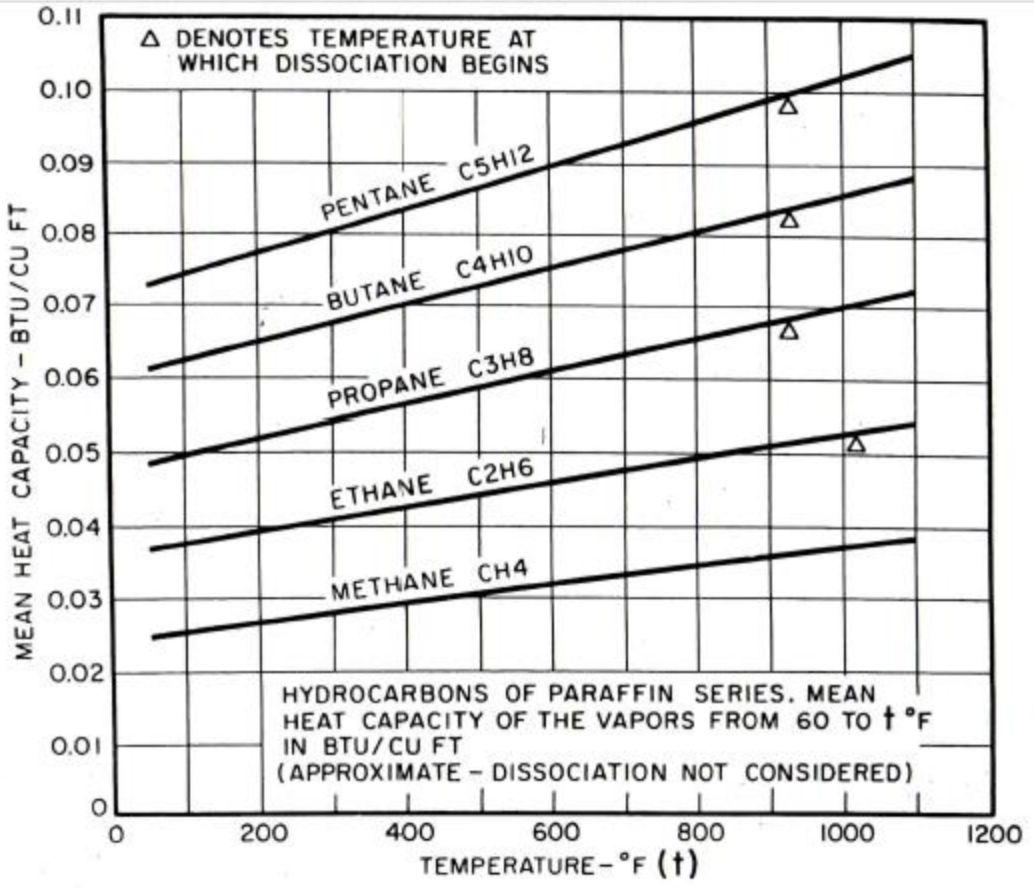



FIG. 5 INSTANTANEOUS SPECIFIC HEAT OF FUEL GAS
(Reference: American Gas Association Publication of 1954, P 124, Edited by Louis Shnidman)